DEVELOPMENT OF A NOVEL FEATURE BASED MANUFACTURABILITY ASSESSMENT SYSTEM FOR HIGH-VOLUME INJECTION MOULDING TOOL INSERTS

A thesis submitted in partial fulfilment for the Degree of Doctor of Philosophy

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ABSTRACT

Selective Laser Melting (SLM) is a versatile fabrication method that provides freedom in design complexity through the development of net or near-net shape metallic components within certain limitations such as dimensional accuracy and surface finish. The rapid development of metallic Additive Manufacturing (AM) technologies and their wide-ranging applications facilitate the unprecedented challenges faced by automotive industries for the production of injection moulding tool inserts in timescales greatly reduced from those experienced when manufacturing using more established and conventional processes. It is accepted that AM has limitations with regard to surface roughness requiring post processing of the parts produced. Global demand is striving for the production of injection moulding tool inserts in terms of higher quality. Previous research was applied to investigate the benefits of AM in the production of low-volume injection moulding tool inserts. Potentially, AM could reduce manufacturing lead-time resulting in reduced processing costs while promising high level of flexibility in design.

For many years it has been established that companies approved the use of AM for the sole purpose of prototyping and product sampling. Due to lack of knowledge of AM technologies, it has never been fully incorporated as a reliable technique for producing high-volume injection moulding tool inserts for the automotive industry, due to implications of previous research on surface finish of AM components, limitations in material use, durability, and incapability of improving product accuracy. Previous research was established for the production of low-volume injection moulding tool inserts. However, there is still a gap in research regarding the capabilities of AM technologies for the production of high-volume injection moulding tool inserts. Moreover, applying each manufacturing process individually is constrained by some technical limitations, therefore, establishing a paradigm that evaluates the manufacturability benefits of AM and subtractive manufacturing in a feature-based system is potentially valuable.

This research addresses the competencies associated with adopting SLM for fabricating injection moulding tool inserts for high-volume production, and how advantageous it can be for the automotive industry. In this work, the tool life of SLM-fabricated injection moulding tool inserts and the functional approval of their respective end-products is analysed. Five sets of tool inserts (ten core and cavity inserts) of different

spare part automotive components were manufactured using subtractive and SLM techniques. The tool inserts were grouped into different studies that assessed mechanical properties, microstructure, and performance when used to create end-use components. One of the studies was established to prove the tool life of SLM-fabricated tool inserts through the production of 150,000 functional components. The tool inserts performance was monitored under actual operating conditions considering high-level demands. The quality of the components produced from the SLM tool inserts were tested for geometric and dimensional accuracy as well as functional approval through an industrial quality control procedure as an end-use product. Products are functionally approved and are established to be within the permissible design tolerances for their application and industrial sector requirements. The results obtained from the different studies concluded that SLM is a viable and competitive approach for the fabrication of injection moulding tool inserts.

Hence, a systematic approach is developed as a feature-based manufacturability assessment system (FBMAS) for the automotive sector to assist users to evaluate manufacturability limitations of SLM and subtractive manufacturing techniques for the production of injection moulding tool inserts. The manufacturability assessment process is based on a set of predetermined design features and geometric requirements which must be identified. Six tool inserts were acquired for the validation process, comparing real-life decisions of the experienced engineers with the outcome of the feature-based system. As a result, the manufacturability assessment system was able to present possible feature base recommendations for the manufacturability of high–volume injection tool inserts.

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RESEARCH CONTRIBUTION TO KNOWLEDGE

The growing challenges facing the automotive industry drives companies and thus researchers to deploy new technologies for manufacturing injection moulding tool inserts. Additive Manufacturing (AM) is well documented as a manufacturing technique with great potential; however, studies lack the evidence that show SLM injection moulding tool inserts can withstand the rigours of high-volume production as covered in the literature review of this thesis. For the most part, subtractive methods are dominating the manufacture of injection moulding tool inserts. This research has been undertaken within the context of manufacturing injection moulding tool inserts for automotive applications using Selective Laser Melting (SLM) and subtractive manufacturing technologies.

The work undertaken in this research is focused on using stainless steel 316L in powder form, as it is the most commonly used grade for metallic powder-bed AM technology, and billet form for subtractive manufacturing. The AM method adopted in this study for fabrication of the injection moulding tool inserts is SLM, whereas CNC machining, die sink electric-discharge machining (EDM), and Wire EDM are the common subtractive manufacturing methods adopted.

The research undertaken offered the following new contributions to knowledge:

- For the first reported time, SLM-fabricated injection mould tool inserts were successfully integrated into a commercial manufacturing environment for the production of after-market automotive spare parts.
- For the first reported time, research was directed towards understanding the tool life of SLM tooling inserts for high volumes of production for the aftermarket automotive sector. Therefore, SLM was used to fabricate four stainless steel 316L injection mould tool inserts for the production of 150,000 components without any noticeable degradation or tool wear.
- Evaluations were conducted to distinguish limitations and to explore a wide range of design features that have an impact on the manufacturability of the tool inserts. After reliability and longevity of the SLM tool inserts was ensured, development of a novel feature-based manufacturability assessment system, specific to SLM, subtractive manufacturing, and injection mould tool insert

production directs the user to consider specific geometric design criteria to ensure viability of tool manufacture. The system recommends the most suitable manufacturing methods based on the defined design criteria.

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List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
3DP	3D Printing
AHP	Analytical Hierarchal Process
AM	Additive Manufacturing
CAD	Computer Aided Design
CNC	Computer Numerical Control
DED	Direct Energy Deposition
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
EDM	Electric Discharge Machining
EDS	Energy Dispersive Spectroscopy
FBMAS	Feature-Based Manufacturability Assessment System
FDM	Fused Deposition Modelling
HSC	High Speed Cutting
HSM	High Speed Machining
IMLS	indirect metal laser sintering
N	Number of Cycles to Failure
PBF	Powder Bed Fusion
UTS	Ultimate Tensile Strength
QFD	Quality Function Deployment
Ra	Surface Roughness
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
S	Cyclic Stress
SEM	Scanning Electron Microscope
SIQ	Sequential Injection Moulding
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

1 Introduction

In this chapter an introduction is presented on the importance of injection moulding for industrial sectors and the use of SLM and subtractive manufacturing techniques for tool insert fabrication. The research aim and objectives are identified, and an outline of the thesis structure is demonstrated. The last section presents the manufacturing approach developed to create guidelines that are to be followed by each of the selected injection moulding tool inserts that support the studies presented in this research.

1.1 Introduction

The continual increase in the demand for tool manufacturing urges tool makers to develop and implement the latest technological means to facilitate the design and production phases. Thus, a number of factors contribute and affect the production of tools, including fine surface finish, durability, lead-time, geometric tolerances and mechanical properties. Several manufacturing techniques involving additive and subtractive technologies have been deployed to produce tools and their assemblies. Each of these manufacturing techniques has its own advantages and disadvantages.

Additive manufacturing (AM) tends to be flexible while providing freedom in design complexity through the development of new parts or from a semi- finished part (Vayre *et al.,* 2012). Compared to subtractive techniques, AM is able to produce the most geometrically complex structures within certain limitations (Vayre *et al.,* 2012; Mellor *et al.,* 2014). Despite this flexibility, surface finish and accuracy of dimensions are of somewhat lesser quality using AM (Xiong *et al.,* 2009). Consequently, to achieve the desired specifications, AM very often requires components to be subjected to additional post-processing methods such as, polishing and post-machining (Xiong *et al.,* 2009).

This research focused on integrating AM and subtractive machining processes to benefit from the advantages of both methods, with a particular industrially focused bias towards tooling for after-market components for the automotive sector. Additionally, this research focused on establishing a decision system dedicated to design requirements and manufacturability assessment of AM-fabricated and subtractive manufactured injection

moulding tool inserts. Provided the success of such integration is proven, solutions are to be proposed for ultimately building metallic tool inserts for high-volume production.

1.2 Research Aim and Objectives

1.2.1 Aim

The aim of this study focuses on testing the use of SLM for the production of injection moulding tool inserts for high-volume production. Furthermore, developing a feature-based manufacturability assessment system for automotive industries that enables engineers to assess and determine the ideal manufacturing technique from SLM and subtractive processes for tool manufacturing. The assessment process is based upon a set of predetermined design criteria that evaluates the manufacturability limitations of design features and providing recommendations to the user on which manufacturing technique to use.

1.2.2 Objectives

- Assessing the use of SLM and comparing manufacturability of SLM and subtractive manufactured injection moulding tool inserts for automotive applications.
- Evaluating microstructure, wear, hardness, surface roughness, fatigue behaviour, dimensional and geometrical accuracy of the adopted manufacturing techniques in tool insert manufacturing.
- Ensuring that the SLM fabricated tool inserts are operative in terms of producing high-volume dimensionally and geometrically accurate products.
- Testing for tool life of the SLM fabricated tool inserts through injection moulding of multiple tens of thousands of parts.
- Testing the functionality of the injected high-volume parts from the SLM fabricated tool inserts with respect to assembly, fitting and optical efficiency.
- Determining the key distinguishable design criteria that act as decision tools for the feature-based manufacturability assessment system based on understanding the strength and weaknesses of SLM and subtractive manufacturing.
- Developing an assessment process through a flowchart to identify the required parameters and constraints.

- Developing a feature-based manufacturability assessment system using MATLAB to assist engineering users and providing them with recommendations for manufacturing.
- Test the FBMAS system for validation and verification.

1.3 Thesis Outline

This research is structured into four main sections consisting of nine chapters as illustrated in Figure 1-1.

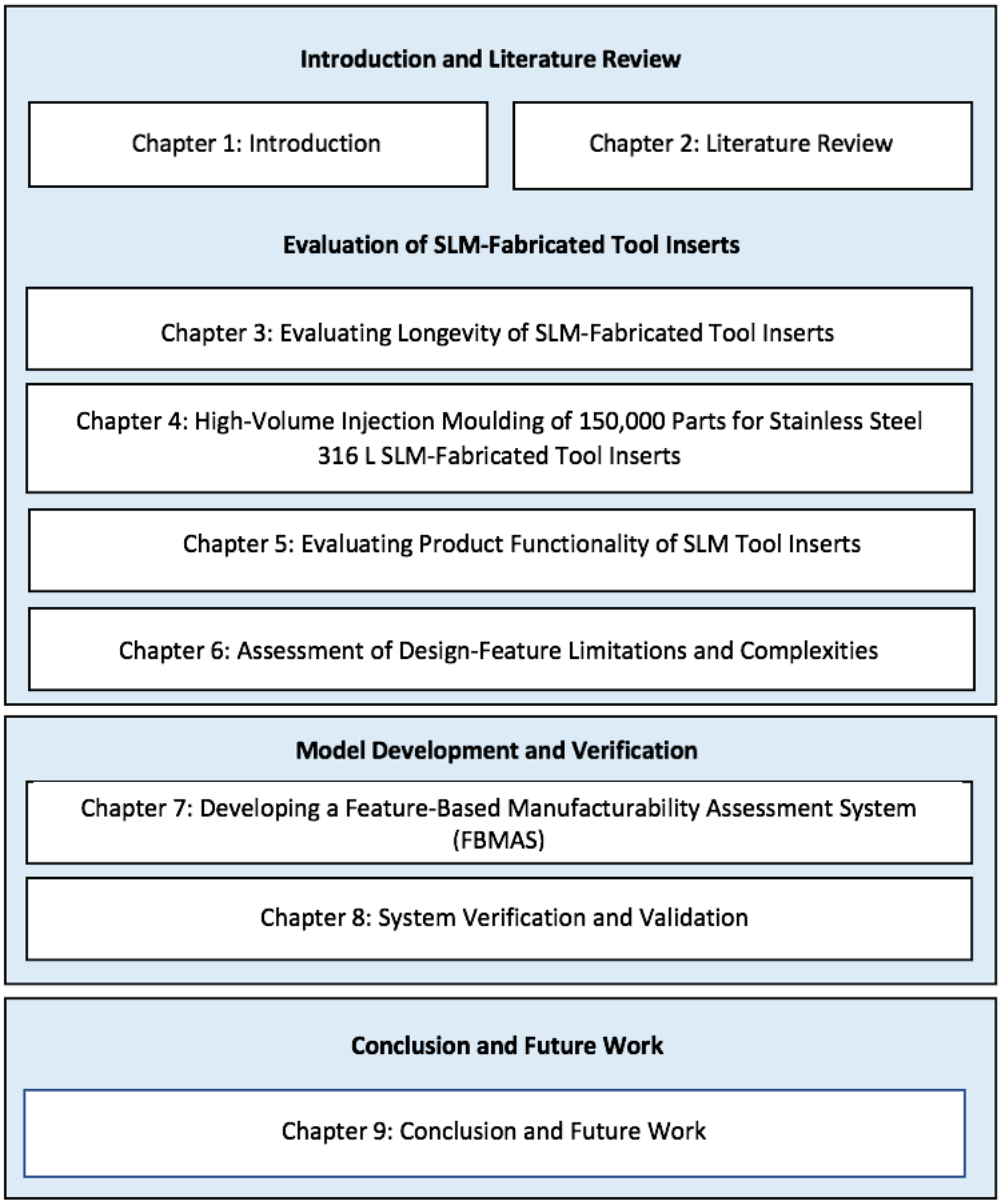

Figure 1-1: Thesis chapters outline.

1.4 Manufacturing Framework

Principally, the manufacturing approach was developed to create a set of guidelines that are to be followed by each of the selected injection moulding tool inserts that support the studies presented in this research. Five studies were pursued that significantly support the research work of investigating the injection moulding tool inserts for the automotive sector applications.

The framework is structured to outline three main stages: design stage, fabrication stage, and examination stage as shown in Figure 1-2. Each of these stages is explained explicitly to provide a comprehensive understanding of the framework.

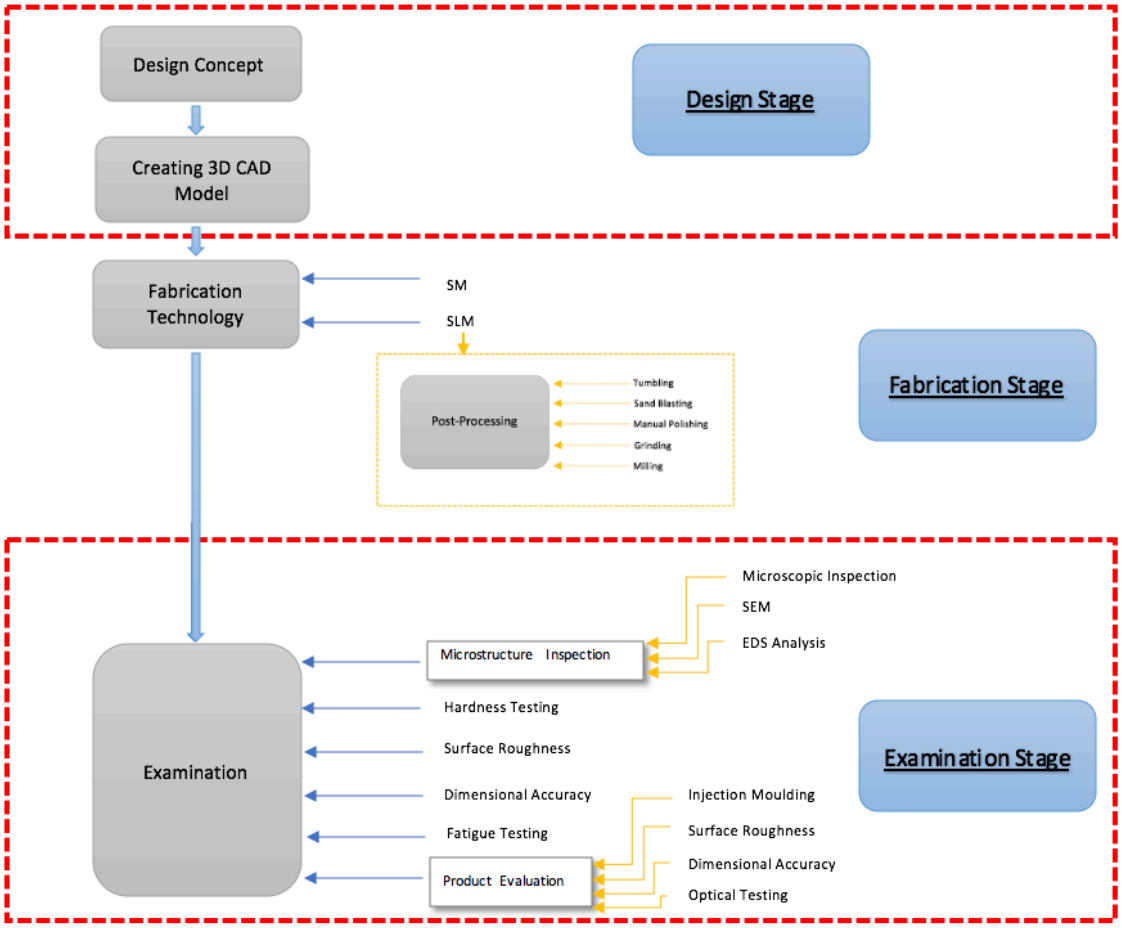

Figure 1-2: Manufacturing framework of injection moulding tool inserts from the design stage until the examination stage.

The design stage presented in this section is the initial stage in the manufacturing framework. Initially, the design concept is the first step where the design developers investigate limitations of the part requested for fabrication. At this point, it is imperative for the designer to distinguish limitations and complexities of the part to assist in deciding the appropriate manufacturing technique that will be adopted for manufacturing the part. Accordingly, the design concept will be aimed towards facilitating manufacturability of the prospective tool inserts. The second step at the design stage, is creating the 3D CAD model of the requested part based upon the adopted design concept.

The fabrication stage presented is the second stage in the manufacturing framework. This section focuses on the two methods of manufacturing adopted for producing the tool inserts, subtractive manufacturing processes such as CNC machining, die-sink EDM, and wire EDM and SLM as an AM process. Moreover, in most instances post-processing is required after an SLM part is produced. Deciding on which processing technique to use varies depending on the required quality and accuracy expected for the produced part. Examples of post processing methods are manual polishing, tumbling, sand blasting, grinding, and milling. The examples included for post processing techniques are limited to what was needed for the studies in this research. Therefore, examining the necessity of incorporating a post-processing technique for the produced part is an issue that the designer must acknowledge during the design stage to compensate for allowances required for further post-processes.

The final stage of the manufacturing framework focuses on the first examination process describing the implemented tests that are focused on examining the tool inserts rather than their produced products. Therefore, Performance tests are expected to be conducted for the tool inserts in the context of microstructure inspection, intermetallic carbide formation analysis, surface roughness inspection, hardness testing, fatigue testing, and dimensional accuracy measurement. The purpose of these tests is to assess performance competencies and limitations of each of the produced tool inserts testing for parameters that impact production. The second stage of examination is product evaluation focussing on evaluating the parts that are to be produced from the tool inserts.

The manufacturing framework originated to guide the development process of the injection moulding tool inserts for all of the five studies in this research. The first study

presented in Chapter 3 and Chapter 4 of this research is focussed on evaluating the reliability and tool life of SLM fabricated tool inserts. In the design stage, all five tool inserts investigated in this study were created from the same CAD model for a vehicle's headlamp adjuster clip. For this study, in the fabrication stage four of the tool inserts were fabricated using selective laser melting, and the fifth tool insert was CNC machined. In the examination stage, reliability and tool life evaluation of the tool inserts was achieved through assessments of manufacturability, microstructural analysis, mechanical properties, conforming quality measures, and dimensional accuracy. Moreover, product evaluation was realised through assessment of the four SLM fabricated tool inserts for wear progression. The effect on the dimensional and geometrical accuracy of the injected components were assessed through Injection moulding of 150,000 functional components.

The second study presented in Chapter 5 targets evaluating product functionality of components produced from the fabricated stainless steel 316 L SLM tool inserts. The same tool insert design was generated for the tool inserts set for fabrication. Two sets of tool inserts were fabricated, an SLM tool insert and a CNC machined counterpart for a vehicle's headlamp reflector. Examining the fabricated tool inserts was instigated in regard to accomplishing acceptable surface quality and achieving dimensional accuracy in contrast to the CNC machined tool insert. Product evaluation was carried out to confirm product functionality, surface quality and dimensional accuracy.

The last three studies presented in Chapter 6 are directed towards assessing design features and manufacturing constraints of subtractive and SLM fabricated tool inserts. Furthermore, assisting in developing a paradigm that assimilates the benefits of SLM and subtractive manufacturing in a feature-based decision system. For this purpose, three vehicle's headlamp plugs with different geometrical features were selected in support of each of the three studies. The three injection moulding tool inserts of the spare part components were selected for their variance of complexity in design and the existence of an extensive range of diverse features to support the scope of each study. In the design stage, the three tool insert CAD models were generated and established for manufacturing. For each study a subtractive manufactured and an SLM fabricated tool insert is investigated. Each of these studies is directed to achieve outcomes that validate the objective of the research work.

2 Literature Review

This chapter provides an overview on injection moulding tool insert fabrication. Firstly, reviewing the possible different manufacturing techniques used in the process of tool insert fabrication. Various applications from previous work and different types of tools used in different industries are reviewed to describe how tool manufacturers have progressed in discovering more methods that could be integrated to improve the manufacturing process. Two main manufacturing processing approaches are reviewed based on a thorough review of previous research: subtractive and AM. Each manufacturing technique exhibits positive competences as well as limitations. Earlier research work on SLM-fabricated injection moulding competence for high-volume production is reviewed to provide a comprehensive understanding. Previously developed knowledge-based decision systems are reviewed to exhibit advantages and shortcomings of previous selection systems that integrate additive and subtractive manufacturing for the production of tool inserts. Finally, the literature reviewed establishes grounds from which a gap in the research is identified and is addressed through the research presented in this thesis.

2.1 Overview of Injection Moulding for Automotive Industry

Regardless of the dynamic technological advancement in product development techniques, tooling is still considered essential and irreplaceable on some occasions despite the fact that it is time consuming and costly (King and Tansey, 2003). Awareness of the demands of the automotive industry requires the use of injection moulding to produce plastic parts that comprise a significant portion of the interior and exterior of a vehicle. Therefore, having an understanding of the capabilities and limitations of the technology is essential for companies to keep up with market competitiveness. Previous research dedicated work to study the fabrication of injection moulding tool inserts for the automotive industry. Earlier work introduced the use of micro-casting for the production of an injection moulding die for an automotive component (Rosochowski and Matuszak, 2000). Mathew and Mastromatteo (2003) demonstrated that stainless steel injection moulding can be utilised to develop new high-performance systems for the automotive

industry. The work of Krajnik *et al* (2004) focused on differentiating between conventional and high-speed cutting velocity and the effect on chip formation of dies for automotive manufacturing. The outcome of the comparison between EDM and HSM has shown numerous benefits to High Speed Cutting (HSC). Moreover, Spina (2004) evaluated the beneficial effects of using sequential injection moulding (SIM) for the fabrication of a plastic arm component. The research work established that using SIM for automotive parts fabrication is advantageous. More research (Petrovic *et al*., 2011; Gu *et al*., 2012) emphasised the global interest of adopting new technologies for tooling in industries such as automotive. Kerbrat *et al* (2011) introduced a new evaluation methodology in the design stage for manufacturability and tested for industrial products from the automotive industry. The outcome of the evaluation enabled the user to focus on the areas of the part investigated that has the most difficulty to manufacture and to decide on which manufacturing method to use.

2.2 Injection Mould Tool Insert Fabrication

Altan *et al* (2001) stated that when producing large volumes of products or sub-assemblies, the quality, lead times, and direct costs all contribute to the economics of the tool manufactured especially in the automotive industry. Those tools are used in production processes that vary in technique and the material used. Such processes are casting, forging, stamping, injection moulding. As determined by the authors for the automotive industry, the manufacturing process of new tools and the try-outs performed to test for the feasibility of the produced products has a direct impact on the entire production process. An example was given on how important the quality of the mould can impact the overall quality of the produced parts of injection moulding lenses.

Thus, tool design and fabrication is vital to the whole production cycle, the following points illustrates the observations of Altan *et al* (2001). Figure 2-1 is an illustration of the injection unit of the injection moulding process.

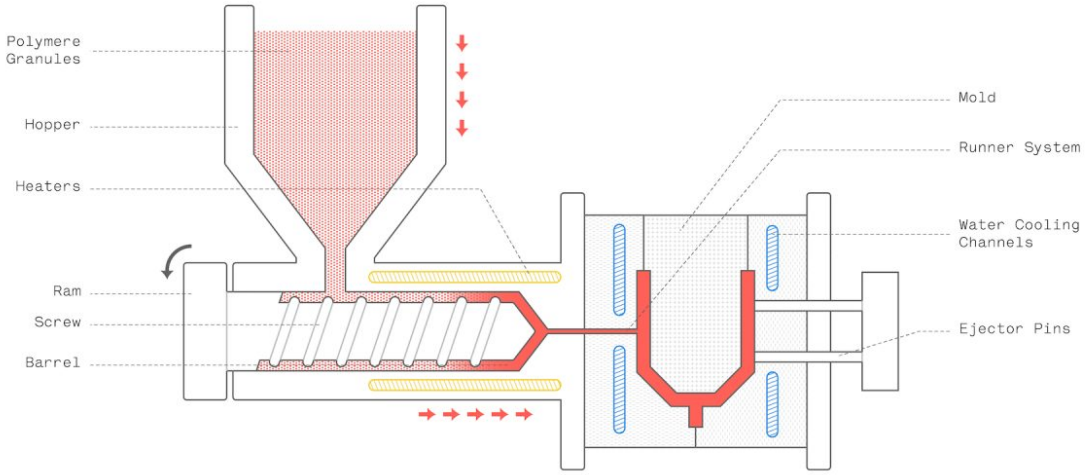

Figure 2-1: Injection unit of the injection moulding (3D Hubs, 2020a).

Tools are considered an element of investment that has a relative significance to production, but not as significant as the machining tools/equipment. Nevertheless, lead time, quality and cost of manufactured products is affected.

Injection moulding tools are typically made from tool steel blocks and involve rough cutting followed by fine finishing machining operations. These tools are complex and create products that have complex geometries. Thus, they require exceptional operations that allow the presence of multi-motion slides, inserts and cooling channels that complicate the overall manufacturing process. Therefore, the manufacture of new tools is a critical factor in determining the feasibility and lead-time of an entire production process.

Therefore, Altan *et al* (2001) summarised that the toolmaking process is faced with certain limitations that need to be overcome to offer flexibility and speed in delivering the final product to market. Understanding that time is a critical factor in the tool making process that demands to be reduced through adopting apt manufacturing technologies. Thus, modelling the process plan of complex tools is recommended to avoid try-out errors in production.

For the purpose of this study, the two main methods of manufacturing injection moulding for automotive components reviewed in this work are additive and subtractive manufacturing.

2.2.1 Subtractive Manufacturing for injection moulding

In subtractive manufacturing, the basic theory for material removal, cutting processes and cutting geometry is quite similar, but the technique and technology applied is different (Krajnik and Kopac, 2004). Subtractive manufacturing utilises any type of material in the manufacturing process and offers high accuracy and surface finish which is essential for tool making processes. Nevertheless, the level of expertise required from personnel is significantly high (Karunakaran *et al.*, 2010). The principal methods of subtractive manufacturing that are reviewed in support to this work are CNC machining, and EDM for manufacturing injection moulding tool inserts.

When considering a product design for machined injection moulding, one must contemplate the designated processes and their constraints, necessary equipment and cutting tools required, process parameters, and material properties. Manufacturing a typical injection moulding tool requires following the listed steps below (Altan *et al.*, 2001; Calvez *et al.*, 2001):

Design part geometry;
Test the process (mould design) using simulation software;
Perform various machining processes to the tool steel (roughing through milling and drilling, semi-finish through milling and EDM, and finishing);
Polishing and assembly;
Pilot runs;
Pre-production qualification status;
Injection moulding processes require that the incoming raw material be shapeless in granulated form. Therefore, it is necessary to design the tool as an experience-based activity. This method adopts process modelling techniques to estimate and evaluate material flow and stresses applied to the tool, determine optimum process parameters, design essential features to perform the process (gates and runners), and finally eliminate any dimensional defects by adjusting the required parameters to maintain process success;
A complete tool is designed to encompass functional parts: cavity, core, insert (for shaping), and punch. The support parts are fixing plates, ejector pins, and holders as illustrated in Figure 2-2.

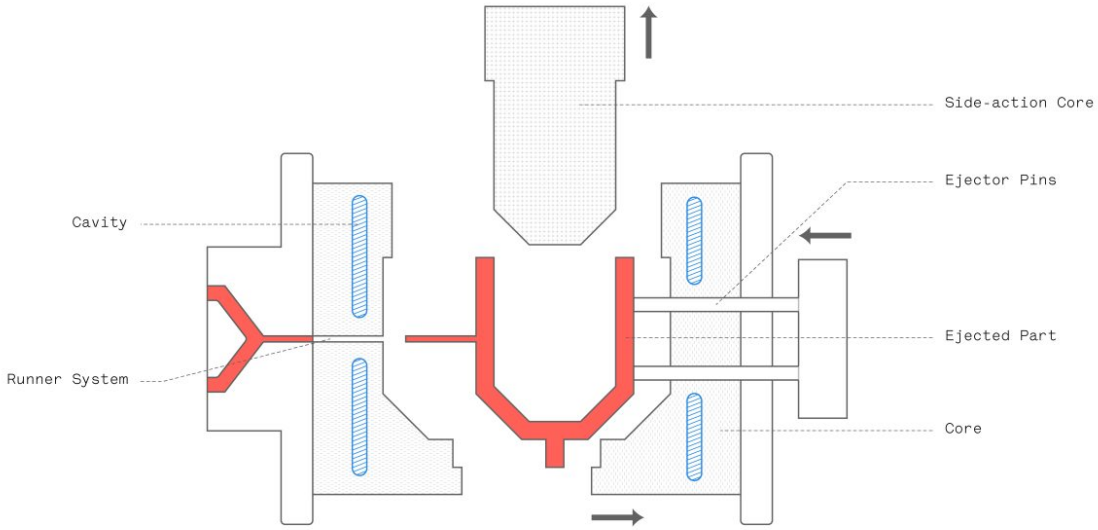

Figure 2-2: Components of an injection moulding tool (3D Hubs, 2020a).

Swamidass and Winch (2002) confirmed that more than 70% of UK and US businesses utilise CNC machining for manufacturing, although it is well recognised that CNC machining produces considerably higher levels of material waste (Newman *et al.*, 2015). Comparisons made by Krajnik and Kopac (2004) between EDM and HSM showed that from an ecological perspective, EDM requires high energy consumption, constant lubrication and cooling, and constant monitoring of the EDM electrode for waste treatment and disposal.

Metal removal manufacturing and EDM are the key methods for tool making. Figure 2-3 is a schematic illustration of the wire EDM process, whereas Figure 2-4 is an illustration of die-sink EDM. Altan *et al* (2001) stated that EDM machines are used 50% of the time to produce blanking dies, while only being used 5% of the time in producing extrusion dies. Another example is the extensive use of EDM in die casting which is five times more in comparison to injection mould tooling due to the presence of deep and thin rib cavities.

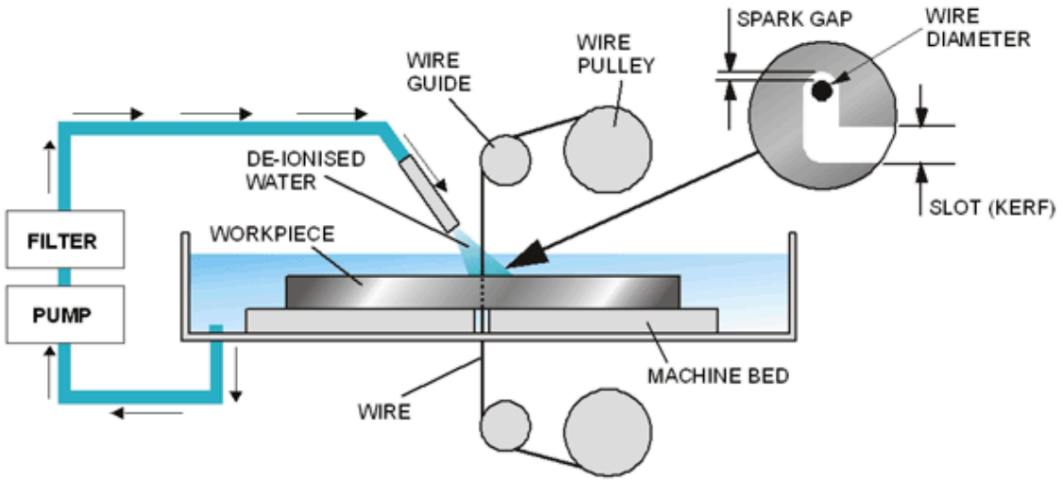

Figure 2-3: A schematic illustration of wire EDM.

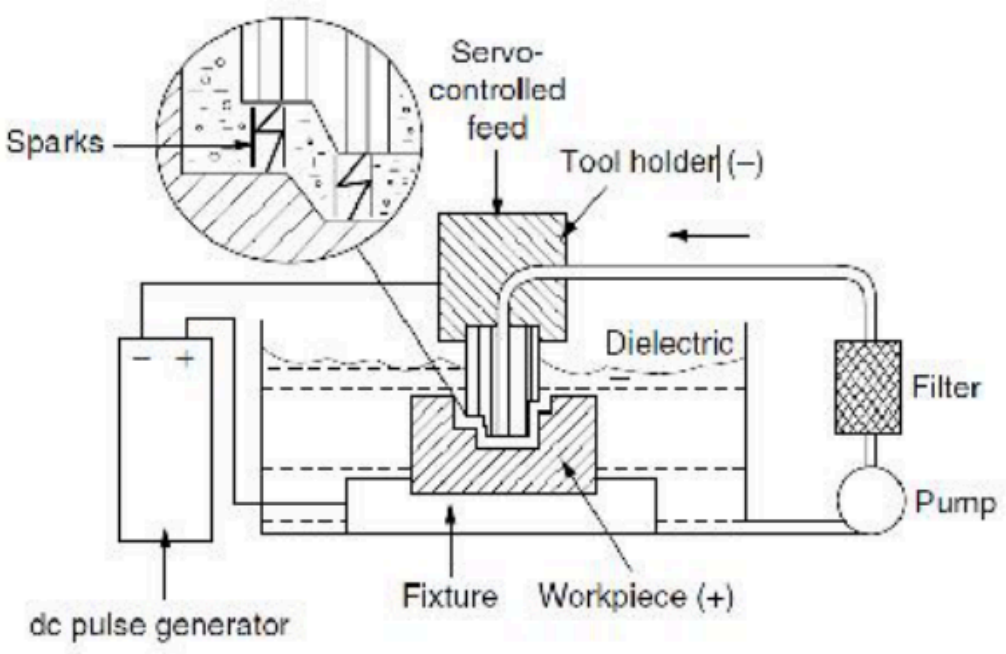

Figure 2-4: Schematic illustration of die-sink EDM.

EDM differs from other subtractive methods in the diverse geometries that can be achieved (Kuzman *et al.,* 1999; Krajnik and Kopac, 2004). However, EDM utilises higher energy consumption and continuous monitoring of EDM electrodes is required during and after processing for waste treatment and disposal are some of the limitations (Kuzman *et al.,* 1999; Krajnik and Kopac, 2004).

Krajnik and Kopac (2004) considered the limitations of machining three-dimensional (3D) surfaces. Only five axis machine tools are capable of milling any surface orientation allowing for more cutter side deviations. However, five axis machine tools and machining costs are far more expensive compared to three axis machining. Several criteria differentiate between conventional machining and HSM, some of these criteria being, cutting speed, spindle speed, dynamic behaviour, and the workpiece material (Ekinovic *et al.*, 2000; Krajnik and Kopac, 2004). The researchers also defined HSM based on the material grade of the workpiece being machined and gave an example of such.

2.2.2 Additive manufacturing for tool inserts fabrication

AM refers to processes in which material is selectively added together in consecutive layers to create a physical 3D part based on geometric data from a CAD model (Mellor *et al.*, 2014). To simplify, AM is often described as the fabrication of physical objects from a three-dimensional CAD file through the joining of layers usually layer-by-layer (CHUA *et al.*, 2003; Gebhardt, 2003; Choi *et al.*, 2011; Khajavi *et al.*, 2014). After the fabrication process is completed, the part is removed from the build chamber and cleaned of excess materials. Depending on the degree of surface finish required, post-processing may be required to achieve the desired surface finish and be ready for application. According to Mellor *et al* (2014), AM has been referred to in the literature as additive processes, additive techniques, additive layer manufacturing, layered manufacturing and freeform fabrication.

Altan *et al* (2001) emphasise the ability of AM techniques to rapidly produce direct and indirect tools such as injection moulding with minimised cost and time while radically reducing design iterations and prototyping. Moreover, AM techniques enhance the productivity of injection moulding, as well as the flexibility of certain AM systems in tailoring the material properties as it is built.

AM techniques enable the production of complex shapes and geometries, but with limitations of poor quality and tolerances. However, machining techniques allow for the production of accurate components with good quality, but with limitations to the level of complexity (Newman *et al.*, 2015). Therefore, applying each manufacturing process individually is constrained by some technical limitations, such as inability to produce

complex geometries, limited use of materials and increased cost of production (Zhu *et al.*, 2013; Newman *et al.*, 2015). Thus, adopting multiple manufacturing techniques within the same production process could reduce possible limitations while enhancing potential opportunities.

(i) Additive manufacturing systems

Several AM technologies have been brought onto the market. The demand on the type of product needed generally sets the parameters for utilisation of the most appropriate technology. Furthermore, the type of material used for building a part normally distinguishes the AM technologies. Injection moulding for high-volume production demands the use of a metal AM technology. Direct Energy Deposition (DED) and Powder Bed Fusion (PBF) are two of the most recognised versatile AM processes (Gu *et al.*, 2012). The prefabricated form of the material in use is in powder form.

DED is often also referred to as Direct Metal Deposition (DMD). The mechanics in which the deposition process works require the use of a specially designed powder feeder that supplies powder through a nozzle. The energy commonly used energy sources are either laser or electron beam (Gu *et al.*, 2012; Karunakaran *et al.*, 2012). However, (Gu *et al.*, 2012) concluded the significant instability in process control and structural properties that may be of direct effect to reliability of applications in industry.

PBF technology is recognised by spreading out the powdered material on the build platform and the powder particles are joined by an energy source such as a laser beam or an electron beam (Karunakaran *et al.*, 2012). In principle Gokuldoss *et al* (2017) stated that laser melting and electron beam operate under similar working conditions. However, there happen to be some dissimilarities. A laser melting process doesn't necessitate a heated powder bed and requires an inert atmosphere, as for an electron beam process a hot powder bed is required under a vacuumed atmosphere. With such heightened working conditions quality and mechanical properties of the fabricated parts are affected. In confirmation, Karunakaran *et al* (2012) signified laser beam has been regarded as the prevailing energy source due to its precision.

SLM is thought to be the most flexible and widely used powder-bed-fusion process using a laser beam that melts powder grains and fuses them together (Herzog *et al*., 2016).

Figure 2-5 is a schematic illustration of an SLM system. Therefore, as stated by Gu *et al* (2012) due to continuous improvements in processing conditions (e.g. layer thickness, laser spot size, laser power, etc.) demand is calling for the production of high density components with good surface finish that compares to conventionally manufactured parts. Significantly promoting microstructural and mechanical properties. One of the main advantages of using SLM technology is the increased functionality of produced parts (Gokuldoss *et al.*, 2017). Mahshid *et al* (2016) emphasised that due to advancements in material development, metallic parts are manufactured using SLM technique which is idyllic for injection moulding.

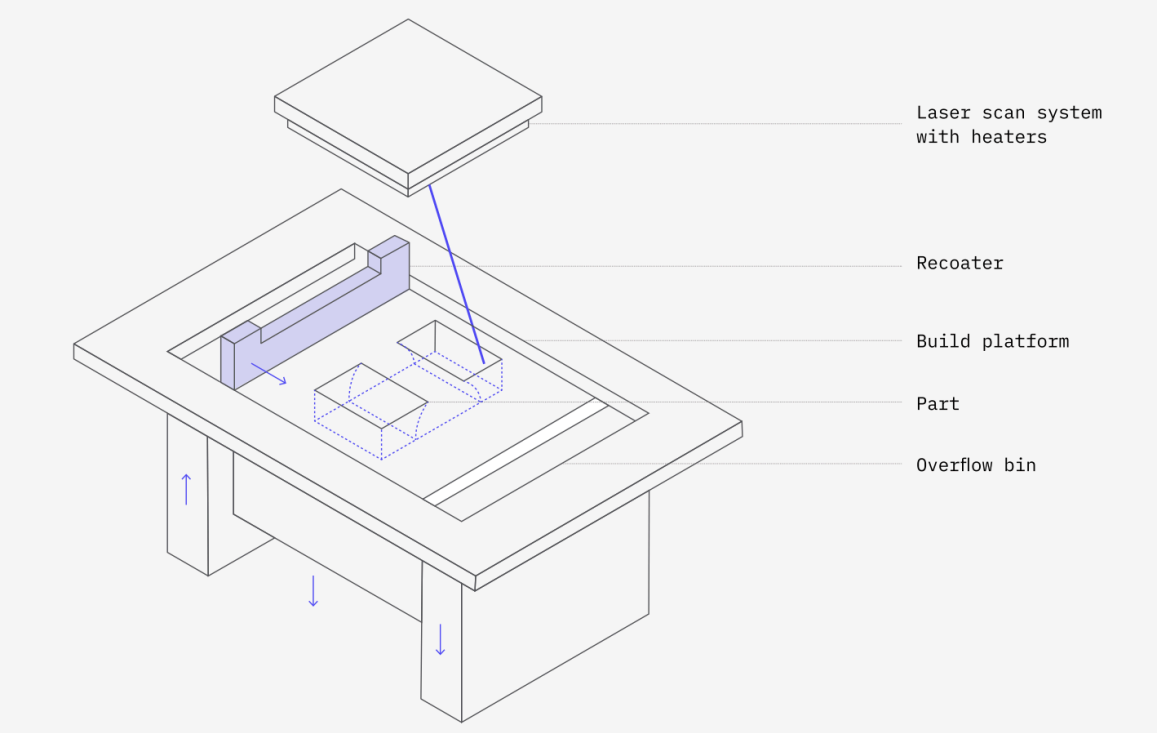

Figure 2-5: Schematic illustration of an SLM system (3D Hubs, 2020b).

Therefore, PBF SLM technology was utilised rather than other AM technologies for the advantageous characterisation in the production of metallic parts. Moreover, for the purpose of producing productive injection moulding tool inserts, SLM technology was aimed for as shown and highlighted in Figure 2-6.

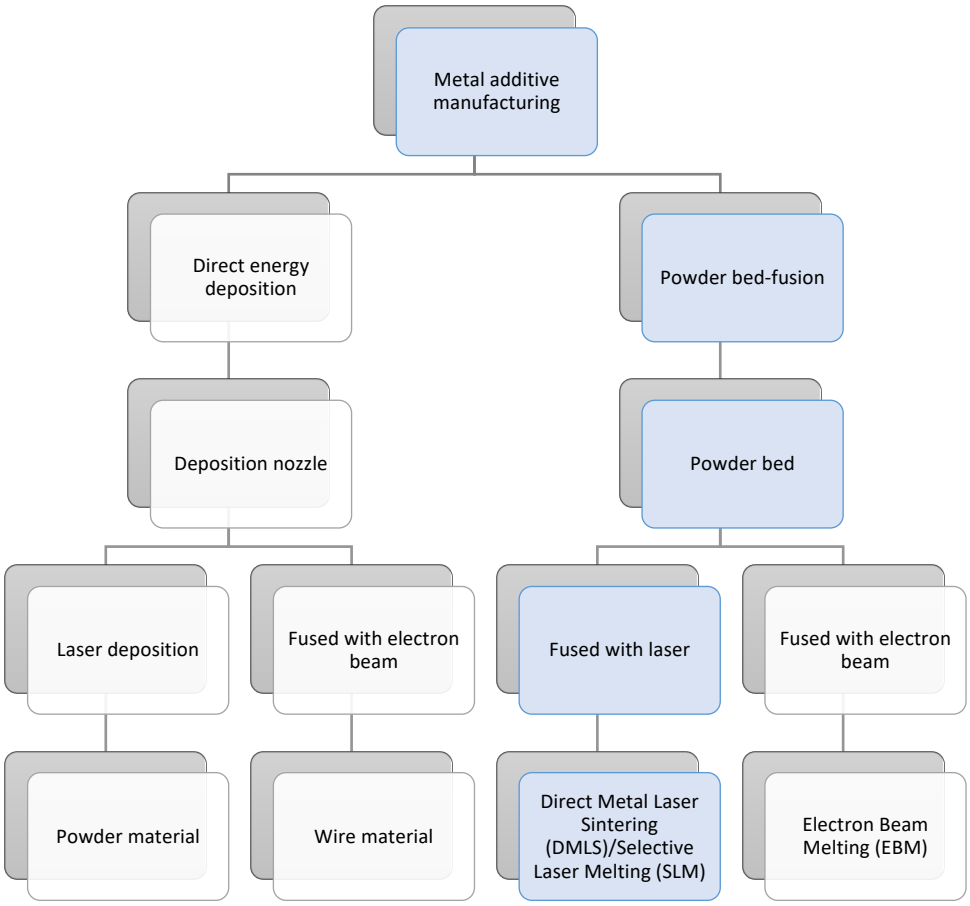

Figure 2-6: Powder bed fusion (PBF) systems (modified from (Markusson, 2017)).

(ii) Additive manufacturing approaches

Three areas have been defined for AM technology, Rapid Prototyping (RP), Rapid Manufacturing (RM) and Rapid Tooling (RT). Kruth *et al* (2007) defined RP as the production of prototypes for visual aid that are often used as models in the development stage of a product. Furthermore, high quality 3D parts with varying complexity, size and shape are produced (King and Tansey, 2003). Rapid Manufacturing (RM) is the direct manufacturing of parts for end-use applications (Lupeanu *et al.*, 2012). Parts are usually custom-designed to meet individual specifications thus, RM is believed to be advantageous (Mellor *et al.*, 2014; Sun and Lal, 2002). Rapid Tooling (RT) is a technique that focuses on the fabrication of moulds rather than prototypes or functional products (Au *et al.*, 2011). There are two approaches to rapid tool manufacturing: direct and indirect tooling. Ding and Au (2004) and Au *et al* (2011) stated that direct tooling does not necessitate the production of a pattern, as tool inserts are produced directly. The use of each depends on the potential characteristics required by the manufacturers and the size

of the production volume (Dunne *et al.*, 2004). King and Tansey (2003) indicated that RT progressed from RP as a mean to directly manufacture tools or prototype tools. As a result, acknowledging compressed time to market solutions. Therefore, direct RT is the method adopted in support of the studies in this research work.

(iii) SLM technology for tool fabrication

The recent growth in the application of AM has motivated researchers to prove the reliability of such a manufacturing approach for tool manufacturing. In recent years, research has been successful in highlighting how AM or more specifically, its application for RT, could be used to overcome the limitations of conventional manufacturing methods.

In conventional toolmaking, there has always been a gap in time between modelling a product and its actual production. However, persistent driving forces are stirred due to global competition among global market companies to reduce this gap and save time while maintaining products with high quality (Ding *et al.*, 2004). To ensure viability of AM technology, geometric and dimensional quality should be improved for rapid tools, while eliminating human intervention, and reducing cost and time to be as close as that attained in the case of conventionally manufactured tools (Nagahanumaiah *et al.*, 2007).

In a study by Khaing *et al* (2001), metal tools with fine details were fabricated using EOS's DMLS. Dimensional accuracy, surface roughness, impact toughness, hardness, and strength of the produced tools were measured. It was found that the tools were relatively soft, the surface was deemed rough, and SEM analysis disclosed the parts to be porous. Therefore, the authors suggested the optimisation of process parameters to improve part quality and accuracy. To improve hardness and wear resistance of the produced tools, low melting point infiltration using silver alloy and nickel plating may be incorporated.

Tay and Haider (2002) acknowledge the positive impact of using DMLS processes for toolmaking, hence, emphasising the significance of improving the quality of the rapid tools to achieve similar outcomes as with traditional moulds. The parts produced were sand blasted before they were plated using electroless nickel plating and/or semi-bright nickel electroplating. Nevertheless, there are still common limitations such as poor

surface finish, low wear resistance, softness and inherent porosity due to the powder-based AM technology employed, requiring the application of various post-processing techniques to achieve satisfactory surface finish along with improved mechanical properties. Thus, post-processing techniques are essential to attain a surface finish that is fit to be compared with a part manufactured on a conventional machine. Therefore, research focused on improving these aforementioned limitations to an acceptable industrial level.

Rossi *et al* (2004) were able to report the distinct variation in values of surface roughness through several surface treatment methods of DMLS fabricated injection moulds. Nickel coating was reported to show the best performance when applied after shot peening and emery polishing, providing higher corrosion and wear resistance to injection moulds. Spierings *et al* (2013) recommended hand polishing and sand blasting of SLM-fabricated stainless steel 316 L components to achieve the desired surface roughness.

Junker *et al* (2015) affirmed the use of selective laser additive manufacturing for the production of moulds for injection moulding. Mahshid *et al* (2016) specified that advances in laser-based AM processes such as SLM technology permitted fabrication of complex metal components that are impossible to achieve using subtractive processes alone. In their work, it is evidently stated that SLM technology displays a substantial improvement in fabricating high-quality injection mould tools.

Löber *et al* (2013) used grinding, sand blasting, electrolytic and plasma polishing to reduce surface roughness of the SLM fabricated parts. Flynn *et al* (2016) reviewed the most common approaches to finishing an AM fabricated metal component through machining, thermal processes, chemical and electrochemical processes. Meanwhile, machining is generally used in near-net shaping processes such as moulding. Additional context is reported within the literature for surface quality expectations of AM metallic parts.

2.3 Injection Moulding for AM Fabricated Tool Inserts

SLM is proving to be an AM technology that is delivering a feasible solution to numerous subtractive manufacturing methods. Parts can now be produced with no limitations for

complex geometries, therefore yielding functional improvement to parts produced. Former studies compared subtractive manufacturing processes with additive manufacturing technologies for automotive applications.

Kerbrat *et al* (2011) appraised results when using AM for tooling application in terms of lead-time and cost in preference to electro-discharge machining process. Additive manufacturing tolerances and overall quality were considered equivalent to subtractive methods. Petrovic *et al* (2011) reviewed various case studies and stated that It is notable that AM has a strong emerging role in the fabrication of injection moulds and automotive industries. Therefore, tool manufacturers have sought out to convert from conventional methods of manufacturing into additive manufacturing technologies. A key advantage of utilising metal additive technologies in the fabrication of injection moulding is the capability of building the moulding insert and then assembling it to the main mould bolsters, therefore, saving time and cost by only fabricating the tool insert instead of building the whole injection mould.

Lupeanu *et al* (2012) examined RT advantages for a redesigned greenhouse clip model when developing a highly complex surface feature of a mould for injection moulding. CAD simulation was utilised to establish the optimal layout for the injection mould cavity and how it was difficult to manufacture using conventional machining technologies.

2.3.1 Assessment of SLM stainless steel 316 L metal properties

SLM of metallic components are revolutionising industries by providing realistic alternatives to subtractive manufacturing techniques. Santos *et al* (2006), Kruth *et al* (2007), and Delgado *et al* (2012) reviewed in their work that several studies in literature clearly stated that part's mechanical properties and quality is commonly dependable on the type of AM technology utilised, material, layer thickness, building strategy, and post processing technique. For that reason, microstructure analysis, mechanical properties, surface roughness, and dimensional accuracy of SLM fabricated stainless steel 316 L parts are reviewed and investigated in this research work. Moreover, Liverani *et al* (2017) affirmed the superiority of metal parts fabricated using SLM over bulk materials in mechanical properties.

(i) Microstructure analysis

It was perceived by Yadollahi *et al* (2015) that process parameters subjected to a material during manufacturing have a direct effect on the microstructure and hence mechanical properties of a part under static and cyclic loading. In the work of Liverani *et al* (2017), the objective of the study was to correlate SLM processing parameters to the resulting microstructure and mechanical properties of the produced component. The experimental results show that the SLM specimens presented a normal austenitic microstructure consisting of melt pools. The main solidification defects detected were binding defects, gas pores, and voids. However, the mechanical behaviour recognized for the SLM fabricated specimens was superior.

A number of studies correlated process parameters with the effect on microstructure and mechanical performance. One such study presented the effect on the microstructural changes of re-melted layers and mechanical properties of SLM components by applying different process parameters (Yasa and Kruth, 2011). Experimental observations were carried out by Yakout *et al* (2018) to evaluate mechanical properties and the quality of the stainless steel 316 L parts produced. The influence of part orientation and dimension on surface microstructure and residual stress is analysed. The outcome to this study was a contribution to improving the use of AM-fabricated stainless steel 316 L for aerospace parts. Hao *et al* (2009) presented a study that determines the optimal SLM process parameters to directly fabricate stainless steel 316 L and hydroxyapatite (HA) composite specimens. Microstructural inspection, hardness testing, visual inspection, and density measurements were conducted to demonstrate the effect of process parameters on the properties of the produced parts. Microstructural examination revealed full layer melting at optimum parameters. Sudhakar *et al* (2018) investigated static properties and fracture morphologies of microstructure. The results from this investigation demonstrated a good level of strength and ductility for fracture morphologies. The SLM-fabricated stainless steel 316 L tensile properties exhibited similarities to those of wrought material. Moreover, microstructural analysis of the SLM samples displayed overlapping and segregation of melt pools comparable to weld fillets.

(ii) Surface roughness

Yasa and Kruth (2011) concluded in his findings that if laser re-melting is applied to the last layer of a part, enhanced surface properties are expected to achieve improved surface roughness of 90%. In the work of Delgado *et al* (2012) the effect of SLM process parameters are investigated on surface roughness, dimensional error, and mechanical properties of SLM stainless steel 316 L and H20 DMLS fabricated parts. It was concluded from the results that part direction significantly affects part quality in terms of surface roughness and dimensional error. Surface roughness of SLM-fabricated technology is a major drawback as stated by Löber *et al* (2013). The purpose of the work conducted is to compare different post processing techniques to demonstrate the effect and improve the surface roughness of SLM-fabricated stainless steel 316 L parts. The effect of different surface treatments on the surface roughness of steel parts produced by SLM was quantified and compared. Song *et al* (2015) reported that when comparing the surface roughness of SLM fabricated parts with parts produced from machining processes, the surface quality of the SLM-fabricated parts show higher surface roughness. Yakout *et al* (2018) concluded from the literature that SLM process parameters, powder characteristics, part design and dimensions, part location on the build plater are significant factors that affect surface quality of stainless steel 316 L parts fabricated by the SLM process.

(iii) Mechanical properties

Micro-hardness testing

The main objective of the work reported in Hao *et al* (2009) is to provide a comprehensive understanding on the effect of SLM process parameters on hardness, tensile strength, density, and microstructure of an SLM-fabricated stainless steel 316 L part. Delgado *et al* (2012) investigated the effect of built direction on the mechanical properties and hardness of the fabricated stainless steel 316 L using DMLS technology. The work of Miranda *et al* (2016) presented a study on the influence of SLM processing parameters on hardness, density and shear strength of stainless steel 316 L components using a statistical analysis method (ANOVA). Microstructural aspects of the produced parts were correlated with the resulting predictive models. Yusuf *et al* (2017) presented an investigation on the

porosity and micro-hardness of SLM-fabricated stainless steel 316 L specimens. When comparing the average micro-hardness values of the SLM specimens to those of wrought parts, the SLM specimens record higher values attributed to the fine microstructure from the rapid melting and solidification rate of the SLM process. Additionally, the SLM-fabricated stainless steel 316L specimens accomplished high densification levels with a low average porosity content. Eriksson (2018) reviewed previous studies for laser PBF techniques reporting higher tensile strength properties comparably to wrought stainless steel 316 L. This is caused due to high solidification and cooling rates that segregate to the boundaries.

Fatigue test

Spierings *et al* (2013) investigated fatigue performance of stainless steel 316 L and 15-5 PH. Influence of surface quality on fatigue life was analysed, and polishing produced an improvement. The work focused on comparing the results of fatigue behaviour of SLM-fabricated parts with those of conventionally processed materials. Moreover, it was proven that the SLM-fabricated stainless steels demonstrate tensile and fatigue behaviour comparable to conventionally processed materials. For stainless steel 316L, the fatigue life is 25% lower than conventional material. However, it can be used to produce parts for real-life applications.

In a study by Riemer *et al* (2014), SLM-fabricated stainless steel 316 L parts are evaluated to demonstrate the fatigue behaviour. The traditionally processed 316L show an ultimate tensile strength (UTS) range between 530 and 680 MPa, the UTS results for the as-built specimens were 565 MPA. the yield strength in the as-built condition was found to be considerably higher at 462 MPA as compared to the traditionally processed at 220 MPA. The results achieved determine good fatigue performance as identified by fatigue strength and crack growth threshold values. Conclusively, it was proven that SLM stainless steel 316 L is a promising candidate for cyclic loading exhibiting similar fatigue properties as conventionally processed parts.

Mower and Long (2016) evaluated the fatigue strengths and behaviour of DMLS stainless steel 316 L and 17-4PH and compared them to those of conventional materials. A wide range of surface characterisation analysis was carried out to correlate surface

topology with fatigue strength. The conventional wrought, annealed 316L yielded at stress 345 MPa, as opposed to the horizontally built DMLS specimens yielded at about 496 MPa. The demonstrated higher yield stress of the DMLS materials is characterised due to the fine crystalline structure created by the rapid solidification during the building. The fatigue strength of the conventional wrought, annealed, machined and polished 316L displayed a fatigue strength of 350 MPa at 10^5. The exhibited fatigue strengths of the DMLS stainless steels fabricated in the horizontal orientation were nearly equal to those of the wrought material. The results demonstrate high ductility with considerable higher yield strength and strain hardening than in wrought 316 L. Additionally, significant increase in fatigue strength was determined due to hot isostatic pressure post processing. Therefore, measured fatigue strengths of DMLS stainless steel 316 L compares favourably with that of conventional materials.

Suryawanshi (2017) conducted a study to investigate the tensile, fracture, and fatigue crack growth properties of SLM-fabricated stainless steel 316 L. Substantial increase to yield strength is noted for the SLM SS 316 L specimens, values were recorded at 430.4 MPA in $\perp$ direction and 511.6 MPA in $\parallel$ direction. As opposed to conventionally machined specimens ranging from 220-270 MPA. The results were analysed and compared with conventionally manufactured counterparts. It was concluded that the yield strength of SLM-fabricated specimens is significantly higher than those of the conventionally manufactured parts due to the rapid solidification process that occurs during SLM.

(iv) Dimensional accuracy and wear characteristics

Dolinšek (2005) investigated wear resistance of sintered tool inserts and wear characteristics. The results of the work relate dimensional accuracies and product parameters to the number of injection shots. Antony *et al* (2014) presented a numerical and experimental investigation on laser melting of stainless steel 316L by evaluating the effect of laser power, scanning speed, and beam size on the geometric characteristics of melt zone. Comprehensively, the results provided a beneficial realization to homogeneity of layer formation AM processes that involve laser beam melting. In addition to that, the effect on surface morphology such as track smoothness, distortion, and irregularities are influenced by laser power and scanning speed. Therefore, the simulation model is capable

of assisting in the decision-making process for producing parts with better quality and avoid thermal distortions and balling phenomena.

Song *et al* (2015) reviewed the advantages of SLM-fabricated parts. One of these advantages is the ability to produce complex and customised parts with a high dimensional accuracy. Therefore, SLM technology can be used in applications in the die and mould industry, medicine, astronautics, and aeronautics. As for the study conducted by Yakout *et al* (2018), comprehensive experimentation of the characterisation of stainless steel 316 L fabricated by SLM was carried out to evaluate the effect of part dimensions on microstructure characteristics.

Mechanical properties and wear characteristics of stainless steel 316 L injection mould tool inserts fabricated using SLM technology have been reviewed in this work. The literature review indicates recommendations from previous research on the appropriateness of utilising SLM technology. Investigations of previous studies evaluated the effect of process parameters on microstructure, micro-hardness, surface roughness, fatigue behaviour and dimensional error of SLM-fabricated parts.

2.3.2 Tool life

Long-term consistent tool use should be capable of producing several thousands of parts before eventually wearing out. To date, other researchers have focused primarily on investigating the use of AM technology for injection moulding for low-volume component production rather than medium/high volume production.

King and Tansey (2003) affirmed in their review that RapidSteel tooling solutions that primarily use steel and copper produce metal tools capable of surviving tens of thousands of cycles. In the review it was specified that this tooling method wears in the same manner as subtractive tooling and is capable of producing more than 100,000 plastic parts although no actual tests were made. This method of tool fabrication is capable of cutting down cost and lead-time. One way of describing this method is polymer coated stainless steel powder infiltrated with bronze offering similar benefits of hardness, high thermal conductivity and durability as P20 steel hardness and durability.

Levy *et al* (2003) and Kruth *et al* (2007) reviewed that RT aims to fabricate long-term consistent tools that are capable of producing multiple thousands or even millions of parts before finally wearing-out. Due to growing market demand, RT technologies are pushed towards fabricating tools that produce large volumes of parts in similar materials as more traditional technologies that are currently in use, highlighting the importance of tooling applications particularly for injection moulding, while other techniques such as sheet metal forming and forging dies were considered for low volume production. Nevertheless, emphasising that the market for RT is still limited, although potential applications are found for soft tools to produce limited volumes of production and hard tools that can produce up to 100,000 parts.

The work of Rossi *et al* (2004) reported the use of DMLS technology in the fabrication of injection moulding prototypes. The tools produced were utilised to create a benchmark that evaluates limitations and problems arising from this technology concerning surface finish. The prototype nickel protected tool was successful in Injection moulding of 500 polypropylene components without any signs of wear showing a potential for this technology.

Godec *et al* (2008) analysed the influence of an indirect metal laser sintering process (IMLS) fabricated mould and that of a classic mould on the properties of moulded parts and their processing parameters in thin-walled injection moulding. Principally, the objective of this analysis was to test the wear level of the thin wall injection moulding in IMLS moulds after 5,000 parts were produced. The basic objective of analysing the capability of the thin-wall injection moulding in hybrid moulds was to check the wear level of the prototype mould inserts. The occurrence of excessive wear of these inserts after the fabrication of the first several thousand of moulded parts would indicate the impossibility of continuing the experiment because of the changes in dimensions and the threat of damaging the mould inserts. After testing for three parameters, length, width and mass of the moulded part, no wear occurrence has been detected showing the advantages of tool inserts made with IMLS.

AM or more specifically its application for RT has exhibited successful outcomes. Wohlers (2010) provided previous studies comparing traditional tool fabrication methods with DMLS for an automotive company. The results were satisfying, having a reduction in

lead-time and cost when using AM for tooling. Traditional machining and EDM took twice as long as DMLS, whilst tolerances and overall quality were considered equivalent. Current research indicates that improving moulding cycle time is an important aspect when considering high-performance tools rather than the time taken to produce the tool.

Rahmati and Dickens (2007) developed rapid injection mould tools using Stereolithography (SL) to accomplish low-volume production of 500 parts. In their work, the maximum number of successful injections of the SL tools was evaluated. Furthermore, additional studies by Zhang *et al* (2017) specified the durability of carbon fibre reinforced photopolymer tool inserts up to 2,500 injections before a deterioration of the tool inserts was noticeably observed. This soft tooling process was suitable for producing intermediate production volumes that range from 1,000 to 10,000 cycles of injection moulding.

Achillas *et al* (2017) debated that AM technologies are not capable of replacing injection moulding for medium and high production volumes. However, it was also stated in their work that RT could be incorporated for low-volume production to achieve shorter lead-time and reduced production cost. Other research analysed and reviewed the use of RT for the production of tools and dies whether direct or indirect for low-volume or high volume production, without conducting a more in-depth evaluation of the number of parts produced (Khaing, Fuh and Lu, 2001; Petrovic *et al.*, 2011; Mellor, Hao and Zhang, 2014).

2.3.3 Product functionality

Process parameters attributed to injection moulding processing have a direct effect on the properties of the produced part. Therefore, it is necessary to recognise and follow the fundamental guidelines that set the processing parameters to accomplish the required part properties.

Nagahanumaiah and Ravi (2009) directed a study where surface characterisation of DMLS mould inserts showed no apparent damage after the production of 5,000 parts. In the study conducted by Nagahanumaiah and Ravi, it was confirmed that using DMLS technology for tooling application is promising in producing few thousands of industrial quality products. Gu *et al* (2012) discusses the necessity of producing parts that meet the

mechanical properties required by industry, hence, emphasising that the role of AM towards functional components that serve industrial sectors, specifically for functional injection mould inserts. Gokuldoss *et al* (2017) reviewed some of the advantages of using SLM technology: wide range of material usage, low cost, flexibility in part production, and increased functionality of the end products. In a study by Mendible *et al* (2017) DMLS tool inserts were fabricated and surface temperature, longevity and part properties were evaluated.

2.4 Design Complexities and Manufacturability Limitations of Design Features

The concept of design features has been categorised and defined into machining and AM features by Le *et al* (2017). Multiple definitions have been proposed in previous research. Sormaz and Khoshnevis (2000) and Le *et al* (2017) defined machining features as volumetric and are associated with a surface feature which contributes to the part boundary. Reviewed by Başak and Gülesin (2004) a feature is a geometric section in a shape that is used in a CAD model that interrelates design and manufacturing information. A feature such as hole, slot, pocket, etc. has several definitions depending on the application, whether shape features, manufacturing features, or geometric features (Başak and Gülesin, 2004).Wang (2015) categorised machining features into surface features, geometric features, and volume features. Surface features interrelates the different faces that define the machining surface, geometric features hold the primary information of geometry, dimension and tolerances, and lastly volume features are the solid volume of the machining feature. Simple elements such as line, circle, etc. don't provide sufficient information for the design for manufacturing. Le *et al* (2017) adopted the definition of machining features that explained it as a set of geometries with attributes for which at least one machining process is identified. As for the definition of AM features, it was reviewed and proposed in the work of (Le *et al* (2017) as a geometrical shape that is associated with attributes with at least one given AM process. The recognised definition in this work is a combination of more than one definition reviewed by Wang (2015) and Le *et al* (2017).

Challenges caused by design complexities during the design stage must be coordinated and overcome by a suitable manufacturing approach. Therefore, essentially the goal is to establish the complex areas of a tool during the design stage. The complex

areas of a tool are likely to impose increased manufacturing lead-time, cost, and challenges in achieving the desired quality levels for the tool. When adopting a manufacturing approach, it is essential to acknowledge limitations and restrictions. AM is a flexible fabrication approach that is entirely different in technique when compared to subtractive manufacturing. AM is capable of fabricating complex and freeform near-net or final shapes. However, there are limiting aspects to surface integrity, dimensional accuracy, and in some instances design restrictions. As for subtractive manufacturing, design restrictions, manufacturing lead-time, and cost are major limitations.

Design for Manufacturing (DFM) as explained by (Kerbrat *et al* (2011) is an approach that "aims to integrate manufacturability aspects during the design stage", as well as determining and avoiding complications at the design stage that may arise in the manufacturing stage thus reducing lead-time and cost and improving product quality as reviewed by Kerbrat *et al* (2010). Moreover, Kerbrat *et al* (2011) highlighted that the main goal of the DFM methodology is to facilitate the manufacturing process adopted. Therefore, it is essential to acquire an in-depth understanding of the manufacturing process and the challenges that might be faced. Mellor *et al* (2014) emphasised that issues that are involved in designing a specific part are clearly and deliberately addressed when in a DFM approach. While Elmaraghy *et al* (2012) stated that the aim of this method of designing is to evaluate and compare different design alternatives. Kerbrat *et al* (2010) stated that the definition of features is specific to the developing process, therefore, machining features are developed for process planning for a mechanical product definition, whereas, there are no features for AM. However, (Le *et al* (2018) clearly identified the extraction approach of AM features from the available information provided by the part with a knowledge of the technological requirements and the available resources.

2.5 Knowledge-based decision systems for fabricated tooling inserts

SLM has shown promising outcomes in the fabrication of tooling inserts. Therefore, numerous researchers have directed their attention to the development of decision-making systems or assessment methodologies to generally integrate the benefits of AM technology in tooling processes. Developing a systematic approach that evaluates the

manufacturability feature limitations of SLM technology in comparison to conventional methods has shown challenges.

Pal *et al* (2007) discussed a methodology where quality function deployment (QFD) and analytic network process (ANP) are integrated to convert customer needs into product technical requirements. The second stage of the study is a decision-making tool used for prioritising the engineering requirements based on customer needs for selecting and evaluating an appropriate RP approach for fabricating a casting tool.

Nagahanumaiah *et al* (2007) presented a systematic approach for manufacturability analysis of moulds produced by RT methods, the approach being founded on three phases: mould feature manufacturability, secondary elements compatibility, and cost effectiveness. The geometric features of the mould core and cavity are evaluated for manufacturability using a fuzzy-analytic hierarchy process (Fuzzy-AHP) methodology, as geometric compatibility for manufacturing a feature is characterised by a pass or fail approach. Additional work has been carried out and presented by Nagahanumaiah *et al* (2008). A computer-aided RT process selection and manufacturability evaluation methodology is presented for injection moulding. The process selection supports mould cost estimation models and process capability databases. The model is based on a QFD process capability mapping with a set of tooling requirements that are prioritised through a pairwise comparison using AHP.

In the work of Nagahanumaiah and Ravi (2009), a generic approach is investigated for using grey relational analysis to quantify the effect of different moulding process variables on selected quality parameters for parts produced from DMLS moulds. Data of dimensional error and weight difference are normalised as often called grey relation generation to define the relationship between the desired and actual experimental data. It was concluded from the work of Nagahanumaiah and Ravi that even after producing 5,000 parts from the DMLS mould, no visible damages were detected. This study confirmed that there is promising potential application to the use of DMLS moulds for producing thousands of parts of industrial quality. However, it was recommended in this study to investigate mould life as it still poses a challenge for further improvement.

Kerbrat *et al* (2010; 2011) developed a methodology that estimates the manufacturing complexity of tools using manufacturability index calculations based on octree decomposition for machining and AM. In this approach, areas with the most complexity are focused on, and the calculated indexes indicate which areas are advantageously machined or manufactured by an additive process to avoid manufacturing difficulties. In this case, tools are seen as separate single modules that are further assembled. The aim of this paper is to introduce a system that may be applied to increase flexibility of the tool and to have a more detailed view of manufacturing complexity. In the work of Kerbrat *et al* it is recommended to introduce other parameters with fuzzy logic to facilitate further researches to develop new manufacturability indexes based on material information and technical specification. Moreover, taking into account the assembly constraints generated by a hybrid modular design.

Townsend and Urbanic (2012) related AM with CNC machining in a holistic approach for design and manufacturing, that defines the strength and weaknesses of each process. Moreover, for any given criteria, one of the processes will show a distinct advantage over the other. The processes are mapped simultaneously to the geometry and function of the part with regard to process strength. In the referred study, modules are created to group part geometry and process selection is determined to fabricate the modules. Functionality is associated with part geometry; hence a systems approach proposes applying an AHP model that quantifies decision-making for process selection.

Ponche *et al* (2014) proposed a numerical chain based on a new design for AM methodology detailing both design requirements and manufacturing specificities. The quality of the produced parts is significantly affected by the physical phenomena occurring during AM processing. Therefore, the methodology proposed in the work offers a new DFAM approach detailing design requirements and manufacturing specifications right from the part design stage that allows optimisation of part geometry for thin-walled metal parts. However, the work of the conducted study is restricted to extruded parts.

Zhang *et al* (2014) proposed an evaluation framework in which quantitative indicators are defined according to the design needs of the specific AM process to convey information from process planning for improving the design. Referring to the user's

manufacturing requirements, the purpose of the framework is to check whether a designed part is suitable to be manufactured by AM processes.

2.6 Research Gap

It can be concluded from previous research that there is lack of application in integrating SLM and subtractive manufacturing technologies. Therefore, for the first reported time this research focussed on successfully integrating SLM and subtractive manufacturing for the production of injection moulding tool inserts for after-market automotive spare parts.

Interest over recent years has been directed towards high-performance tool inserts. However, only examples of tools of low-production volumes were given in recent literature. Research addressed the capability of using SLM technology in manufacturing injection moulding tool inserts, and none addressed high-volume production tool inserts of thousands of products. Therefore, more research must be oriented towards tooling of high-volume production using SLM technology and presenting the necessary means for investigating the outcomes. This research focuses on the production of SLM tool inserts and assessing their durability and quality through high-volume production of injection moulding. Even equipment producers have no proof of actual results to confirm tool-life and wear resistance of injection moulds fabricated using SLM technology.

From the literature it can be noted that some of the previous research was focussed on developing decision systems and methodologies that focus on design requirements and manufacturability evaluation for AM tool inserts. Other research developed systematic approaches that estimated manufacturability indexes to determine which module of a tool is manufactured using AM or machining. There is no system that integrates manufacturability feature limitations for AM and machining technologies for manufacturing injection moulding tool inserts. The systems developed do not provide the user with recommendations or explanation of the systems' outcome. The reviewed research lacked in presenting an approach that compiles the benefits and limitations of SLM-fabrication and subtractive manufacturing technologies for injection moulding inserts. For that system, manufacturability features are defined and evaluated to assist users interactively with recommendations for process selection.

.

3 Tool Insert Fabrication and Testing

In this chapter the research presented focuses on a study that assesses performance measures and tool life of SLM-fabricated tool inserts that has been pursued through application in the automotive industry. The guidelines depicted in the manufacturing framework have been followed by the study presented in this chapter. First, in the design stage, the CAD for the injection moulding core and cavity tool inserts is generated. Secondly, in the fabrication stage, the core and cavity tool inserts are manufactured using the designated methods. And finally, in the examination stage, the assessments and test procedures are carried out for the fabricated tool inserts and their respective products.

Two methods of manufacturing have been identified for fabricating the injection moulding tool inserts in support of this study; Subtractive Manufacturing and SLM. The tool insert is for a (spare part) component of a headlamp's adjuster clip that was selected as it was deemed an ideal item to support the focus of this study. The prime responsibility of this component is to hold together the vehicle's headlight's housing with the reflector, while allowing adjustment to the reflector's position. This component is essential to the functionality of the vehicle's headlamp and is produced in high volumes. Figure 3-1 illustrates a headlamp's adjuster clip component before assembly to a vehicle's headlamp.

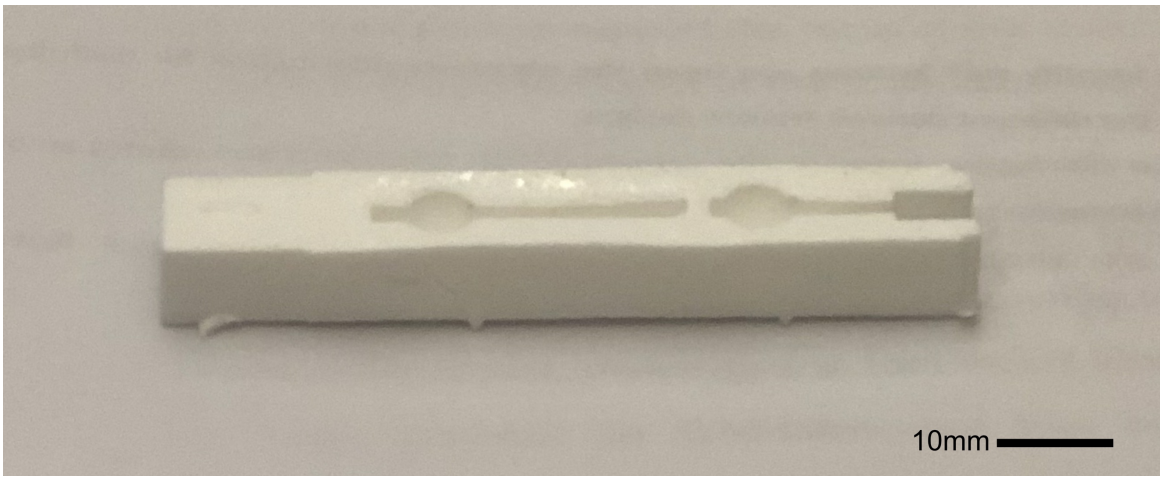

Figure 3-1: Adjuster clip component.

Therefore, the purpose of this study is to assess the performance of the SLM-fabricated tool inserts to test for parameters that impact high volumes of production.

The examination stage is divided into two sections: the first section is tool insert examination and is discussed in this chapter. As for the second section, product functionality evaluation and is discussed in Chapter 4. In this chapter, tool insert longevity is investigated. Firstly, an SLM-fabricated tool insert and a CNC-machined counterpart are investigated to test for microstructural analysis, performance measures, manufacturability, mechanical properties and dimensional accuracy. Secondly, an assessment is dedicated to evaluating the SLM-fabricated tool inserts in terms of performance measures, mechanical properties, and dimensional accuracy prior to and after multiple thousands of cycles of injection moulding.

3.1 Tool Insert Design

The part design for both the core and cavity inserts was created as one solid body for each insert as shown in Figure 3-2. The design method adopted agrees with the manufacturing methods implemented, being CNC machining and SLM. The range of dimensional tolerances allowed for the core insert was between ±0.2 mm and ±0.3 mm and ±0.5° for the draft angle. For the cavity insert, the design tolerances for the draft angle was set as the core insert at ±0.5°, and the dimensional tolerances were set to range between ±0.1 mm to ±0.3 mm with the minimum tolerance attributed to the internal features that have an impact on the final dimensions of the end-product (Table 3-1).

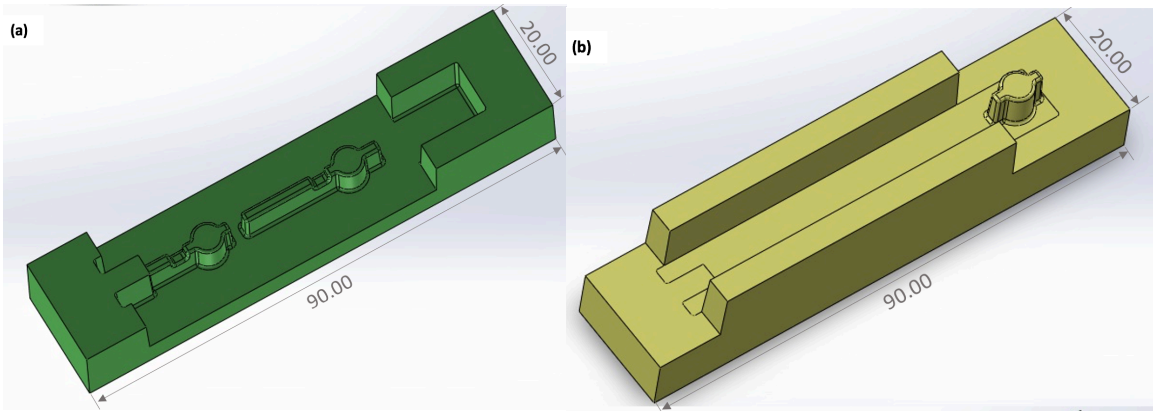

Figure 3-2: Design illustration of Adjuster clip tool (a) core and (b) cavity inserts in mm.

Table 3-1: Core and Cavity dimensions (including design tolerances).

Core Insert			Cavity Insert		
Dimension	Measurement (mm)	Tolerance (mm)	Dimension	Measurement (mm)	Tolerance (mm)
A	15	0.3	A	19.1	0.2
B	12	0.3	B	10	0.3
C	10	0.3	C	92	0.5
D	92	0.5	D	55.4	0.2
E	19.5	0.2	E	6	0.3
F	6	0.3	F	20	0.2
G	90	0.2	G	10	0.2
H	5	0.2	H	90	0.1
I	26	0.2	I	56	0.1
J	16	0.2	J	8.7	0.2
K	2	0.2	K	2	0.2
L	4	0.2	RL	2.6	0.2
M	12.7	0.2			
N	9.5	0.2			
O	5	0.2			

The tool insert's core and cavity under study with the associated measurements and the acceptable design tolerances are illustrated in Figure 3-3 and Figure 3-4. Design tolerances attributed to the tool inserts are set by the injection moulding designers located in the factory where the tool inserts were manufactured. Guidelines to the design tolerance standards that the designers work with are obtained from Drake (1999) and Henzold (2006)

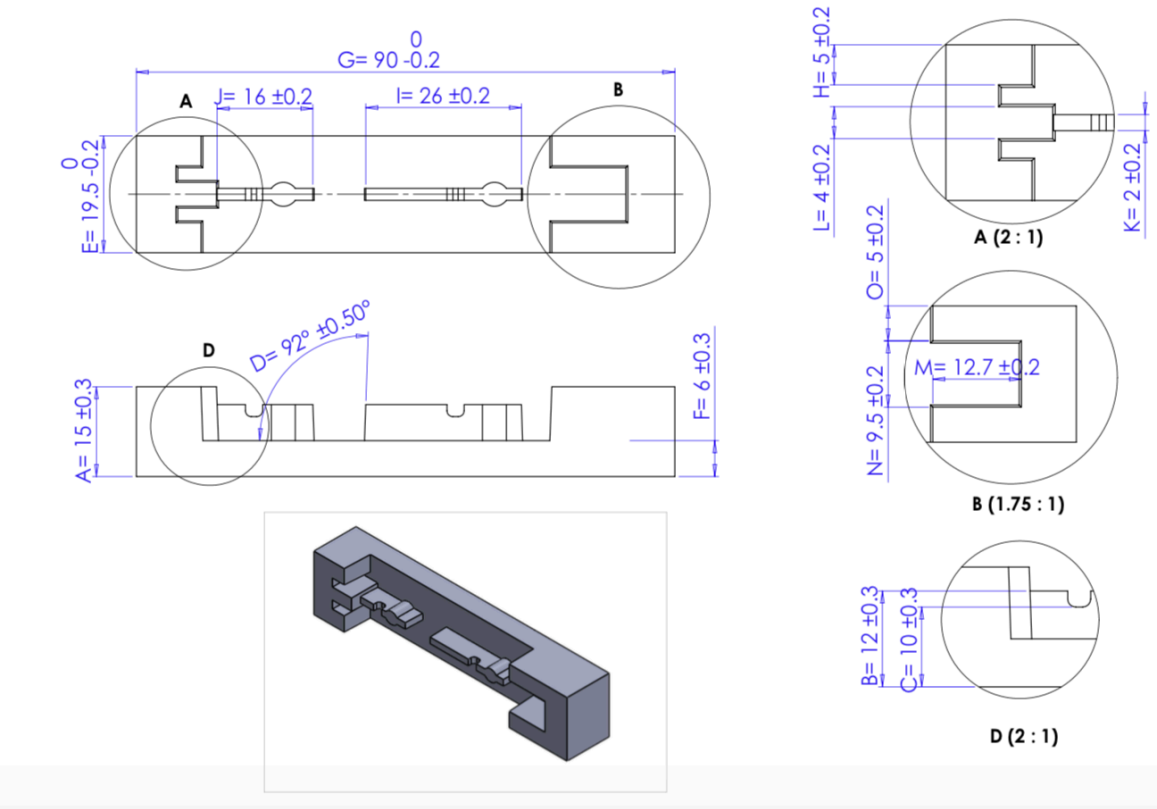

Figure 3-3: Core insert illustration with tolerances indicated in mm.

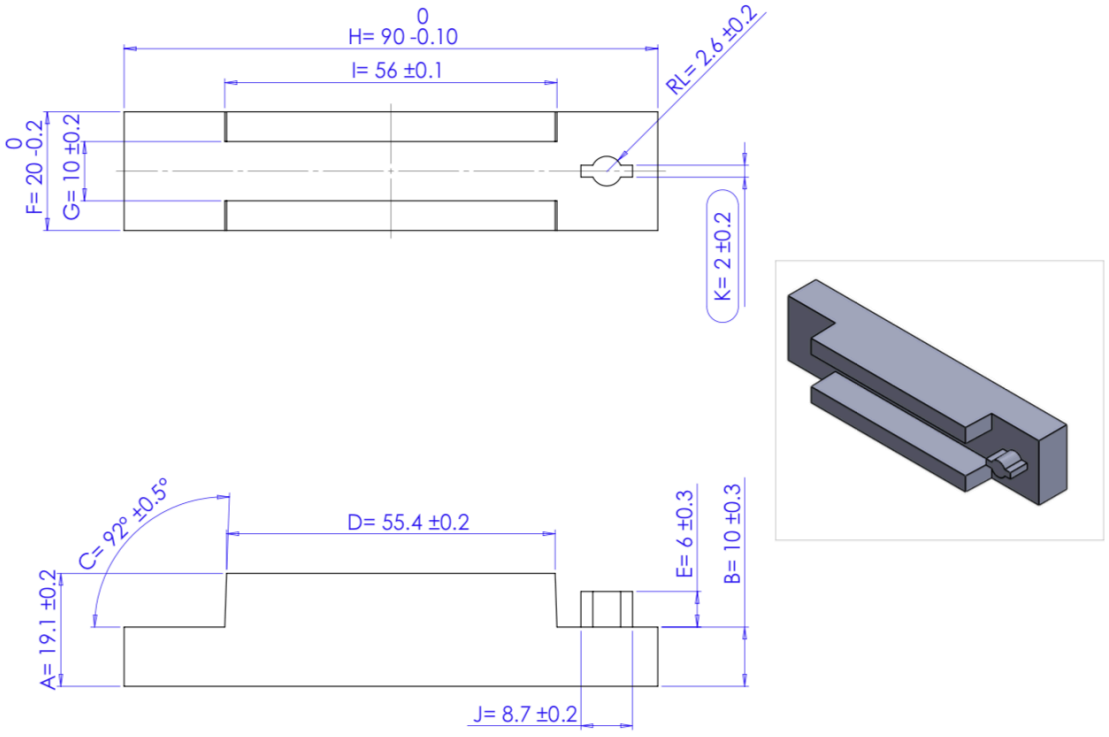

Figure 3-4: Cavity insert illustration with tolerances indicated in mm.

3.2 Tool Insert Fabrication

Stainless steel 316 L was the material used for fabrication in this study. Maintaining the same material for the tool inserts for both subtractive and AM techniques is imperative to ensure consistency of the results. The material used for SLM-fabrication was in powder form, while the machined material was in billet form. One set of tool core and cavity inserts was manufactured using CNC machining and four sets of tool core and cavity inserts were fabricated using SLM technology.

3.2.1 CNC-machined tool inserts

The CNC-machined core and cavity inserts was manufactured at an automotive spare parts company in Alexandria, Egypt on a 3-axis First V 700 machines with maximum spindle motor power of 5.5-7.5 KW and 10,000-15,000 RPM. Two end-mill carbide tools and one ball nose cutter were used for the bulk material removal. The diameters for the tool cutters were 4, 16 and 4 mm respectively. The material supplied for manufacturing was Stainless Steel 316L due to high wear resistance, good toughness, and higher chromium levels. Figure 3-5 shows the CNC manufactured tool insert core and cavity.

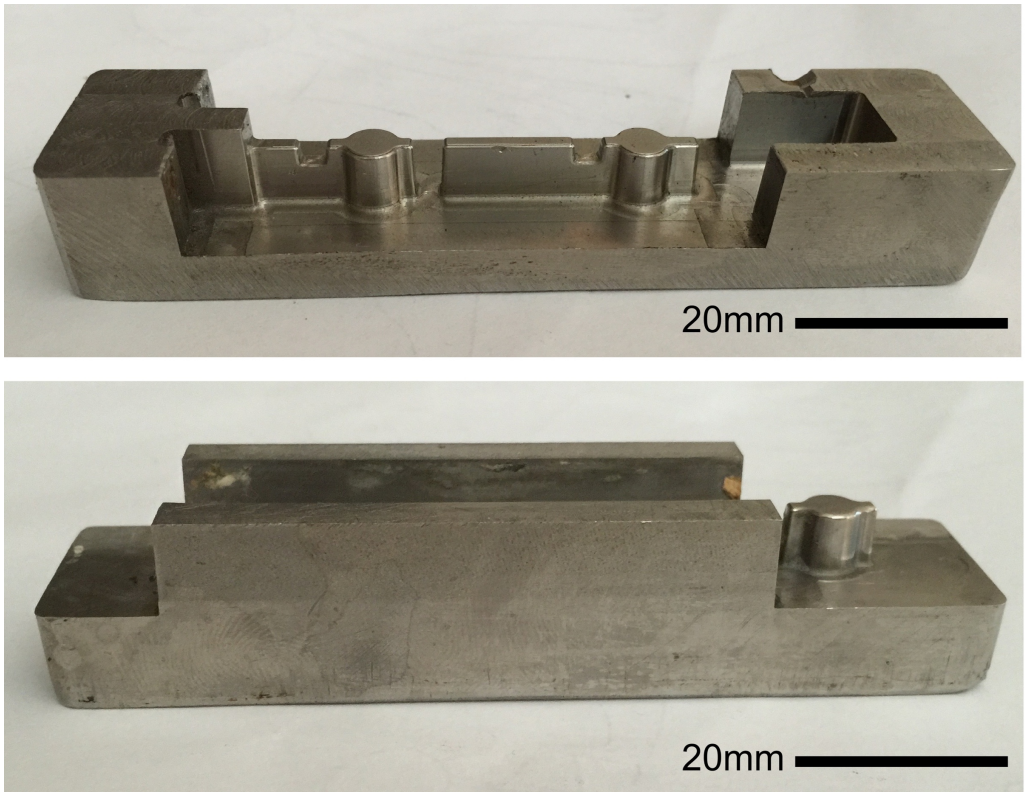

Figure 3-5: CNC-machined core and cavity tool inserts.

3.2.2 SLM fabricated tool inserts

SLM technology has been used to fabricate four tool inserts of a similar geometry for an after-market automotive spare part headlight's adjuster clip. The four SLM-fabricated tool inserts were built at Croft Additive Manufacturing Ltd (Warrington, UK) on a ReaLizer SLM 250 with a laser power of 200 W;, build orientation is shown in Figure 3-6. The material provided for fabricating the inserts was Stainless Steel 316L powder supplied by LPW Technology Ltd (Runcorn, UK), with particle size nominally in the range 45-150 μm and a layer thickness of 50 μm. Simultaneously, the four tool insert specimens were fabricated directly from 3D CAD data models using the SLM process. The maximum part dimensions were 90mm x 20mm x 15mm, with the final fabricated tool insert shown in Figure 3-7. Parts were scaled in the CAD model to compensate for allowances caused by shrinkage during cooling of the injected products.

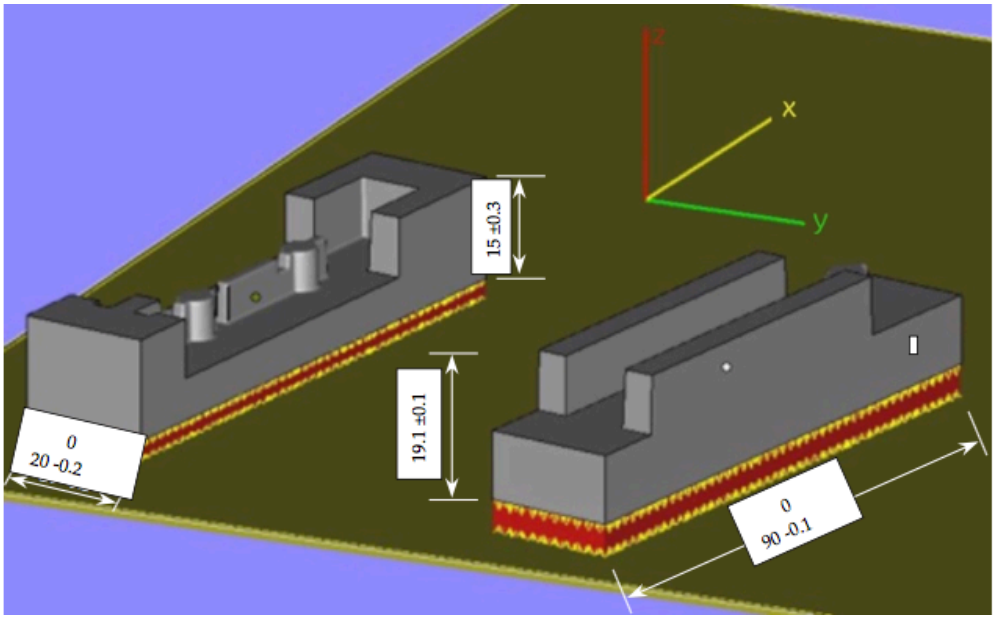

Figure 3-6: Part orientation, layer structure, and main dimensions (mm) during sintering process.

During the SLM fabrication process, the hatch X and Y distance is set at 0.1 mm respectively. Initially, sand blasting was used to remove the excess powder after the fabrication process, with further manual polishing to ensure mating of the cores with the cavities of each set of inserts.

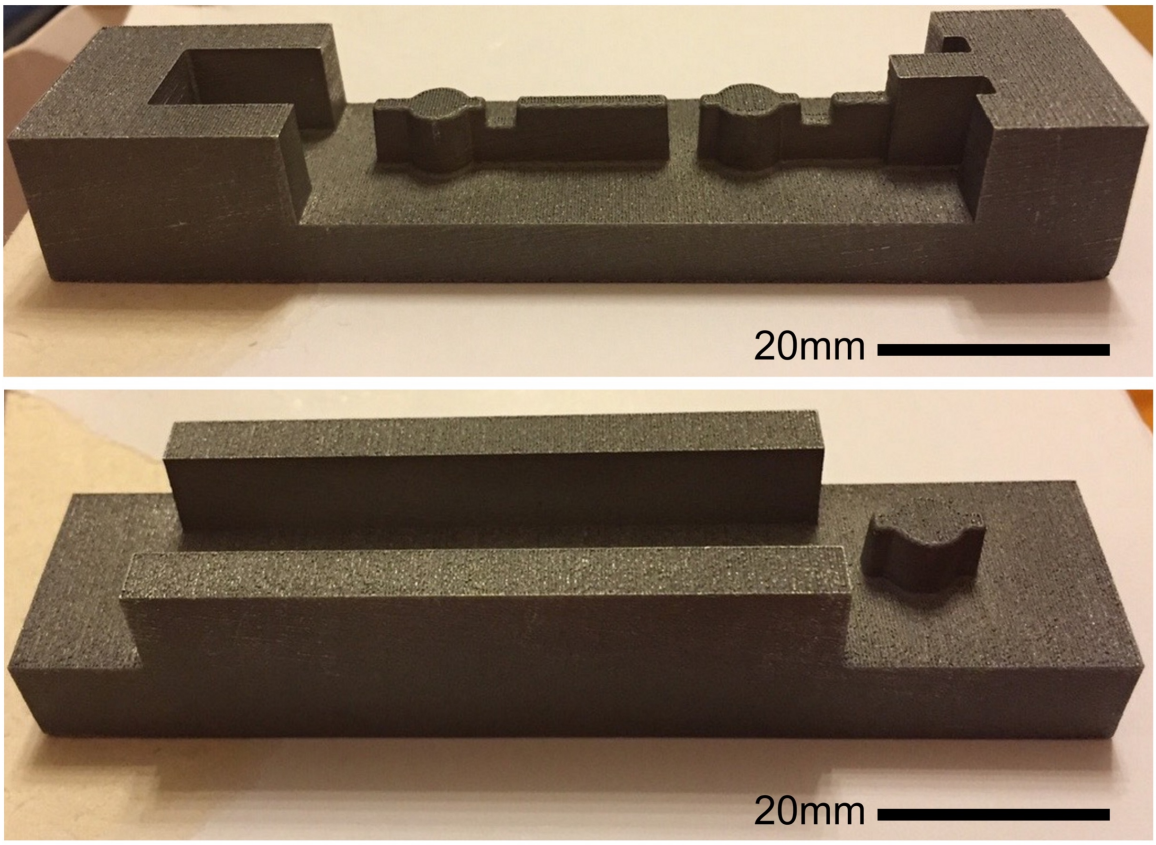

Figure 3-7: SLM-fabricated core and cavity tool inserts.

3.3 Tool Insert Assessment

Evaluating performance measures of the SLM fabricated tool inserts with respect to subtractive manufactured tool inserts require extensive experimental work.

Experimental procedures were carried out at two stages, the first stage of assessment provides a comprehensive understanding of the morphology and mechanical properties of SLM-fabricated components with comparison to their conventionally manufactured counterpart. As for the second stage of assessment, the same performance tests of the first stage of assessment were performed for the four tool inserts prior to and after multiple thousands of injection moulding (injection moulding is discussed in Chapter 4) in the context of surface morphology, mechanical properties, and dimensional and geometrical accuracy.

The following experiments were implemented in the sequence below:

- Spectral analysis
- Microstructure Inspection
- Hardness test
- Surface roughness
- Wear rate
- Fatigue test

3.3.1 Spectral analysis

The elemental chemical composition of fabricated tool inserts was determined using a Spectral Analyzer. Table 3-2 illustrates the standard chemical composition values of Stainless Steel 316L and how this compares with the SLM and CNC manufactured versions. The data obtained correlate to the standard acceptable range of Stainless Steel 316L (AK Steel, 2007). However, the slight variation in the elements' weights between the CNC and SLM inserts is expected to have a direct influence on the performance and hardness of the inserts. Notably, the increase in Nickel and Molybdenum weights is expected to have a directly strengthen the SLM samples. The standard value of Carbon in stainless steel 316 L depicts low carbon content of approximately 0.03%. The minimum percentage indicated by the standard for the Carbon content is attributed to no need of heat treatment and post-processing after manufacturing.

Table 3-2: Chemical composition of SS 316L (wt.%).

	wt %								
SAMPLE	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
SS 316 L STANDARD (AK STEEL, 2007)	0.035	0.75	2	0.045	0.03	16-18	2-3	10-14	Balance
CNC	0.079	0.411	1.43	0.026	0.017	16.645	2.09	9.9	68.283
SLM	0.071	0.41	1.52	0.023	0.021	16.057	2.38	10.397	69.03

3.3.2 Microstructure inspection

The SLM and CNC manufactured tool insert were prepared for inspection by optical microscopy using a Carl Zeiss Axiovert 200 microscope. To reveal the microstructure, polished samples were immersed in a chemical acidic solution for 20 minutes; the solution

contained 96% pure white Alcohol, 2% Nitric Acid (with a concentration of 69%) and 2% Hydrochloric Acid. After removal from the solution, the specimens were cleaned in distilled water.

Looking at the microstructure formation of the CNC machined inserts showed the same distribution of grains as with the optical microscope. However, the presence of large numbers of gas pores is noticeable as shown in Figure 3-8 (b) and (c). When comparing the microstructure of Stainless Steel 316L of both the CNC machined core and cavity with the standard microstructure, there are no apparent differences (Odnobokova *et al.*, 2014).

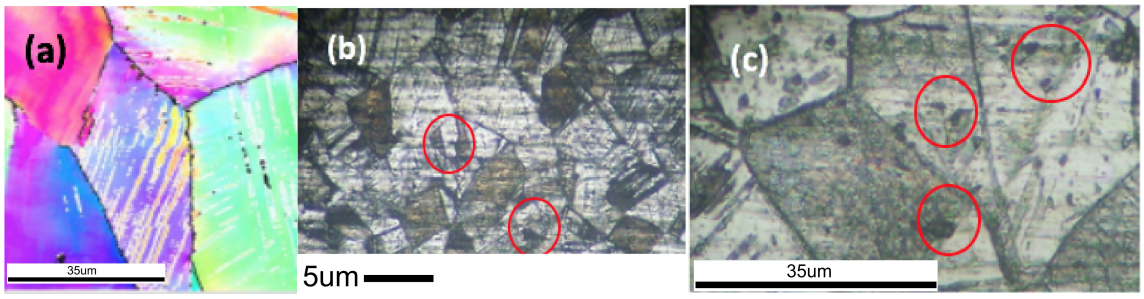

Figure 3-8 Comparison between (a) Standard Stainless Steel 316L (Odnobokova *et al.*, 2014) and (b) CNC machined core and (c) CNC machined cavity microstructure at (200x and 500x magnification).

Grain size and boundaries were indefinable in the SLM tool inserts due to distortion caused by sintering of stainless steel 316L powder. Inspection of the SLM-fabricated specimens suggested the presence of carbides and porosity along the surface of the layers. Nevertheless, the non-uniform distribution of temperature during the build causes unpredictable formations and influences the uniformity of grain sizes. Images were captured as shown in Figure 3-9, magnified to 200x and 500x respectively. Image capturing was repeated three times for each of the five regions of interest chosen on the same specimen to confirm evidence that higher contents of carbides are detected. Those precipitates that tend to segregate toward the layer boundaries are believed to be impurities, intermetallic carbides, or oxides. Such occurrence stirred attention for further investigation using a Scanning Electron Microscope (SEM) to analyse the morphology and particle composition of both the CNC and SLM tool inserts.

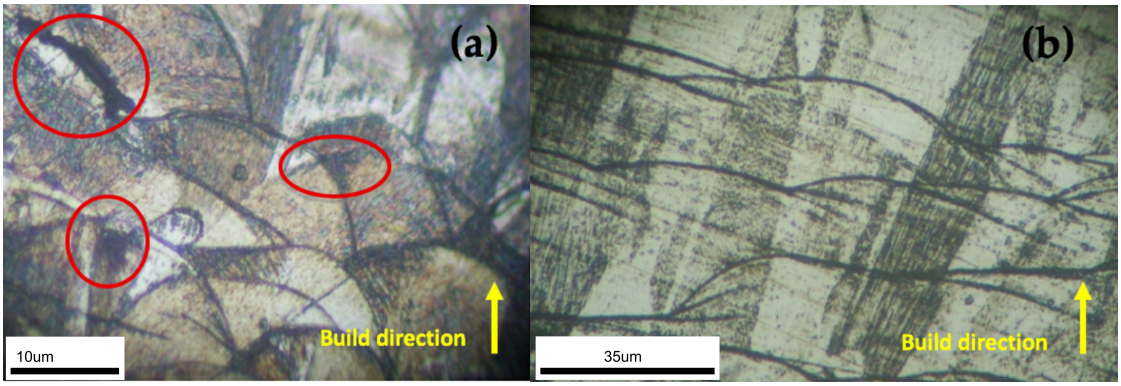

Figure 3-9: 200x (a) and 500x (b) magnification of inspected specimen on Carl Zeiss Axiovert 200 with evidence for presence of carbide inclusions.

SEM analysis was conducted at the American University of Cairo (Cairo, Egypt). An ultra-high-resolution Leo Supra 55 SEM was the equipment used for testing to observe layer structure, surface morphology, and microstructure of the SLM fabricated tool inserts. The presence of pores in the CNC inserts is justified by the fact that the Stainless Steel 316L used for machining was initially cast and such inclusions are anticipated. The presence of gas pores depending on their shape and size are expected to cause defects on the surface in the form of surface porosity as shown in Figure 3-10.

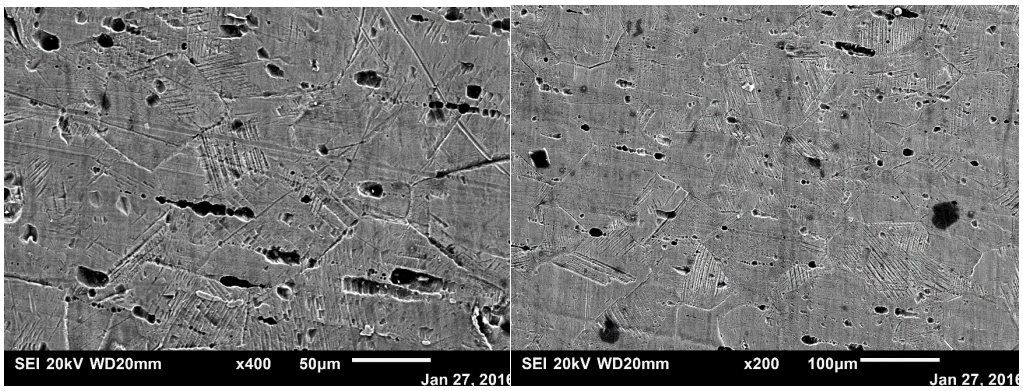

Figure 3-10 Representative SEM microstructure of Stainless Steel 316L for CNC machined tool inserts (a) presence of gas pores (b) grain formation.

The SEM conducted at the American University of Cairo was linked with an Energy Dispersive Spectroscopy (EDS) system employed to detect particle formation, chemical composition, and intermetallic inclusions of the sintered specimens. Melt pools are aligned in an interlacing arrangement as a result of laser scanning patterns and rapid solidification, therefore a distortion to grain structure and boundaries causes

considerable difference to microstructure scales for sintered stainless steel 316L (Kruth *et al.*, 2004). As highlighted in Figure 3-9 the presence of intermetallic carbides is concentrated in some regions more than others along the layer surface of the sintered specimens. Three measurements of the layer thickness were recorded for a particular region of the layer as shown in Figure 3-11.

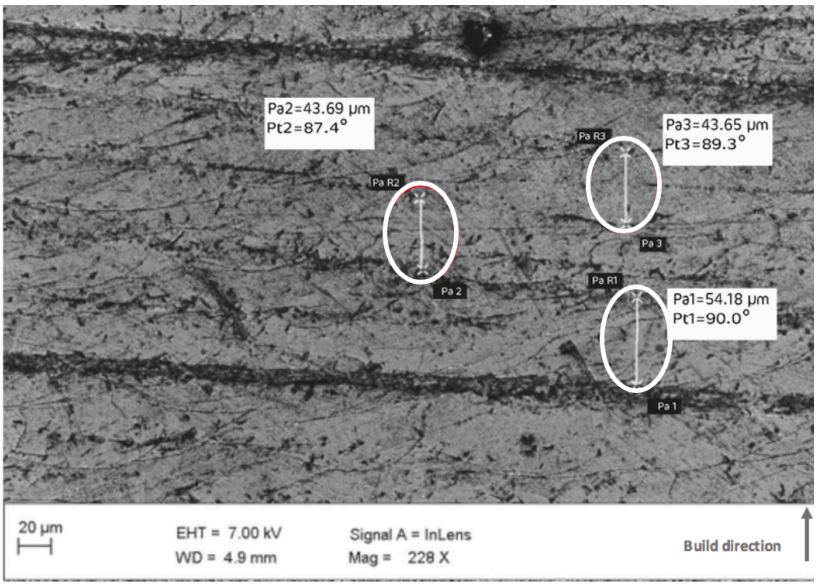

Figure 3-11: micrographs of SLM tool insert surface with recorded layer thickness at three different points.

The average recorded layer thickness is 47.17 µm at 228x magnification. The procedure was repeated three times for each region, with five separate regions considered. The pre-set value on the machine for layer thickness is set at 50 µm but is known that variation in layer thickness can be as a result of heat dispersions along the built layer. Since increasing layer thickness increases the porosity, hardness eventually decreases with this increase in layer thickness (Chatterjee *et al.*, 2003). The presence of gas pores depending on their shape and size are also expected to cause defects on the surface in the form of surface porosity. The specimens were examined for porosity inclusions, and it was determined that gas pores are identified as shown in Figure 3-12. As a result, further mechanical tests were conducted to examine the mechanical properties of the SLM-fabricated tool inserts.

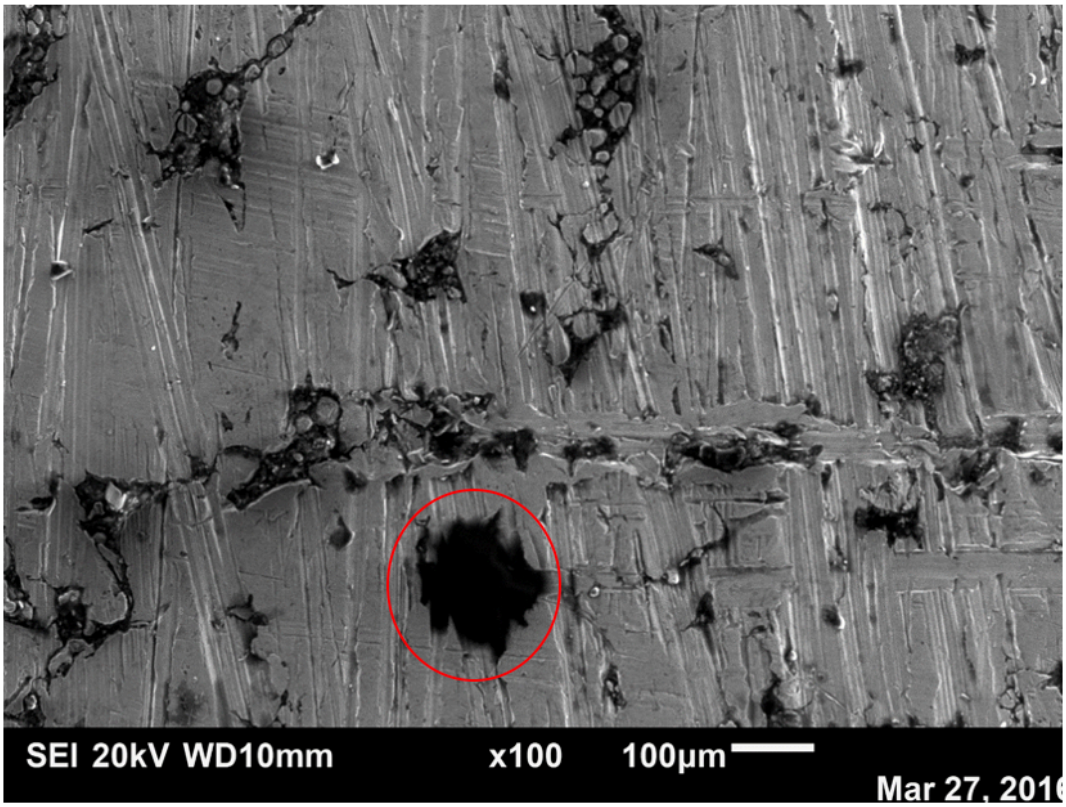

Figure 3-12: Pores inclusion in SLM fabricated Stainless steel 316 L specimen.

Images captured from the SEM provide significant evidence that formation of intermetallic carbides is present along the layer surface of the sintered specimens. Carbide formation is concentrated in some regions more than others, specifically along the boundary of each individual layer. During the laser melting process, the presence of high concentrated weights of chromium, nickel, and molybdenum in Stainless Steel 316L allows carbides to form, resulting in reinforcements of some mechanical properties such as hardness and wear resistance. The prospect of knowing the elemental type of intermetallic particle that is formed involves extensive analysis. An EDS system was employed to detect the type and size of intermetallic particles that may cause carbide formation. Quantitative analysis of the alloying elements of Stainless Steel 316L was conducted. As stated previously, Chromium has the greatest weight concentration followed by Nickel and Molybdenum. Figure 3-13 shows a micrograph of the presence of intermetallic particles along the layer boundary. The image capture process is repeated three times for the specified region, with five separate regions considered. At higher magnification, cellular structure and carbide formation was revealed.

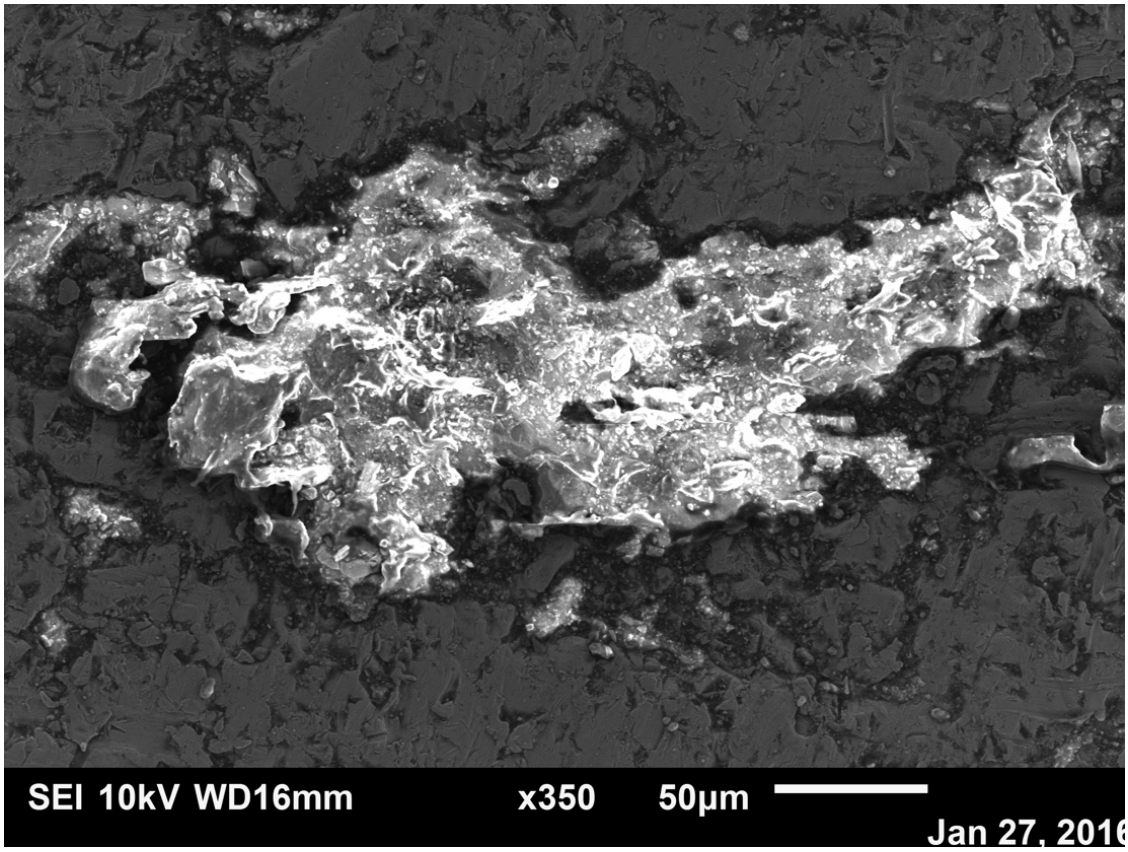

Figure 3-13: Magnified intermetallic carbide segregation along layer boundary.

Figure 3-14 provides a summary of the results from the EDS analysis. The data indicates the type of intermetallic particle with the highest concentration level is Chromium accounting for 4000 intensity counts. Nickel accounts for 1000 counts, and Molybdenum has the lowest concentration level of 500 counts. Carbon was not counted nor classified in the EDS measurement, because it should only account for less than 2 wt.% of the chemical composition, which is in good agreement with the alloy balance (Trelewicz *et al.*, 2016). However, Silica is accounted for with a high concentration level due to the presence of an impurity within the formed carbide particle. Elemental segregation of intermetallic particles is believed to impact wear resistance characteristics of a given material causing the material to be brittle which may affect tool insert longevity. Therefore, injection moulding of the tool inserts is essential to examine durability and wear resistance of the SLM-fabricated tool inserts.

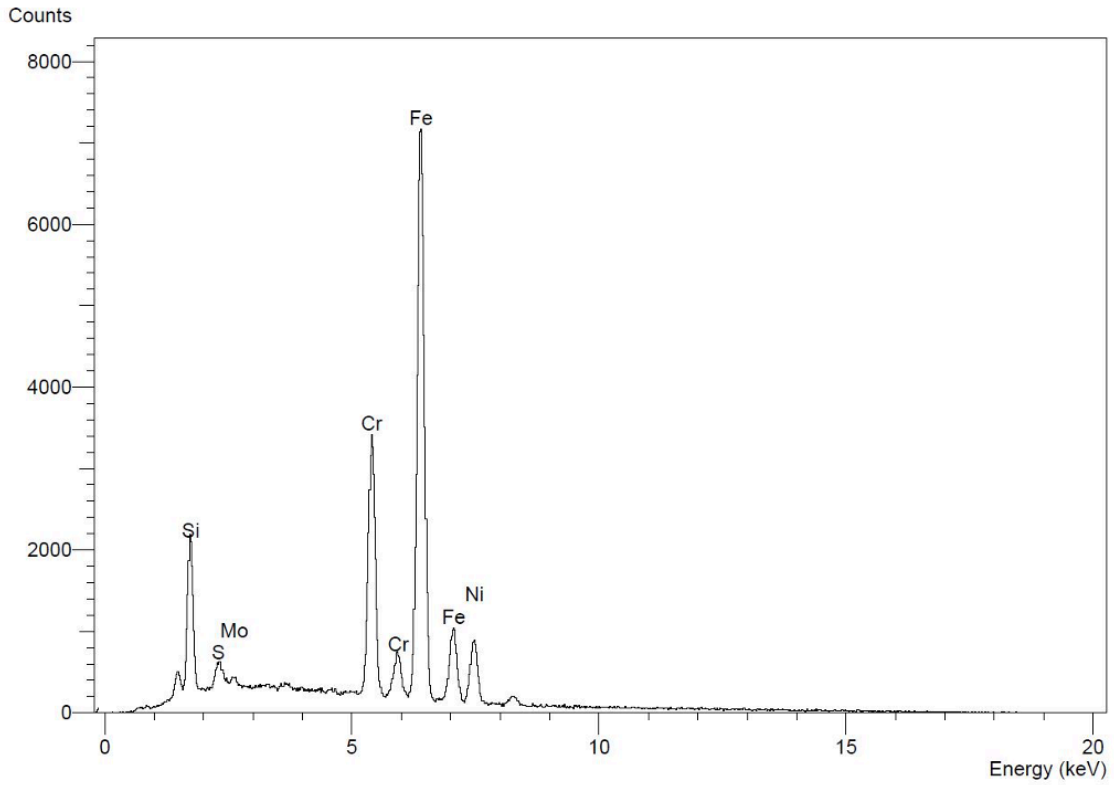

Figure 3-14: Elemental analysis using EDS for intermetallic particles segregated towards cell boundary, and demonstrating the enrichment of Cr, Ni, and Mo at the boundaries.

3.3.3 Surface roughness

In order to assess and quantify the roughness of the SLM-fabricated tool inserts in comparison to the CNC tool inserts, initially, one of the SLM-fabricated tool inserts was acquired for experimental work. A Talysurf profilometer was used to measure the surface roughness of the SLM and CNC machined tool inserts right after fabrication. Figure 3-15 illustrates a 2D drawing of the core and cavity inserts with the surfaces that have been selected and measured: surfaces A, B1, B2, and C. The surfaces were selected in regard to the frequency in which the core and cavity are in contact during the injection moulding process. Table 3-3 presents the average roughness (Ra) values of the SLM specimens depicting rather high values for surface roughness.

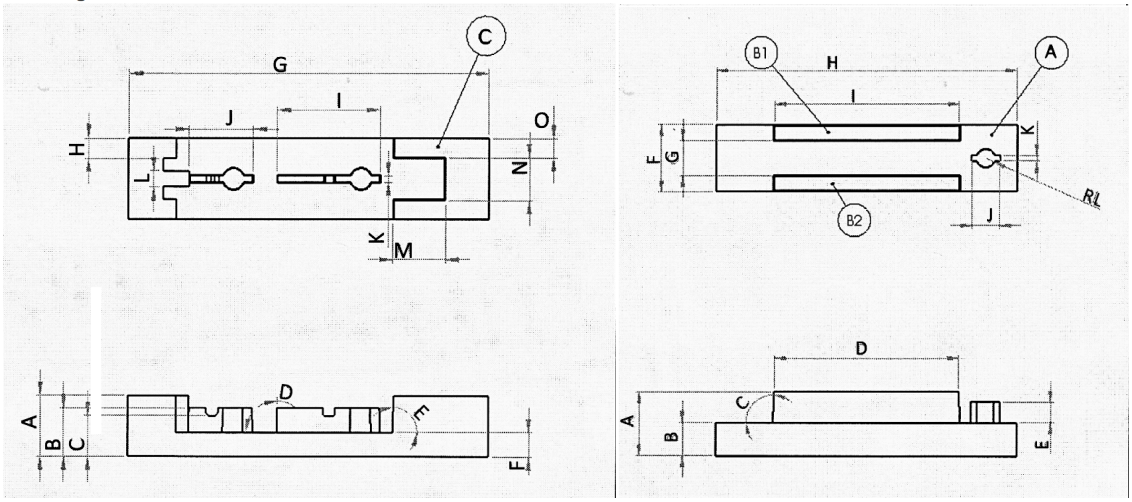

Figure 3-15: 2D illustration of the tool insert's core and cavity.

Table 3-3: Average surface roughness (Ra) measurements of SLM tool inserts after fabrication.

Surface	Ra (μm)
A	10
B1	14
B2	14
C	15

Therefore, post processing was deemed necessary to refine the surface of the SLM inserts to ensure accurate mating of the core and cavity for the injection moulding process. After polishing of the surfaces, surface roughness of the SLM and CNC tool inserts was measured using a Laser scanning Microscope Keyence VX-100. Shown in Table 3-4 are the average roughness values of the SLM and CNC tool inserts. The measured roughness values of the SLM core and cavity show a substantial decrease in roughness when compared to the measurements recorded prior to post-processing. However, it is evident that the CNC samples present a superior surface roughness when compared to the SLM inserts prior to post processing. As for surface A, the SLM sample recorded a relatively high value of 7.5 μm after polishing was executed. The increased value of the surface roughness is a result of controlled post-processing to avoid deviation from dimensional tolerance to such a critical surface that is in constant contact with surface C. Hence, surface roughness of the SLM inserts improved with post processing while the CNC machined insert initially recorded better surface quality prior to polishing. Therefore, the remaining three SLM fabricated tool core and cavity inserts were post-processed to maintain an improved surface roughness prior to injection moulding.

Table 3-4: Average surface roughness (Ra) of SLM and CNC tool inserts.

Surfaces	CNC Ra (μm)	SLM Ra (μm)
A	1.9	7.5
B1	1.5	1.5
B2	1.6	1.1
C	0.8	1.1

The second stage of assessment investigated the four SLM-fabricated tool inserts. Surfaces of the four SLM tool inserts that are in contact due to mating of the core and cavity have been chosen for investigating the surface roughness. Roughness measurements were conducted before and after the injection moulding process (results for both will be presented in this chapter). In order to assess and quantify the roughness of the SLM specimens, a Talysurf contact profilometer was used.

For each tool insert, four values for surface roughness were recorded from each of the core and cavity tool insert surfaces. Surfaces A, B1, B2 are located on the cavity inserts, and C on the core inserts as illustrated in Figure 3-15. Final measurement values are an average of three readings for each surface. The purpose of measuring surface roughness is to investigate the effects of injection moulding on the surface texture of the tool inserts.

Table 3-5 demonstrates the variation in surface roughness before and after the injection moulding process. For Tool insert 1, an increase occurred to all values of the measured surfaces after 10,000 injections, with an evident significant increase in values specifically for surfaces A and C. The increase of surface roughness for these particular surfaces is explained by the constant contact of the two halves of the tool inserts during the injection moulding process, and eventually leading to coarseness of the surface due to friction between the two halves. For Tool insert 2, an increase in the values of surface roughness is noticeable after 20,000 injections along the mating surfaces of the core and cavity. For Tool 3 insert after 30,000 injections, readings show an increase in surface roughness for surfaces A, B1, B2, and C as compared to measurements before injections. Finally, for Tool insert 4, surface roughness deteriorates for all inspected surfaces and more significantly for surface C after 40,000 injections.

Table 3-5 Average roughness (Ra) measurements.

Measurements before injection	Measured Surfaces Ra (µm)				Measurements after injection	Measured Surfaces Ra (µm)			
	A	B1	B2	C		A	B1	B2	C
Tool insert 1	7.5	1.5	1.1	1.1	Tool insert 1 (10,000 injections)	14	1.6	1.9	5
Tool insert 2	7.8	1.2	1.1	0.8	Tool insert 2 (20,000 injections)	9.7	3.0	4.0	2.7
Tool insert 3	7	1.0	1.5	1.8	Tool insert 3 (30,000 injections)	8.2	3.2	4.0	2.7
Tool insert 4	7.5	1.5	1.1	1.1	Tool insert 4 (40,000 injections)	10.0	2.5	2.5	9.0

3.3.4 Hardness

A micro-hardness test was employed to determine the Vickers hardness for the CNC and SLM-fabricated specimens. Measurements were acquired using a Leco Vickers micro-hardness test, with 10 Kg load subjected to each half of the tool inserts with a dwell time of 15 s. The test is performed on one of the perpendicular end surfaces of each of the tested specimens as shown in Figure 3-16 to avoid indentation to the remaining critical surfaces.

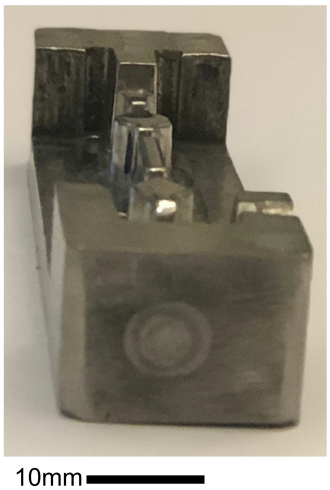

Figure 3-16: Indentation mark of the micro-hardness test.

For the first stage of assessment, the micro-hardness test was performed on the CNC-machined and one set of the SLM tool inserts. The average recorded value of the core and cavity of the CNC-machined tool inserts is 270 HV. Whereas, the SLM-fabricated core recorded an average hardness value of 241 HV, whilst the cavity's value is 238 HV.

For the second stage of assessment, the micro-hardness test was performed twice for the four SLM fabricated tool inserts. First, micro-hardness tests were performed individually for the four tool inserts after SLM-fabrication and before the tool inserts were mounted for injection moulding. Secondly, micro-hardness tests of the four tool inserts were conducted after the injection moulding process was completed (results will be presented in this chapter).

For each specimen, two measurement values were recorded to monitor variation in hardness values before and after injection moulding. The values recorded are the resultant average of three readings from the same region. Figure 3-17 illustrates the changes observed in the hardness values according to the stage in which the test was performed. The core and cavity halves of tool insert 1 have comparable values of 242 HV when tested prior to injection moulding. After 10,000 injections, tool insert 1 was dismounted and further micro-hardness tests were undertaken. For the core half, the hardness value had increased to 259 HV and the cavity half increased to 264 HV. For the second tool insert the same test procedure was conducted, the core and cavity had hardness readings of 243.3 HV and 237.6 HV respectively. After 20,000 injections, the second tool insert was dismounted, and hardness tests were performed. The core hardness value increased to 263.3 HV, while the cavity increased to 259.6 HV. The core and cavity hardness readings before commencing injections for the third tool insert were 237.6 HV and 240 HV respectively. At 30,000 injections, the third tool insert is dismounted, the core hardness reading increased to 263.6 HV and for the cavity the hardness value increased to 258.3 HV. The fourth tool insert recorded hardness values of 241 HV and 238 HV for the core and cavity respectively before injections. After 40,000 injections, the hardness value for the core insert increased to 238.3 HV and 248.3 HV for the cavity.

The values for each core and cavity are given in Figure 3-17. It is noted that there is a minor increase to the hardness value from the initial material before injection moulding is commenced. This increase in hardness could be explained due to changes of the temperature to which the tool inserts are exposed during the injection moulding process which has a strong influence on the phase composition, the microstructure and the mechanical performance of 316L stainless steel (Gubicza *et al.*, 2016).

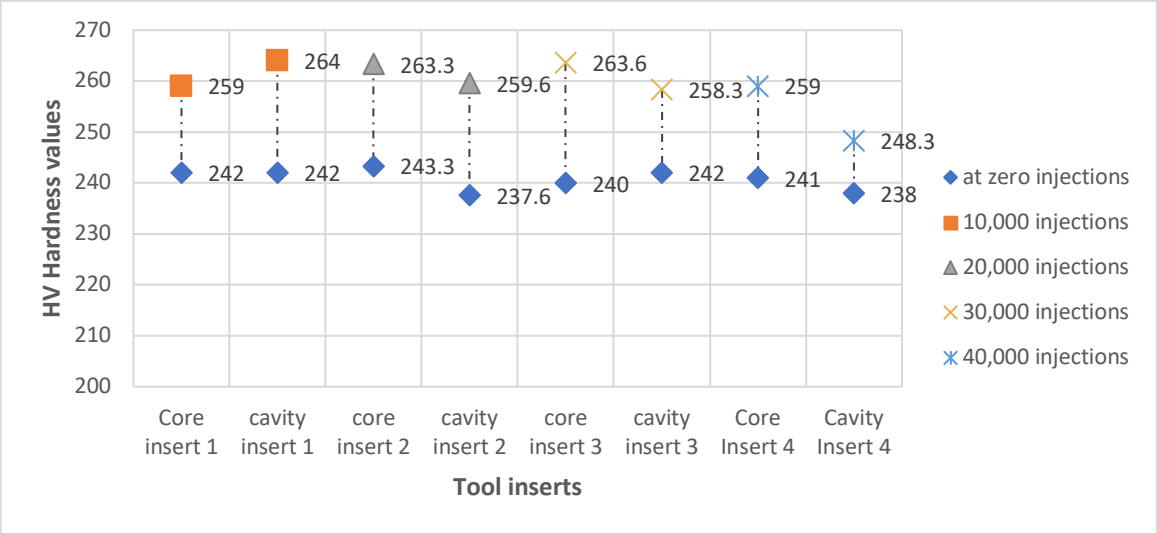

Figure 3-17: Changes in micro-hardness of the SLM specimens depicts variation prior to and after injection moulding using each tool insert.

3.3.5 SLM fatigue test

Laser melting technologies are prone to porosity inclusion due to over-melting or under-melting which could lead to cracking and low fatigue resistance (Zhang *et al.*, 2017). In this research, the main focus is injection moulding that subjects a tool insert to multiple thousands of cyclic loads. The inclusion of pores creates local stress concentrations that can trigger crack formation. As highlighted in previous studies, surface roughness and porosity are causes for premature fatigue failure for powder-bed fusion parts (Zhang *et al.*, 2017). Edwards and Ramulu (2014) reviewed that pores act as a foundation to crack initiation caused by stress concentration. Siddique *et al* (2015) and Zhang *et al* (2017) reviewed previous research that recounted high density of 99.5 % for SLM fabricated parts still contained pores that were found critical in fatigue performance and caused crack formation.

The purpose of conducting a fatigue test in this research was aimed to provide correlations between the mechanical properties of SLM-fabricated stainless steel 316 L specimens with injection moulding processing. Concluded from the previous experimental evaluation, the different microstructure tests performed on the SLM fabricated tool inserts showed the inclusion of pores along the melted layers. Therefore, it was imperative to test the fatigue performance of the SLM specimens that can promote a significant effect on the tool inserts durability.

The experiment was set up to test 25 SLM stainless steel 316 L fabricated specimens at different constant-stationary loads which create a constant bending moment that would cause the specimen to fail. Figure 3-18 is a 2D illustration of one of the typical standard fatigue specimen geometries as derived from Fatigue Dynamics (1993) and demonstrated in Appendix C.

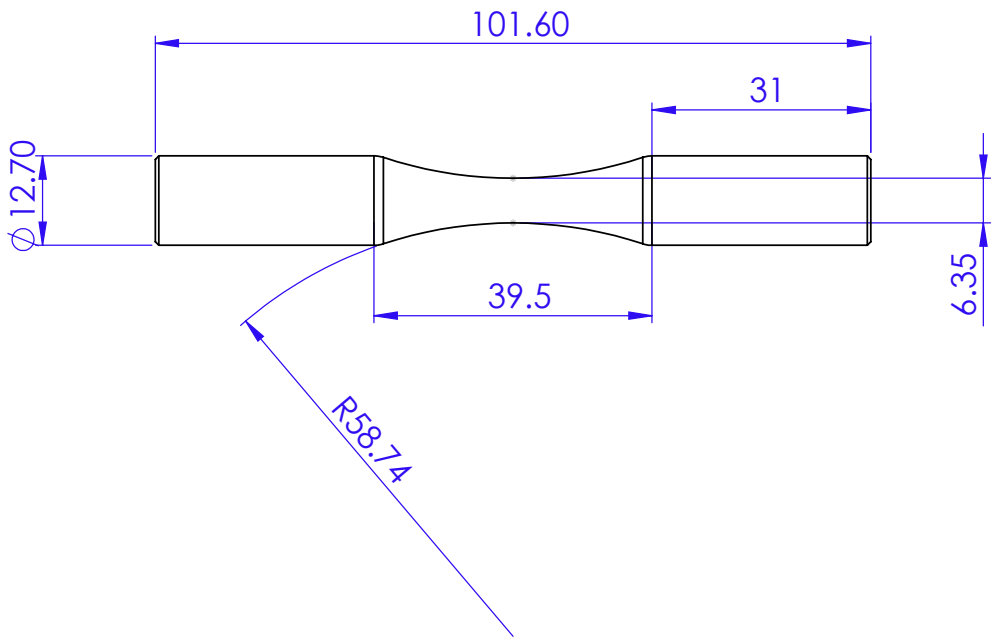

Figure 3-18: 2D illustration of fatigue specimen (mm).

Stainless steel 316 L powder was supplied by LPW Technology Ltd (Runcorn, UK), with particle size nominally in the range 45-150 μm and used for the production of 25 test specimens for fatigue testing. The specimens were built on a ReaLizer SLM 250 in a vertical orientation perpendicular to the powder bed. The specimens were fabricated and tested without any surface treatment, except for typical sand blasting as a surface treatment to surface roughness. Figure 3-19 shows an example of the twenty-five SLM stainless steel 316 L fabricated specimens.

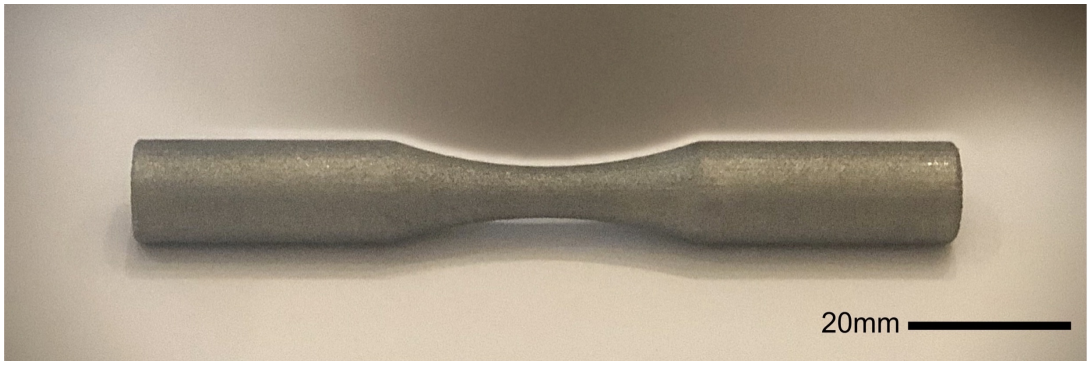

Figure 3-19: Sample SLM stainless steel 316 L fabricated fatigue specimen prior to testing.

The rotational fatigue test was performed using a Rotating Beam Fatigue testing machine model RBF-200, the motor is ½ HP and 115 volts. The test setup was run five times at different moment force of 50, 40, 30, 20, and 10 in. lb. for each run five specimens were cycled to achieve the maximum number of cycles until failure under a given load and a constant speed of 5,000 rpm. First, to calculate cyclic stress the moment of inertia (I) has to be determined as shown in Equation 1. The cyclic stress is calculated using the equation as shown in Equation 2.

Equation 1: Moment of Inertia

$$\left(\frac{\pi}{64}\right) * D^4$$

Equation 2: Cyclic Stress

$$\sigma = \frac{MY}{I}$$

Where, D= Diameter of specimen at minimum cross section (in.)

σ = Cyclic stress (Psi)

M = Moment force (lb in.)

I = Moment of inertia

Cyclic stress is calculated, the output from the machine is in imperial units and the values are converted to SI units of MPa. Table 3-6 represents the cycles to failure of each specimen at different cyclic stress values, and the average number of cycles until failure.

Table 3-6: Represents cycles to failure of the applied loads for each specimen.

Cyclic stress (σ)	Specimen #	Cycles to failure (N)	Average
225	1	98,600	103,820
	2	109,800	
	3	124,100	
	4	81,400	
	5	105,200	
180	6	271,500	2,984,00
	7	288,400	
	8	354,900	
	9	297,500	
	10	279,700	
135	11	1,296,400	1,169,140
	12	1,224,000	
	13	1,016,800	
	14	1,279,200	
	15	1,029,300	
90	16	1,954,700	2,049,680
	17	2,027,100	
	18	1,893,800	
	19	2,113,200	
	20	2,259,600	
45	21	3,317,900	3,418,000
	22	3,560,400	
	23	3,642,100	
	24	2,747,200	
	25	3,822,400	

It is evident that as the loads decrease, the number of cycles to failure increase, until a cyclic stress (σ) of 45 is tested and produced no failure at an average number of cycles of 3,418,000. Therefore, the test had to be terminated proving no necessity to continue testing the specimens. As a result, when correlating the results from the fatigue test of the SLM-fabricated specimens with the actual injection moulding process of tool inserts it is safe to conclude that SLM-fabricated tool inserts are capable of withstanding

multiple million injections with no failure. Figure 3-20 is a sample of one of the failed specimens.

Figure 3-20: Sample fatigue specimen after failure.

The test data are processed to calculate the Stress (S) against the number of cycles (N). The specimens were run until failure occurs and the results are plotted as a material's S-N curve as shown in Figure 3-21.

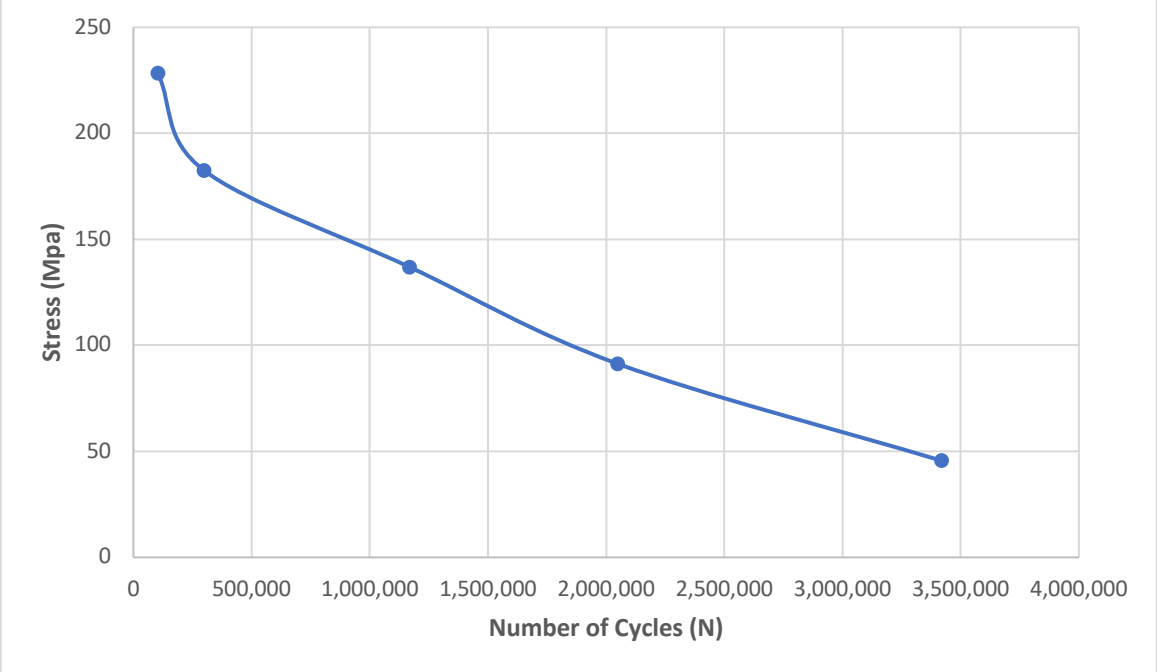

Figure 3-21: S-N curve of SLM stainless steel 316 L fabricated specimens.

3.3.6 Dimensional measurements

Additional dimensional analysis is essential to identify deviation in measurements from the nominal values and tolerances after the tool inserts are SLM-fabricated and CNC-machined. Specific dimensional measurements were accounted for as highlighted in Figure 3-15. Furthermore, Table 3-7 and Table 3-8 illustrate the specified measured values of both the core and cavity in relation to the geometric CAD measurements. A 1.5% shrinkage allowance is deliberately considered for polypropylene injection. The CNC machined tool insert shows no noticeable deviation in dimensional values, whereas the SLM tool inserts show slight dimensional errors.

Table 3-7 Dimensional measurements for core tool insert.

Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)
A	15	14.9	-0.1	**I**	26	26	0
B	12	12.05	0.05	**J**	16	15.8	-0.2
C	10	10.05	0.05	**K**	2	2.03	0.03
D (DEG)	92°	91° 47’	-13’	**L**	4	4.01	-0.01
E (DEG)	88°	88° 13’	13’	**M**	12.7	12.71	0.01
F	6	6	0	**N**	9.5	9.4	-0.1
G	90	90.1	0.1	**O**	5	4.9	-0.10
H	5	5.15	0.15				

Table 3-8 Dimensional measurements for cavity tool insert.

Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)
A	19.05	19	-0.05	**G**	10	10	0
B	10	10.05	0.05	**H**	90	90	0
C (DEG)	92°	92° 18’	18	**I**	56	55.96	-0.04
D	55.4	55.45	0.05	**J**	8.7	8.8	0.1
E	6	6.06	0.06	**K**	2	2.06	0.06
F	20	19.95	-0.05				

As for the second stage of assessment of the SLM tool inserts, further analysis is necessary to determine deviation in measurements from the nominal values after the tool inserts are fabricated, to detect the existence of wear. Polypropylene was the material used for the injected products, so a 1.5% shrinkage allowance for injection moulding is

compensated for during the design stage. Specific dimensional measurements were accounted for in each core and cavity of the four SLM tool inserts. A Zeiss Abbe Horizontal Metroscope and a Zeiss Universal Measuring Machine were used for measuring the dimensional accuracy of the specimens. The appointed tolerances were set according to the company's standards for tool manufacturing. The dimensions for each core and cavity are illustrated in Figure 3-3 and Figure 3-4 for the four SLM-fabricated tool inserts. Dimensional accuracy of all the tool inserts was examined for each of the 15 core dimensions and the 12 cavity dimensions specified. Each is the resultant average of three measurements for the same dimension. All 15 core and 12 cavity dimensions were investigated for each tool insert, but four internal and external dimensions for each tool insert are displayed in this chapter as a representation of the rest of the dimensions and their outcomes. The four dimensions selected for this study are dimensions I and N shown in Figure 3-3 (core), and dimensions E and G shown in Figure 3-4 (cavity). Table 3-9 is an illustration of the dimensions used for measurement assessment of the tool inserts.

Table 3-9 Dimensions used for measurement assessment of tool inserts.

Dimension	**Location**	**Type**
I	Core	External
N	Core	Internal
E	Cavity	External
G	Cavity	Internal

Dimension I of the core inserts is an external dimension and has a nominal value of 26 mm and a design tolerance of ± 0.2 mm. Measurements were recorded for the four tool inserts after the SLM process and before injection moulding was initiated. Measurements taken before injection for Core halves 1, 2, 3 and 4 are the range of permissible design tolerance. It is noted that changes in dimensional accuracy are interpreted as progressive wear due to the many thousands of components produced through the injection moulding process. All four cores were subjected to wear in addition to deviation from the maximum permissible tolerance.

Dimension N of the core inserts is an internal dimension with a nominal value of 6 mm, with a permissible design tolerance of ± 0.2 mm. Measurements recorded before injection moulding for Cores 1, 2, 3 and 4 are within the acceptable range of tolerance.

Measurements recorded after injection moulding are for cores 1, 2 and 3, and 4 lie out of the upper limit of the accepted tolerance.

For the tool cavities, dimension E is external with a nominal value of 6 mm and ± 0.3 mm design tolerance. the measurements recorded before injection moulding indicating that the four cavities remain inside the acceptable range of values,. However, recorded values of the measurements taken after the injection moulding indicates that the cavities have experienced wear.

Dimension G is an internal dimension of the tool insert cavities. The nominal value is set at 10 mm with a ± 0.2 mm design tolerance. Measurements documented for the four cavities show that the values are within the acceptable tolerance range. the recorded values of the cavities after injection moulding demonstrate that wear appears for cavities 2 and 4. Cavities 1 and 3 lay within the accepted range of measurements. After analysing the recorded data for measurements taken before and after injection moulding for the four SLM tool inserts, it was noted as illustrated in Figure 3-22 that wear does increase as the number of injections increase, but not necessarily in a consistent ratio to the number of injections. However, changes in dimensional accuracy are sufficient to confirm that the tool inserts are susceptible to wear due to the progressive and continued loads exerted on the tool inserts by the injection moulding process. Table 3-10 illustrates the recorded measurements of dimensions I, N, E, and G before and after the injection moulding process and the deviation from the upper and lower permissible tolerances of each dimension.

Table 3-10: Dimensional measurements before and after injection process and deviation from permissible tolerances (mm).

	Dimension I			Dimension N		
Tool Number	Measurements before injection (mm)	Measurements after injection (mm)	Deviation from permissible tolerance (mm)	Measurements before injection (mm)	Measurements after injection (mm)	Deviation from permissible tolerance (mm)
Tool insert 1 10,000 parts	25.8	25.72	-0.08	9.48	9.81	0.11
Tool insert 2 20,000 parts	25.8	25.47	-0.33	9.50	9.92	0.22
Tool insert 3 30,000 parts	25.9	25.64	-0.16	9.55	9.77	0.07
Tool insert 4 40,000 parts	25.8	25.70	-0.10	9.70	9.81	0.11
	Dimension E			**Dimension G**		
Tool Number	Measurements before injection (mm)	Measurements after injection (mm)	Deviation from permissible tolerance (mm)	Measurements before injection (mm)	Measurements after injection (mm)	Deviation from permissible tolerance (mm)
Tool insert 1 10,000 parts	5.80	5.46	-0.24	10.0	10.05	0.05
Tool insert 2 20,000 parts	5.84	5.63	-0.07	10.0	10.4	0.4
Tool insert 3 30,000 parts	5.67	5,47	-0.23	10.04	10.2	0.16
Tool insert 4 40,000 parts	5.67	5.48	-0.22	10.04	10.34	0.3

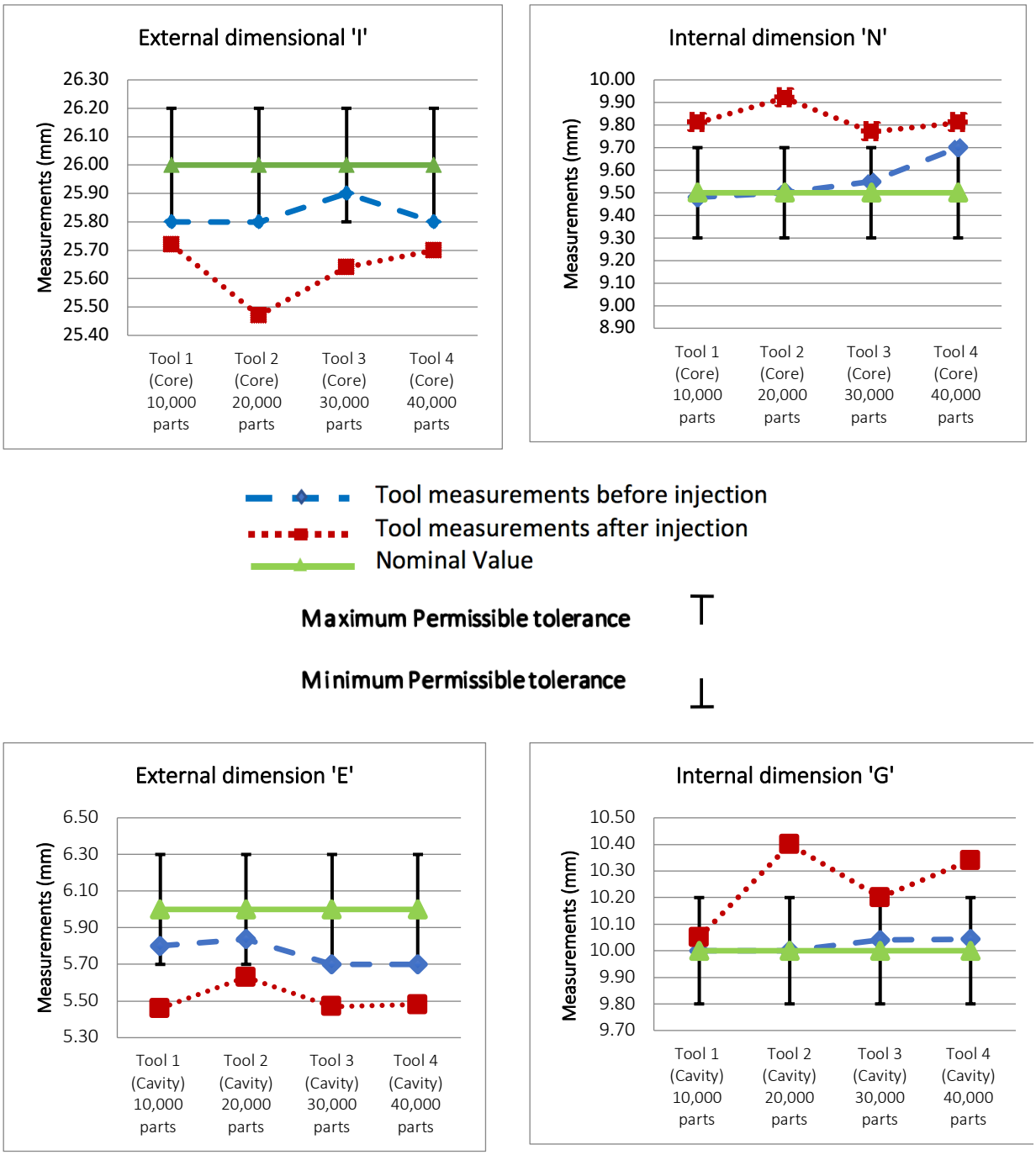

Figure 3-22: Dimensional measurements of core and cavity of the tool inserts with upper and lower tolerances.

3.4 Summary

The design approach adopted in the adjustable clip tool inserts were similar when designing the inserts for subtractive manufacturing and SLM-fabrication. The same CAD model design was generated for both methods of manufacturing, the core and cavity inserts were designed as a whole part design with the permissible design tolerances

accepted for both technologies of manufacturing. No obvious limitations or restrictions were encountered during the design stage.

The results obtained from the first stage of assessment in this chapter is published by (El Kashouty *et al* (2015) and presented in Appendix A verified the success of SLM manufacturing technology as compared to CNC machining for the production of a tool insert of a headlight's adjuster clips. No significant difference was remarked upon while comparing the CNC machined and SLM fabricated tool inserts. Further results led to the following conclusions. The SLM tool insert is productive and achieves significant benefits in terms of product functionality and dimensional accuracy. During the spectral analysis test, chemical composition of both tool inserts was within an acceptable range as compared to the standard composition of Stainless Steel 316L. Micro-hardness of the CNC machined inserts recorded a slightly higher value when compared to the SLM inserts.

It is noted that when analysing the microstructure of the SLM tool inserts, grain size and boundaries were indefinable due to distortion caused by melting as compared to the CNC machined insert. Therefore, the specimens were further analysed using SEM to detect the distinctive differences in morphologies and compositions of the CNC and SLM specimen surfaces. The layer thickness was measured to be within the range of the machine pre-set working conditions. It was determined that the CNC specimen includes a relatively large number of gas pores that resulted from the initial casting process of the Stainless Steel 316L. The SLM specimen displayed a rather notable phenomenon where intermetallic carbide formation is present along the sintered border of the layers. This segregation of intermetallic particles is expected to increase wear resistance, but it may also influence the strength of the material and increase brittleness. As for the surface roughness, SLM inserts lag behind the CNC-machined inserts since the SLM does need post-processing operations as opposed to the CNC inserts. Finally, the resulting dimensional measurements of the SLM product showed minimal differences in comparison to the CNC product proving product reliability.

As for the second stage of assessment published by El Kashouty *et al* (2019), experimental work conducted on the four stainless steel 316L tool inserts fabricated using SLM lead to the following conclusions and presented in Appendix B. The four SLM tool inserts were fabricated in the confines of the same build chamber with the same working

conditions. The inserts produced proved to be comparably alike with no distinctive variation.

Microstructure analysis using an SEM microscope confirmed the inclusion of high content of carbides. Evidence of intermetallic carbide formation detected concentration of carbides in some regions more than others, specifically along the edge of each individual layer. The existence of carbides caused by the laser melting process resulted in reinforcing some mechanical properties of the specimens produced such as hardness and wear resistance. EDS analysis was used to present the type of intermetallic particle with the highest concentration level. The elements with the highest concentration were Chromium, Nickel, and Molybdenum respectively.

Surface roughness was measured at two stages, before and after the injection moulding process to investigate the effect of injection moulding on the surface texture of the tool inserts. It is concluded that an increase in surface roughness occurred to most values of the measured surfaces of each tool insert after the completion of injection moulding. Micro-hardness tests were performed for each of the four specimens at two stages, before injection moulding commences and after completing production runs of each tool insert. It was established that a minor increase to hardness values occurred after injection moulding of each production run. As for dimensional accuracy examination, four dimensions were considered in this study before and after the injection moulding process.

The fatigue test conducted in this chapter aimed to provide correlations between the mechanical properties of SLM-fabricated stainless steel 316 L specimens with injection moulding processing. Testing fatigue performance of the SLM specimens is essential to demonstrate the effect on the tool inserts durability. It is concluded from the test results that as the cyclic stress decreases, the number of cycles to failure increase, until a threshold was reached where no failure occurs for the test specimens.

The tool inserts were fabricated within the accepted design tolerances with awareness that the SLM fabricated inserts require further post-processing to improve the surface finish after fabrication. For each core and cavity, an internal and external dimension were analysed, dimension I and N for the core inserts and dimension E and G for the cavity inserts for the four SLM-fabricated tool inserts.

4 High-Volume Injection Moulding of 150,000 Parts for Stainless Steel 316 L SLM Fabricated Tool Inserts

In Chapter 3, the tool inserts have been successfully fabricated and manufactured using SLM and CNC machining methods. Assessments were carried out to investigate the tool inserts performance characteristics. This chapter concludes the second phase of product functionality assessments of the examination stage of the manufacturing framework. The four SLM tool insert sets were evaluated for wear and dimensional accuracy through injection moulding of 150,000 functional products.

4.1 Pilot Injection Moulding Test

For the pilot injection moulding test, the SLM and CNC-machined tool inserts were both mounted on the same bolster. Therefore, both sets of inserts would be subjected to the same operational parameters and conditions, ensuring direct comparability of the results. The average cycle time was approximately 30 seconds. The net weight for the SLM-derived product was 4.20 g, whilst the CNC-derived product was 4.24 g. 500 mouldings were batched into two packages, one for the SLM product and the other for the CNC-machined product. Ten samples from each package were selected for measurement at 10 different points. These measurements with their corresponding nominal values are given in Figure 4-1. More importantly, it should be highlighted that the resulting dimensional measurements (as shown in Table 4-1) of the SLM product have minimal error in comparison with the CNC product. Despite this fact, the SLM tool insert measurements have shown deviations from the nominal values. This deviation in results can be interpreted to be caused by the shrinkage allowance of the Polypropylene injected parts.

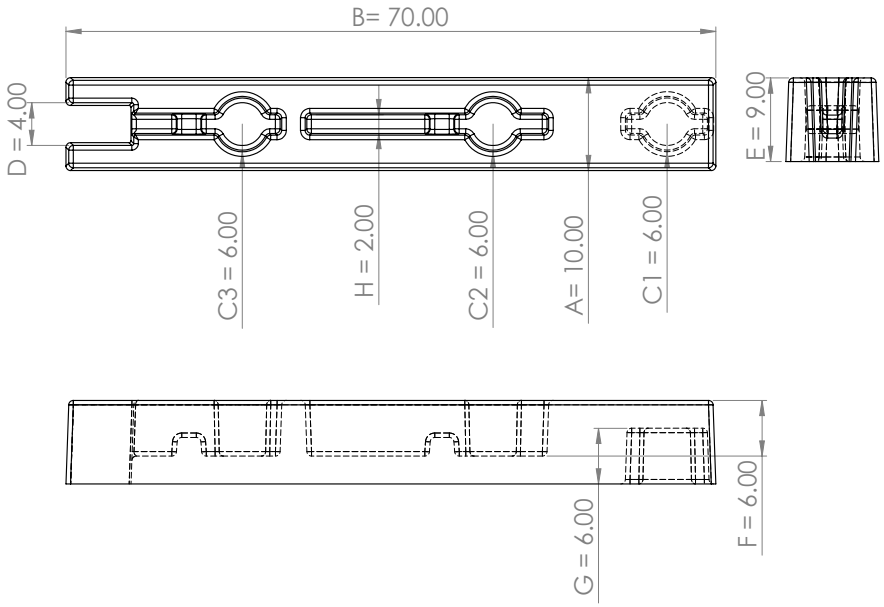

Figure 4-1 Adjuster clip measurements in mm.

Table 4-1 Dimensional measurements for CNC and SLM products

Dimensions	Nominal values (mm)	Average CNC product measurement (mm)	Standard deviation (mm)	Average SLM product measurement (mm)
A	10.00	9.75	0.04	9.75
B	70.00	69.03	0.05	69.64
C1 (Φ)	6.00	5.78	0.04	5.80
C2 (Φ)	6.00	5.67	0.05	5.20
C3 (Φ)	6.00	5.66	0.05	5.50
D	4.00	4.00	0.00	4.00
E	9.00	8.77	0.05	8.80
F	6.00	6.20	0.01	5.90
G	6.00	6.00	0.02	5.75
H	2.00	2.02	0.04	1.95

4.2 Injection Moulding of 40,000 Parts

Injection moulding was performed on a Nurnak MMRJ 130-225 Injection moulding machine with clamping force of 100 ton at Al Fouad Co. for Automotive Spare Parts (Alexandria, Egypt). Polypropylene was chosen as the material for injection moulding with a feed stock rate of 25 grams/stroke, injection pressure 75 bar and the temperature is maintained constant at 220°C. During the injection moulding process, the tool inserts

temperature was constantly monitored using an infrared heat detector and maintained at room temperature to avoid overheating of the tool inserts. Moreover, the melt temperature was controlled to ensure consistency and uniformity of the process parameters.

The four sets of tool inserts were fitted into the same bolster with the same working conditions to ensure parametric consistency. The steel mould base plates were machined with rectangular pockets to fit the tool inserts. Figure 4-2 Illustrates the inserts after they were mounted on the bolster. The average calculated cycle time is perceived to be approximately 34 seconds. 19 g is the total weight of the product tree with four attached products. The net weight of the individual part is 4 g.

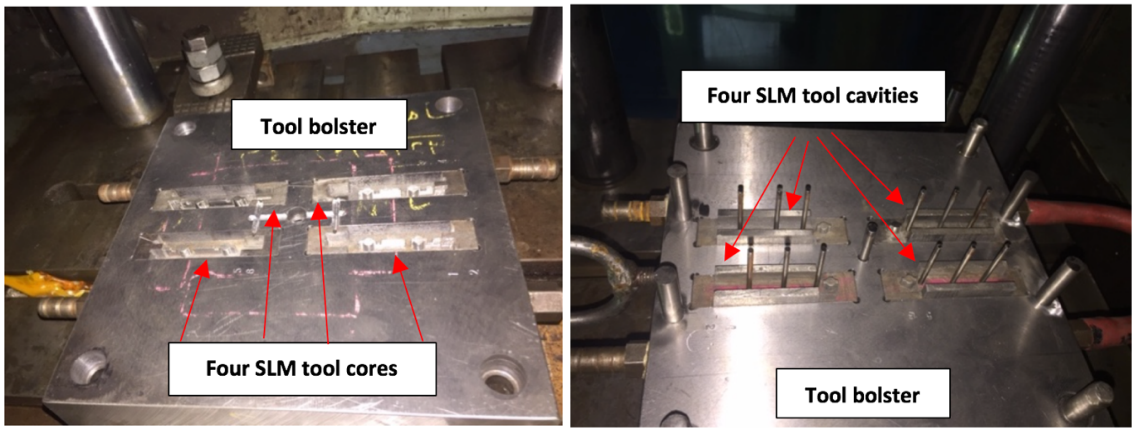

Figure 4-2: Four sets of tool inserts mounted on the bolster.

The injected products were grouped into smaller batches of 500 pieces for each run. A run is the number of injections that a set of tool inserts must undergo in one continuous session. For tool insert 1, the tool insert is run for 10,000 injections then it is stopped, and the tool insert is dismounted for inspection and quality checks. The same procedure is carried out for each set of tool inserts until 40,000 injections are completed. Four runs are carried out for run 1 (10,000 injections), run 2 (20,000 injections), run 3 (30,000 injections) and run 4(40,000 injections). When injection is initiated, polypropylene is rapidly pushed into the cavity and as a result a sudden pressure increase is exerted on the tool inserts, this pressure increase is the highest pressure reached during the injection process. Therefore, after successive thousands of injections the applied force on the core features may cause fracture, cracks, or wear that eventually change dimensional accuracy

of the produced parts. Therefore, a number of products were selected to analyse possible variation in dimensional measurements as injection moulding progresses.

4.3 Sampling

It is certain that product measurements are required to prove accuracy of the tool inserts, and therefore functionality of the products. However, measuring the whole population is not realistic therefore a sample size is necessary to represent the targeted population. The sample sizes are determined based on a sampling equation as shown in Equation 3 (Montgomery and Runger, 2003):

Equation 3: Sample Size

$$n = \left[\frac{Z_{\alpha/2}}{E}\right]^2$$

Where, n = sample size E = maximum permissible error depending on population

Z = standard normal score from normal curve table based on degree of confidence interval

Confidence interval = 90% $\alpha = 0.1$

Henceforth, the sampling equation is used to determine the optimum sample size for each of the four runs. The maximum permissible error varies from each run depending on the increase in product population. For runs 1 to 4, the maximum permissible error was set at 0.2, 0.15, 0.1 and 0.1 respectively. Therefore, the number of samples to be selected from run 1 is 42 samples, 80 samples for run 2, 120 samples for run 3 and 166 samples for run 4. Each run is divided into smaller batches of 500 and labelled consecutively from 1-500, 501-1000 and henceforth. For each batch, two samples are randomly selected for measuring and the average value is taken for those two values. A total of 10 dimensional measurements are measured for each selected sample and values are recorded against the nominal values. Figure 4-3 is an illustration of the part with the dimensional features identified for measuring. Two dimensions of the part produced are selected for discussion, the selected dimensions and their outcomes are representation to the rest of the unstated dimensions.

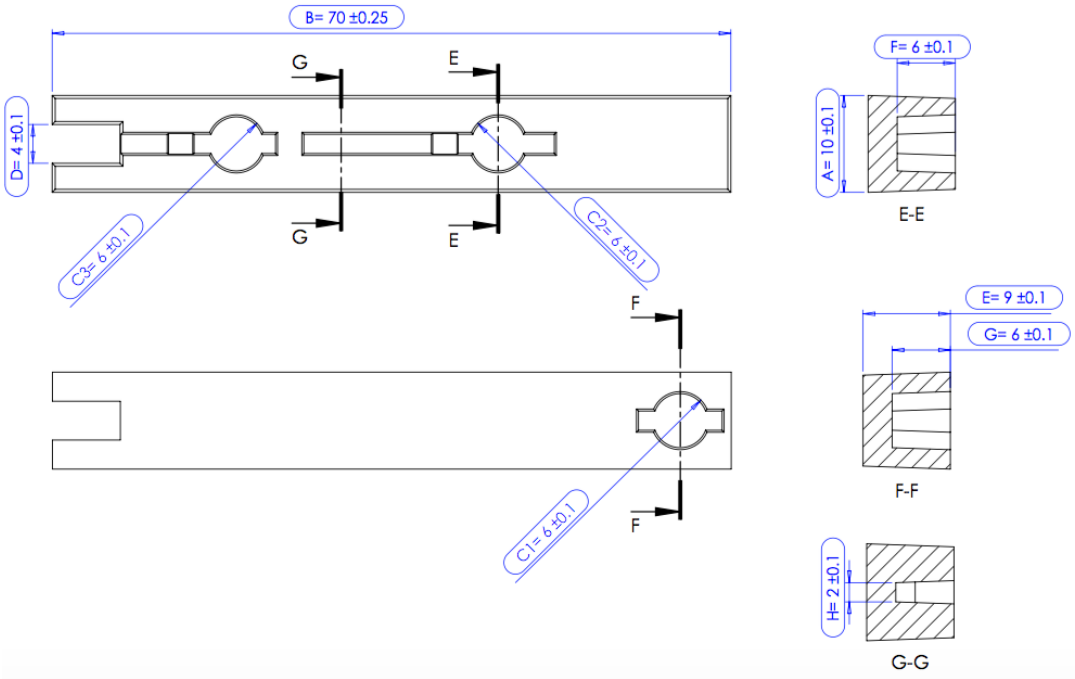

Figure 4-3: Injected part illustration with dimensional measurements and tolerances.

Figure 4-4 demonstrates deviation for dimension D over time. Production runs are categorised into four runs depicting batching of 10, 20, 30 and 40 thousand parts per run. For each run, a number of samples were randomly selected for functional inspection and dimensional accuracy. From each batch of 500 parts 2 parts are randomly selected and their average measurements is recorded for the batch. For run 1, there are 21 batches, 40 for run 2, 60 for run 3, and 83 for run 4. The average measured values for runs 1 and 4 are 21 samples from the former and 83 samples from the latter. Values were defined to be within the range of acceptance ensuring functional approval of the end product. Measured values are spread along the nominal value range. Values for run 1 and 4 have a direct linear regression trending towards the nominal value limit. As for run 3, most measured values are within the acceptable tolerance range of ± 0.1 mm and spreading along the nominal value line. However, some values are dispersed outside the limit zone resulting in an inverse linear regression diverting away from the nominal values. Therefore, a positive linear regression of values depicts the development of wear on the specified tool inserts as a function of the number of progressive injections. Measured values of run 2 differ from the rest of the runs with the most dispersed data at the beginning of injection moulding and gradually drift towards the acceptable range within the limits of the nominal values.

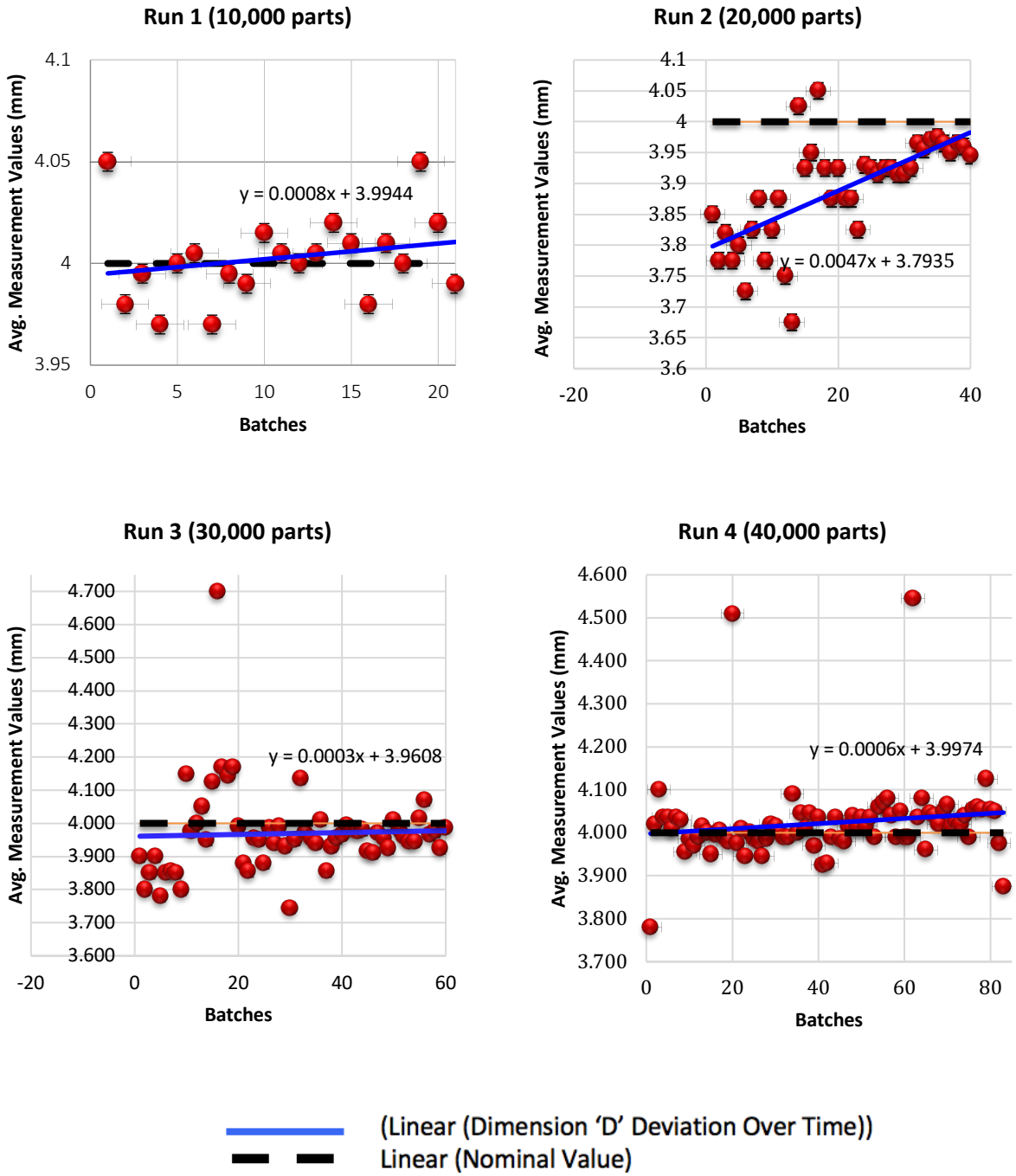

Figure 4-4: Sample measurements for dimension 'D' deviation over time for run 1, run 2, run 3, and run 4.

Measurement values for Dimension H are illustrated in Figure 4-5 for runs 1, 2, 3, and 4 respectively. ± 0.1 mm design tolerance is set to ensure acceptability of the part as an end product. The majority of measurements taken for the randomly selected samples are within the tolerable range with very few samples scattered off the range.

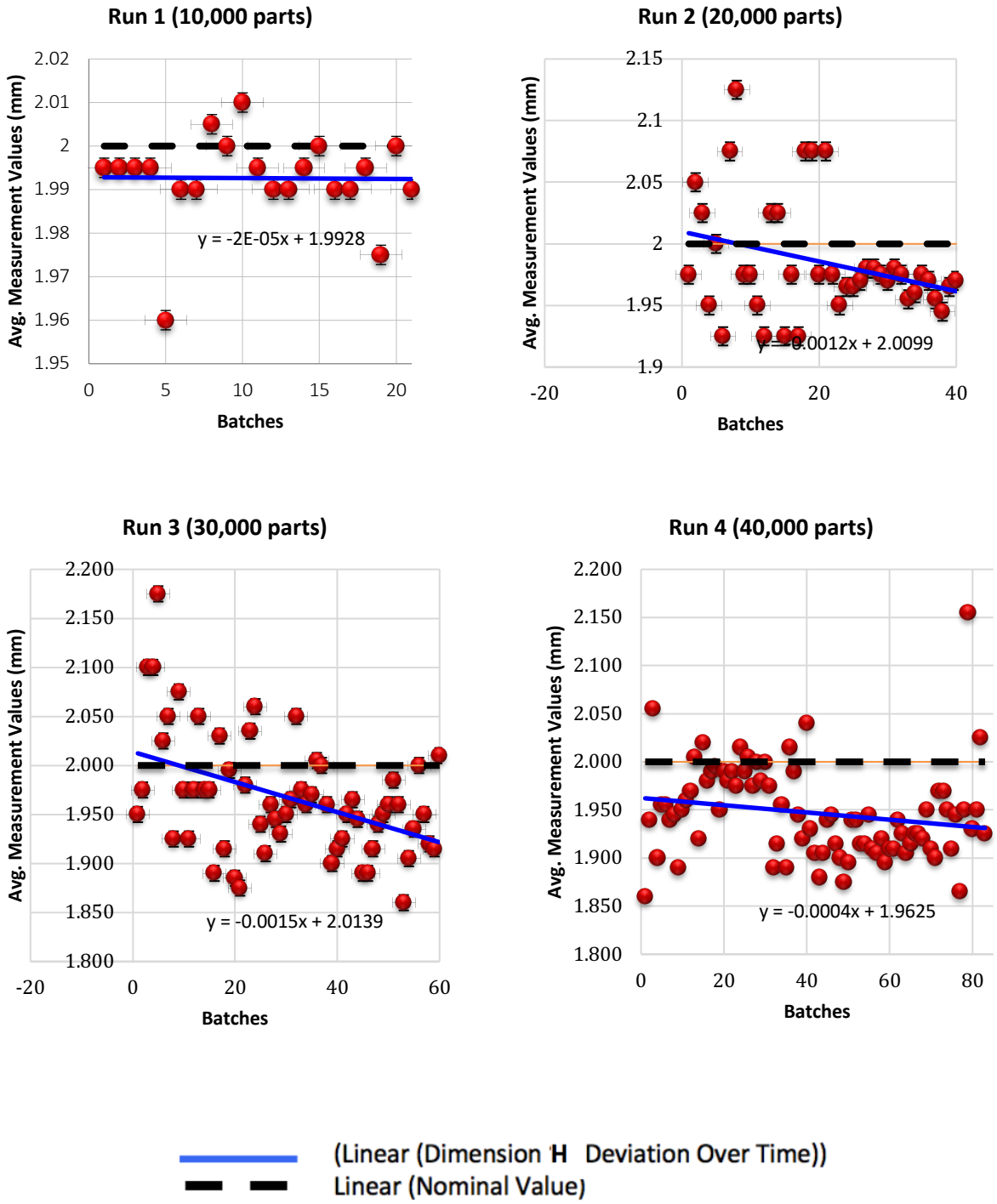

Figure 4-5: Sample measurements for dimension 'H' deviation over time for run 1, run 2, run3, and run 4.

Moreover, the formation of data represents a negative linear regression that emphasises potential progression of wear as the number of samples increase, hence increase in injections.

4.4 Injection Moulding of 150,000 Parts

Previous research was reviewed by Nagahanumaiah and Ravi (2009) and it was clearly stated that there has been no published work on the quality and effect of injection moulding on DMLS fabricated tools. Hence, the work of Nagahanumaiah and Ravi (2009) was capable of producing 5000 parts. The work of Dolinšek (2005) indicated the recommendations made by EOS that metallic moulds are capable of withstanding 100,000 injections but with no practical proof to tool life and wear resistance. The purpose behind the high-volume production study was to ensure that no damage will occur to the tool inserts after successive thousands of injections.

40,000 injections were the limit reached for the fourth tool insert and no signs of fracture, cracks, or wear were noticeable. Therefore, a new goal was set to further guarantee that the fourth tool insert could withstand more injections runs. The goal was to reach 150,000 injections in total with no apparent failure to either the tool insert or the produced components. 40,000 components were already produced from the fourth tool insert during the high production study; therefore 110,000 additional components are to be produced for the purpose of this study. Each run is set to produce 10,000 components, each batch is divided into smaller batches of 1,000 components and labelled consecutively from 1-1000, 1001-2000 and henceforth. Figure 4-6 is an illustration of the batching process of the injected parts.

Figure 4-6: Sample batch production of 1000 components of injected parts.

The same sampling equation is used to determine the optimum sample size for the production runs. The maximum permissible error was set at 0.1. Therefore, the number of samples to be selected for each run were 170 samples. For each batch of 1,000 components, 17 samples are randomly selected for visual inspection and fitting. Figure 4-7 displays one sample from each of the eleven runs after injection of 10,000 from each run. From each run, 170 samples are selected for inspection, the parts are inspected and compared together to identify if there are significant defects. After the inspection process, the parts are fitted to a headlamp housing to ensure product functionality. Shown in Figure 4-7 is a sample illustration of the fitting process. As a result, the parts are deemed acceptable in terms of visual inspection and product functionality. Moreover, the samples appear to be in an acceptable shape showing no signs of flash, cracks, or imperfection. Therefore, the tool insert proved to be in faultless form and it is expected to continue production of multiple hundreds of thousands before failure occurs.

Figure 4-7: Sample demonstration of visual inspection and component fitting to headlight housing.

4.5 Summary

It can be concluded from the pilot injection moulding test that the resulting dimensional measurements of the SLM product showed minimal differences between the CNC and SLM produced parts proving product reliability of the SLM product.

The four tool inserts were run for 10,000, 20,000, 30,000, and 40,000 injections respectively. Applied forces caused by multiple thousands of injections were expected to cause faults to the tool inserts which is subsequently expected to affect the products dimensional accuracy. Sample products were selected for each run to analyse possible variations in dimensional measurements as the injection moulding process progressed. Two dimensions were selected for consideration, dimension D and H of the parts produced. For dimension D, most of the recorded values were within the accepted tolerance range. Recorded values of the batches demonstrate a direct linear regression trending towards the nominal value, verifying the progression of wear. As for dimension H, the recorded measurements of the four runs were within the accepted range of tolerance. Data represented depicts the progression of wear in a direct relation with the batch size. Finally, it is concluded that even though wear clearly progresses as the number of injections increase, the end-products are functionally and dimensionally acceptable.

After the tool inserts proved to be successful in producing tens of thousands of functional products, more production runs were initiated to guarantee longevity of the tool inserts. In this study, the fourth tool insert that produced 40,000 products continued production until 150,000 parts were produced. The number of samples selected for inspection for each of the eleven runs was 170 samples. Parts were visually inspected and functionally approved through fitting the parts in the headlight's housing to ensure product validity. The parts proved to be functional and visually acceptable showing no signs of defects.

There is a direct proportional relationship between wear and the number of injections. However, steadiness in the wear rate was noted amid large production runs. Wear is acknowledged as a result of the progression of the injection moulding process. However, steadiness in the wear rate was noted amid large production runs. Alterations

to dimensional accuracy verifies that the tool inserts are liable to wear due to successive loads by the injection moulding process.

5 Evaluating Product Functionality of SLM Tool Inserts

Chapters 3 and 4 highlighted the functional success with regard to technical performance and tool life of the SLM-fabricated tool inserts, through the injection moulding of 150,000 functional parts. This chapter presents the work of the second study.

The demand for injection moulding in the automotive industry is distinctively high and challenging. Companies are faced with unprecedented challenges due to increased complexity of designs and taking into account manufacturing limitations. The purpose of the study in this chapter is to evaluate product functionality of parts produced from an SLM and CNC-machined injection moulding tool inserts. Examination was implemented in the context of evaluating and analysing dimensional accuracy, surface quality, and product functionality of the respective produced part. In support of this study a vehicle's reflector was selected for investigation. This study follows the guidelines set by the manufacturing framework developed for this research. The CAD model of the reflector's tool insert is developed in the design stage. The research has been pursued through the manufacturing of two tool inserts in the fabrication stage, the first is fabricated using SLM while the other tool insert is manufactured using CNC milling. Finally, in the examination stage, tests are performed to assess the fabricated tool inserts in terms of manufacturability, surface roughness, and dimensional accuracy. Moreover, further tests were necessary to evaluate light reflectivity, surface roughness, and dimensional accuracy of the reflector produced.

5.1 Tool Insert Design

For the purpose of this study, a reflector is a component that can be part of a vehicle's light unit or is a detached unit on its own. In the case of this study, the reflector is a detached unit that is assembled separately from the main lighting unit in a vehicle. The cavity insert is a rectangular shaped design that is embedded in the main cavity plates of the bolster, shown in Figure 5-1. The range of dimensional tolerances allowed for the

cavity insert was between ±0.1 and ±0.25 mm, the minimum tolerance was attributed to the outer dimensions of the insert that will later be assembled in the main tool plates.

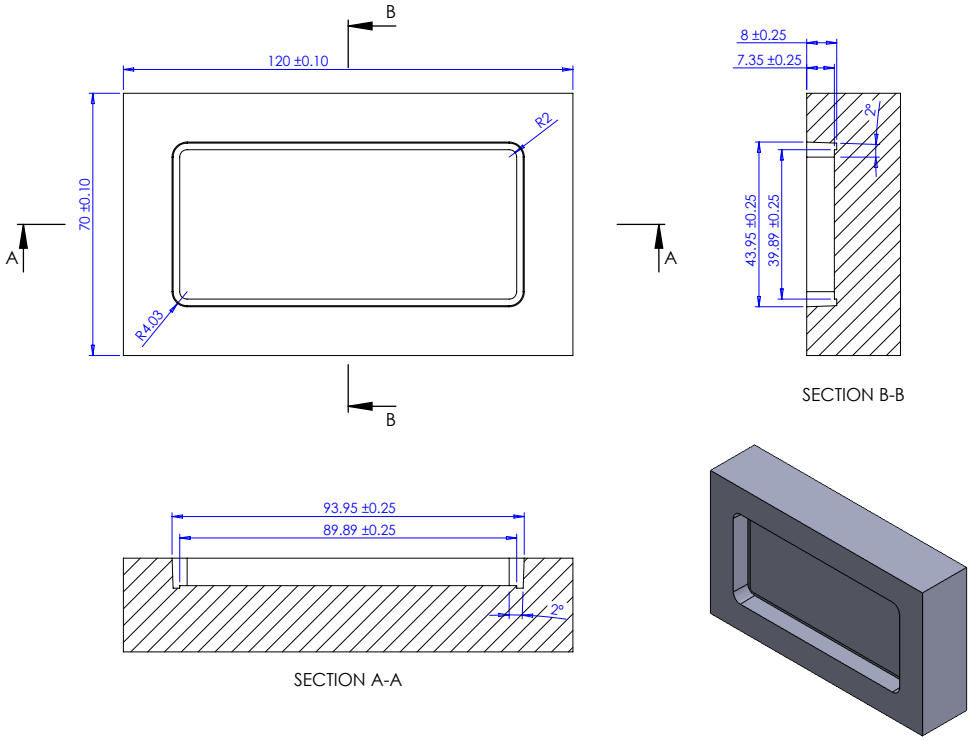

Figure 5-1: 2D illustration of the manufactured cavity insert in mm.

The part design of the core insert is of a complex nature that resides in the surface topology as a repetitive pattern design. Figure 5-2 is a 2D CAD illustration of the tool insert with the appointed nominal values and their tolerances. Tolerances vary in measure depending on how critical the measurements contribute to functionality. For this design state, the part is designed as one whole part with no constriction to the method of manufacturing adopted. Dimensional tolerances for the core insert was between ±0.1 and ±0.5 mm.

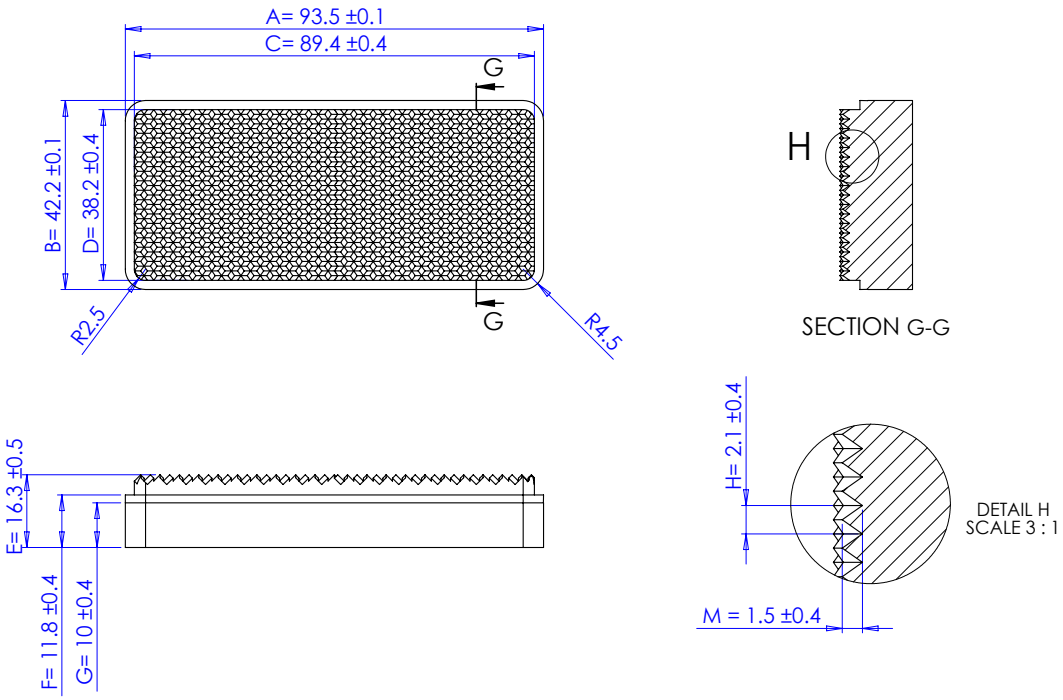

Figure 5-2: 2D illustration of the fabricated core insert Tool insert and section view G-G of surface H

5.2 Tool Insert Fabrication

For this study, the tool inserts required for producing a vehicle's reflector were investigated. Two tool inserts are fabricated using additive and subtractive manufacturing methods. The first core insert was manufactured using CNC milling, while the other core insert was fabricated using SLM. The CAD design adopted for both tool inserts was identical. Therefore, the same design was executed once on a CNC milling machine and another on an SLM machine as shown in Figure 5-2. Due to the simplicity of the design, the cavity was manufactured using CNC milling as a main component of the tool palette as shown in Figure 5-3.

Figure 5-3: CNC machined cavity of the reflector tool inserts.

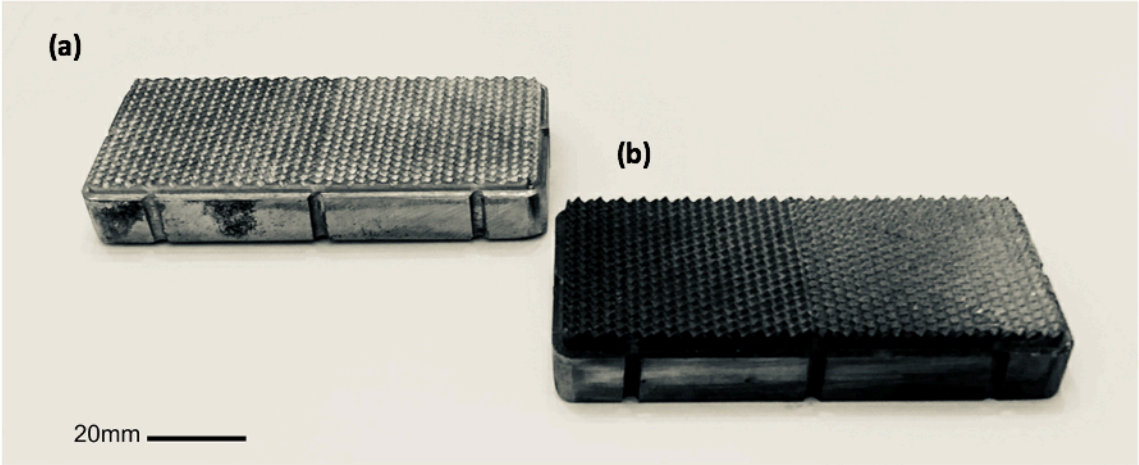

Figure 5-4: (a) CNC manufactured tool insert. (b) SLM fabricated tool insert.

5.2.1 CNC-machined tool inserts

The first core tool insert was manufactured at an Al Fouad Co. for Automotive Spare Parts located in Alexandria, Egypt. An Okuma 3-axis CNC milling machine was used to manufacture the tool insert with a spindle motor power ranges from 18.5 to 22 KW at 15,000 RPM. Three carbide tapered end mills were used for machining the pattern on the insert. The shank diameter of the end mills was 4 mm. Tip diameters of the three machine tools were 0.25, 0.5, and 1 mm respectively.

The cavity insert was manufactured at the same facility as the core insert in Alexandria, Egypt. The machine used for manufacturing the cavity was a 3-axis First V 700 machine with a Siemens control unit and a maximum spindle motor power of 5.5-7.5 KW. Three carbide end mills with shank diameters of 3, 4, and 8 mm were used at 5000-10,000 RPM range.

5.2.2 SLM fabricated tool insert

The second tool insert was built at Croft Additive Manufacturing Ltd Warrington, UK. The machine used was a ReaLizer SLM 250 with a laser power of 200 W. Stainless Steel 316L was the material provided for fabricating the inserts. The powder material was supplied by LPW Technology Ltd (Runcorn, UK), with particle size nominally in the range of 45-150 μm with the built layer thickness being 50 μm. Sand blasting was used to remove the excess powder after the fabrication process.

5.3 Experimental Evaluation of Reflector's Tool Insert and Produced Part

Tests were performed in two stages; the first stage was responsible for assessing the fabricated tool inserts. The second stage accounts for assessing the functionality of the end-product by measuring the surface roughness, dimensional accuracy, and light reflectivity from the vehicle reflectors. Following fabrication, the tool inserts were mounted on the same bolster for injection moulding to manufacture end-products for additional tests. Therefore, the inserts were exposed to the same operational conditions, to ensure consistency of results.

Injection moulding of the tool insert was carried out on a Nurnak MMRJ 130-225 injection-moulding machine with a clamping force of 100 Ton. The polymer used for injection was Polystyrene, with an injection pressure of 55 bar at a temperature of 220-240 °C. The average cycle time to produce two parts in one impression was approximately 42 seconds. The net weight for the SLM-tool insert enabled product was 14 g, whilst the CNC produced reflector was 16 g. The CNC produced reflector is slightly heavier in weight for the following reason: during the manufacturing process the cutting tools are expected to reach the designated depth. Due to the complexity of the surface design, tool insert rubbing leads to tool offset errors and shorter tool life that causes poor finish of the machined surface (Pratap and Patra, 2018).

5.3.1 Tool insert assessment

Following fabrication, tests are performed to assess the fabricated tool inserts. The following tests were executed in the sequence below:

- Surface roughness of the tool inserts
- Dimensional Accuracy of the tool inserts

(i) Surface roughness measurement

Constant contact of the two mating halves of the tool inserts during the injection moulding process may eventually lead to coarseness of the surface due to friction between the two halves (Colton *et al.*, 2001). Due to the complex nature of the surfaces, non-contact profile and roughness measuring equipment is required to perform the necessary investigation. The equipment used for measuring the surface roughness was a Laser scanning Microscope Keyence VX-100 with a laser spot diameter of 0.4 μm. The laser microscope operates on the data provided from the overall surface instead of following a specific line to achieve more accurate and consistent results.

For this test, the measured surface for both the SLM and CNC-manufactured tool inserts was surface H, shown in Figure 5-2. Section G-G demonstrates a detailed view of the surface topology and how surface roughness measurements were sought.

Roughness was calculated on an area of 55.42 mm^2 to ensure that the whole area of the side surface of the prism shape is covered as shown Figure 5-5. For each tool insert, three random points were approached and measured. Values were recorded, and the final roughness value was an average of the three readings as shown in Table 5-1. The purpose of this test was to investigate probable variation in surface texture that may be caused due to use of different manufacturing techniques.

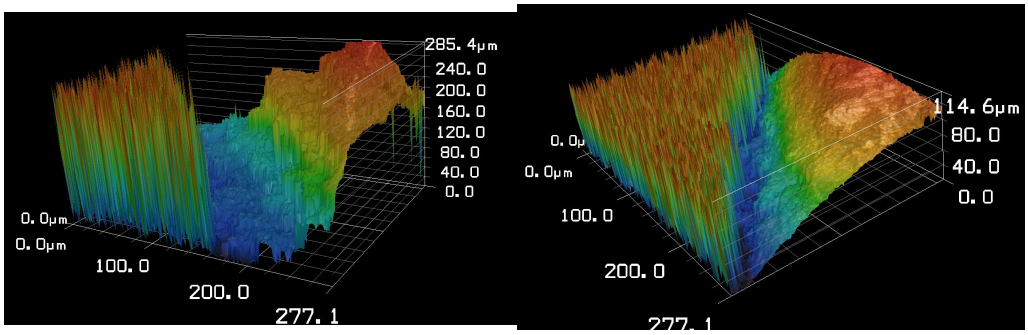

Figure 5-5: Surface roughness topology of CNC-machined insert (left) and SLM-fabricated insert (right)

Table 5-1: Surface roughness measurements (Ra) of CNC and SLM tool inserts

Machining Process	Roughness Measurement (Ra)
CNC machining	64.889 µm
SLM	30.278 µm

Surface roughness of the CNC-machined insert proved to be significantly higher compared to the SLM-fabricated insert, due to the complexity of the surface topology and repetition of the patterned feature on the surface (Pratap and Patra, 2018). Surface roughness values were examined by experts from the field of industry to approve the measured values.

(ii) Dimensional accuracy evaluation

Identifying deviation in measurements from the nominal values after the tool inserts are fabricated was necessary to achieve a complete assessment of the functionality of the products. Therefore, the CNC and SLM-fabricated tool inserts were both evaluated in comparison to the pre-set nominal values. The same evaluation process was repeated for the produced samples from their corresponding tool inserts and were similarly evaluated.

A FaroArm Platinum 3D scanner with a ± 0.036 mm volumetric accuracy was used to scan the appointed surfaces with the required dimensions for measurements for both the CNC and SLM fabricated tool inserts. The Geomagic Control X metrology software was used to deliver a comprehensive analysis of the inspected surfaces to detect and identify deviation in measurements of the fabricated parts from the nominal values.

Dimensions that are of interest to this study and have a direct effect on the product evaluation are A, B, F and H. The objective of this analysis is to determine the deviation that occurred from the nominal values for the tool inserts. For the CNC-machined insert shown in Figure 5-6, dimension A is the total length of the insert and deviation was recorded at -0.0406 mm from the nominal value within tolerance range of $\pm$ 0.1 mm. Dimension B is the total width of the insert, three values for deviation were recorded within the tolerance range $\pm$ 0.1 mm, the values are -0.092 mm and the other two values are -0.115 mm, and -0.130 mm crossing over the high limits. Deviation inconsistency between the three points of measurements is interpreted as a misalignment during machining in the X axis. Dimension F is the thickness of the insert's base, the average recorded deviation value is 0.0863 mm within the tolerance range of $\pm$ 0.4 mm. Four average values were recorded for deviation in dimension H, -0.044 mm, 0.013 mm, 0.274 mm, and 0.303 mm, and -0.238 mm, all values are within the acceptable tolerance range $\pm$ 0.4 mm. fluctuation in deviation values is a result of cutting tool wear therefore, cutting tools were changed multiple times to maintain consistency to measurement accuracy.

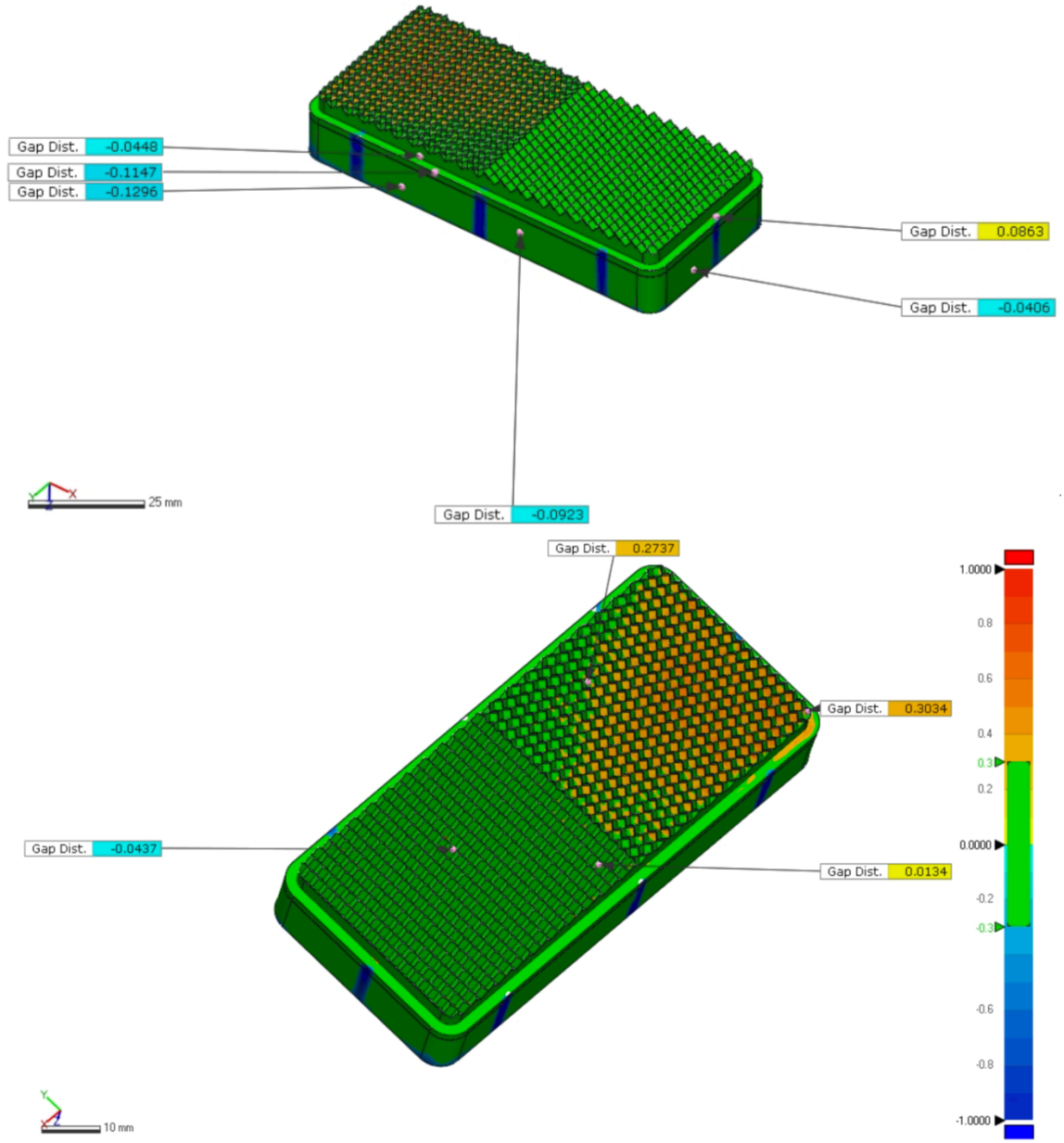

Figure 5-6: Deviation analysis of fabricated CNC insert from nominal values.

The same analysis process was adopted for the SLM-fabricated insert. The dimensions that were evaluated are A, B, F and H. Shown in Figure 5-7 is an illustration of deviation analysis, for dimension A two values were recorded for deviation from the nominal value 0.007 mm and -0.118. The first value is within the tolerance range of $\pm$ 0.1 mm while the second value tends to cross over the high limit, the change in deviation is interpreted as a misalignment during fabrication in the Y axis due to shrinkage caused by the sintering process. Deviation in dimension B records three values within close range to

tolerance ± 0.1 mm, the values are -0.115 mm, -0.144 mm, and -0.139 mm. The average recorded value for deviation in dimension F is 0.041 mm within the tolerance range of ± 0.4 mm. four average values were recorded for deviation in dimension H, -0.079 mm, -0.147 mm, -0.240 mm, and -0.238 mm, all values are within the acceptable tolerance range ± 0.4 mm.

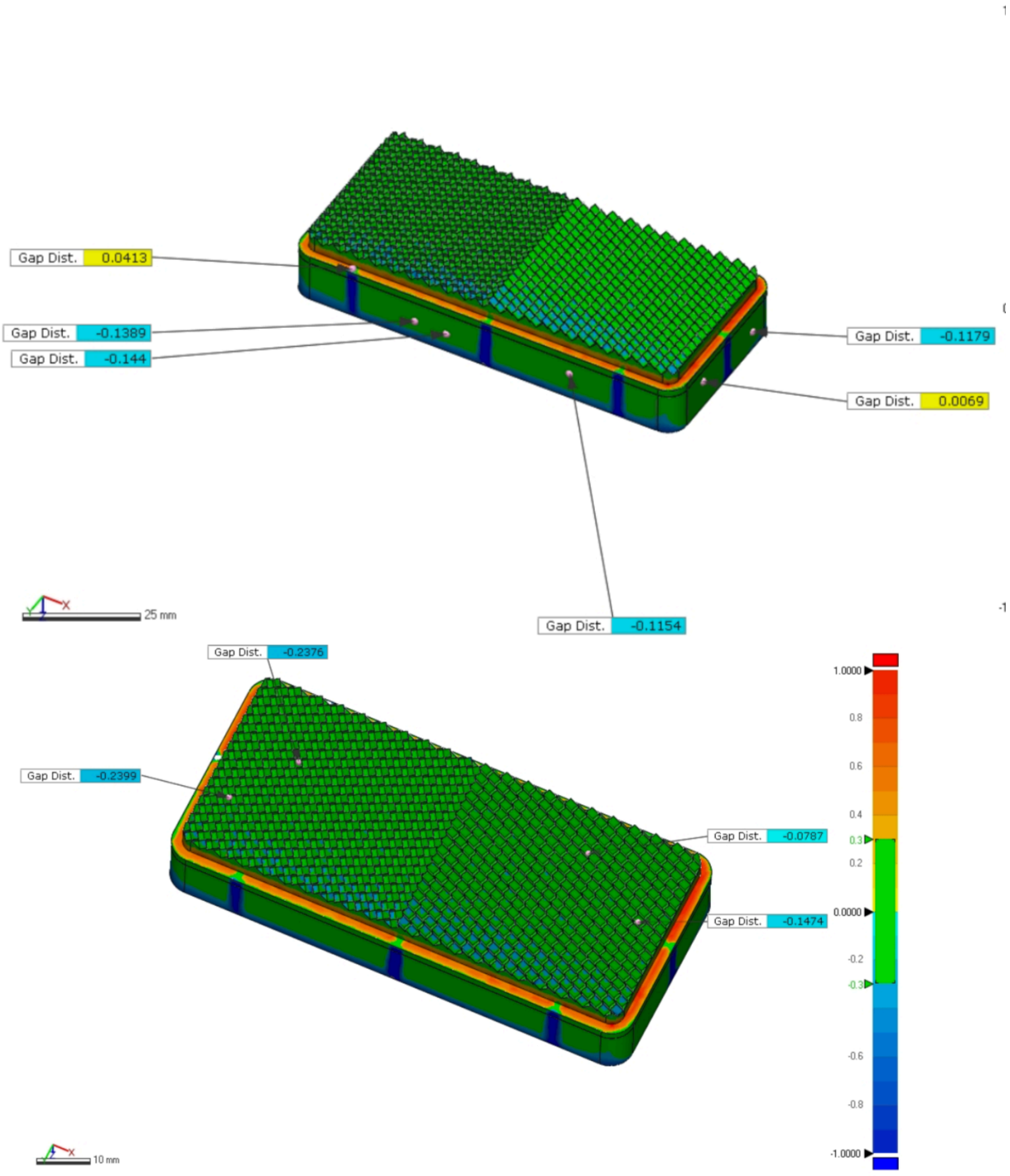

Figure 5-7: Deviation analysis of fabricated SLM insert from nominal values.

The angled position of the patterned feature leads to a high level of geometric complexity on the surface of the inserts. The complexity presented on the surface was difficult to manufacture consuming multiple cutting tools due to the repetitive sequence during processing and causing inconsistency. On the other hand, the SLM-fabricated insert provided no hardships during the fabrication process proving to be prominently competent in terms of dimensional accuracy.

5.3.2 Product Assessment

After examining the SLM and CNC-fabricated tool inserts, the second stage in the assessment process is to evaluate functionality of the respectively produced reflectors. The following tests were executed in the sequence below:

- Surface roughness of the produced reflectors
- Dimensional Accuracy of the produced reflectors
- Light reflectivity testing of the produced reflectors

(i) Surface roughness measurement

After investigating roughness of the CNC and SLM tool insert surfaces, the same test was repeated for their respective products. The measured surface is H as shown in Figure 5-8 with a detailed illustration of the surface topology.

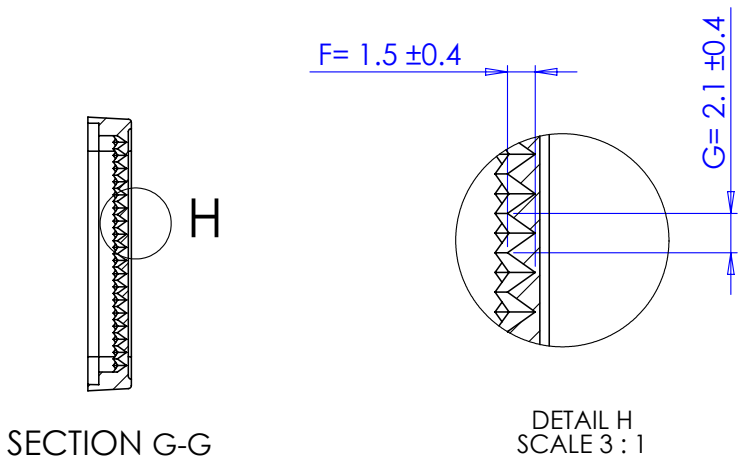

Figure 5-8: 2D section view illustration of the produced sample

A close-up detailed view is illustrated in Figure 5-9 to demonstrate the geometrical feature design of the prism-shaped pattern of the internal reflector's surface topology. The side surfaces of the prism shape topology were the targeted area for measurements.

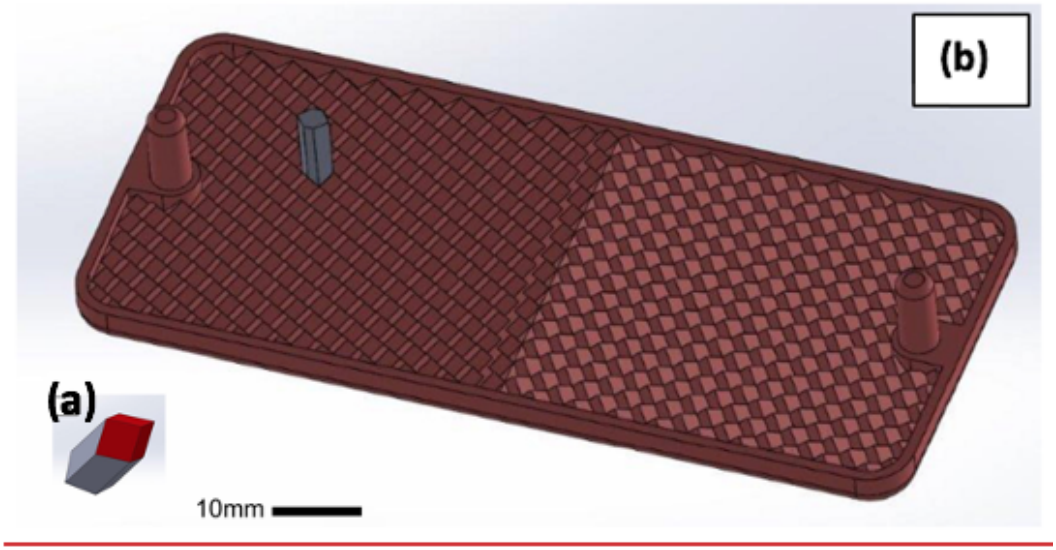

Figure 5-9: (a) A close-up view of the prism-shaped pattern topology of the reflector (b) produced reflector.

For each measuring trial the roughness was calculated on an area of 55.420 mm^2 to ensure that the whole area of the prism-shaped surface is covered as shown in Figure 5-10. Three values were obtained, and the average was calculated to provide the final roughness values as shown in Table 5-2. Surface roughness proved high for both the CNC and SLM produced inserts. The increase in surface roughness value of the CNC produced reflector was described as a result of the injection moulding process. The complexity of the surface topology and the high value of surface roughness of the CNC tool insert affects the ejection process of the reflector causing tiny cracks and deformation to the textured features on the reflector. Therefore, the outcome of the conducted tests proved that the SLM-fabricated inserts and hence the SLM-produced inserts proved to have relatively lower values of surface roughness with respect to their counterparts and were deemed acceptable.

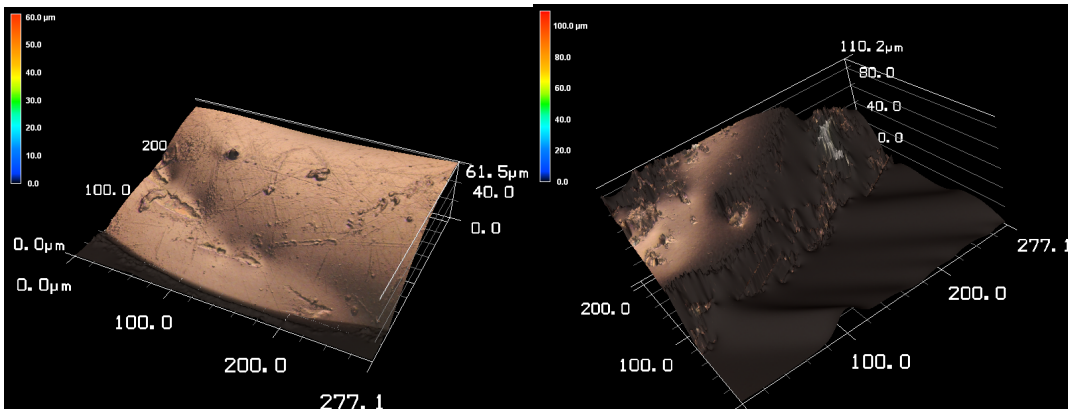

Figure 5-10: Surface topology of CNC-produced reflector (left) and SLM-produced reflector (right)

Table 5-2: Surface roughness measurements (Ra) of CNC and SLM-produced reflectors

Reflector Insert	Roughness Measurement (Ra)
CNC machined	30.965 µm
SLM	27.570 µm

(ii) Dimensional accuracy evaluation

A 2D CAD design of the produced sample product with the corresponding nominal values and tolerances are illustrated in Figure 5-11.

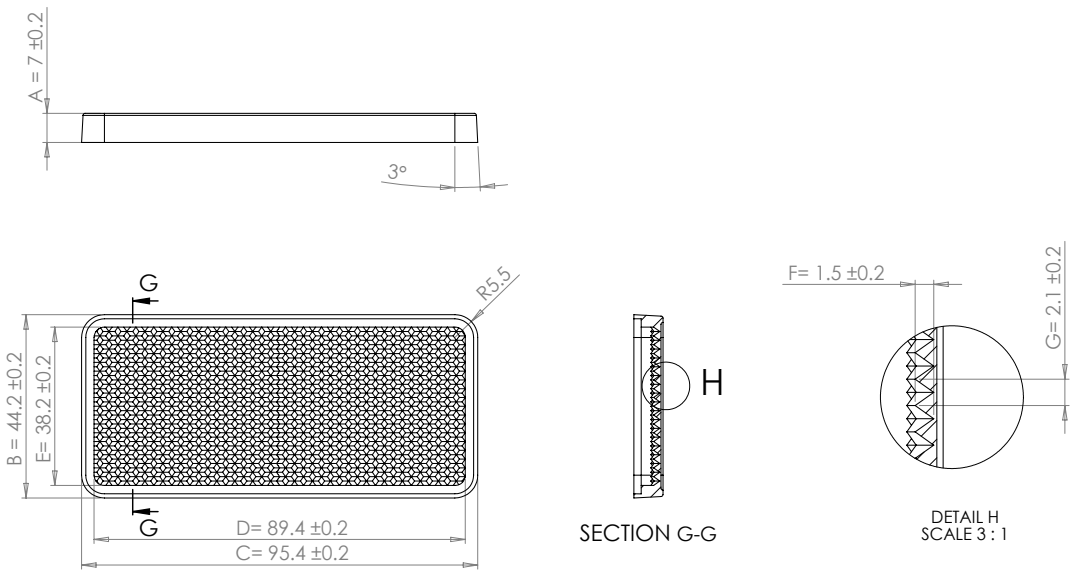

Figure 5-11: 2D CAD illustration of the produced sample product.

Deviation from nominal values for the CNC-produced reflector is shown in Figure 5-12. The following dimensions B, C and resultant of F dimension acquired from insert dimensions are of interest to this study. Dimension B is the overall width of the produced reflector, two average deviation values are recorded, -0.0907 mm, and -0.1395 mm. Deviation is acceptable within the tolerance range of ± 0.3 mm. Recorded average value of deviation from C dimension is -0.3674 mm crossing over the tolerance range of ± 0.2 mm. The increased deviation is a result of a misalignment during machining of the insert in the Y axis. Two deviation values recorded for the measured from the patterned feature on the internal surface of the reflector, 0.8671 mm and 1.0208 mm. These values are remotely beyond the acceptable tolerance range of ± 0.4 mm.

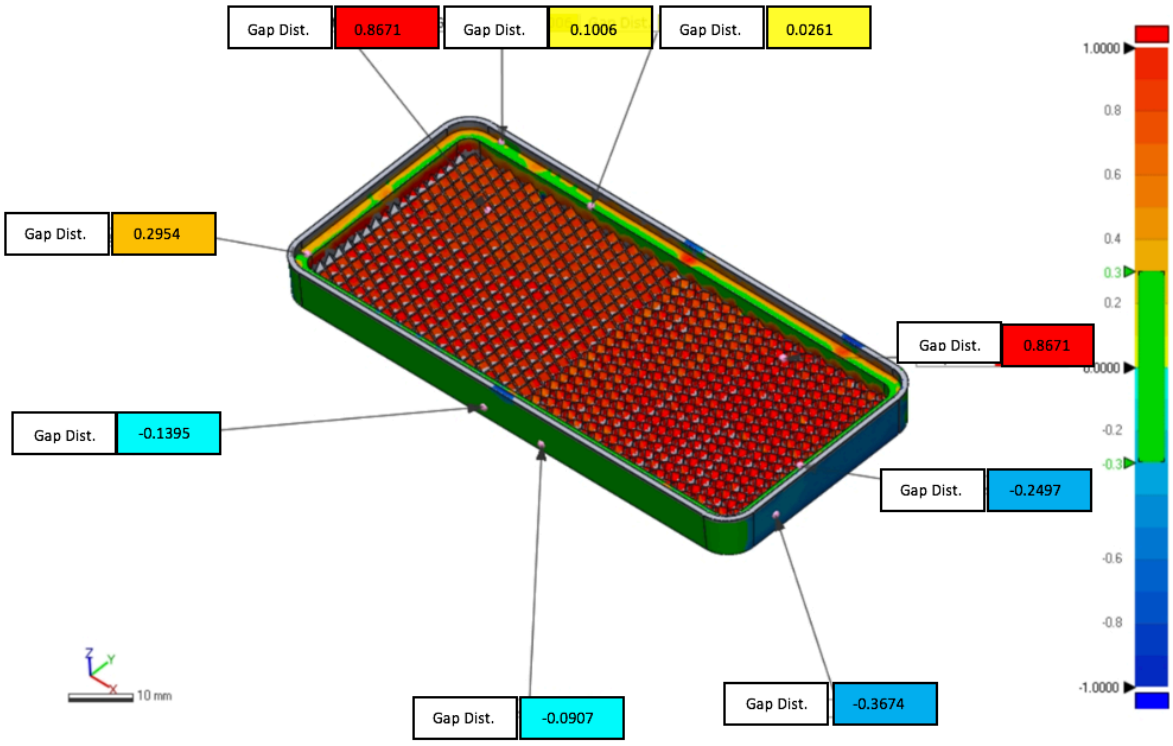

Figure 5-12: Deviation analysis of the produced CNC sample.

During the injection moulding process, complications occurred as a result of difficulties encountered during the machining process of the insert. The angled position and small measurement value of the patterned prism shape displays a high level of geometric complexity hindering complete access to the cutting tool on the surface, resulting in low wall thickness of the prism-shaped feature exhibiting a crater like view as shown in Figure 5-13.

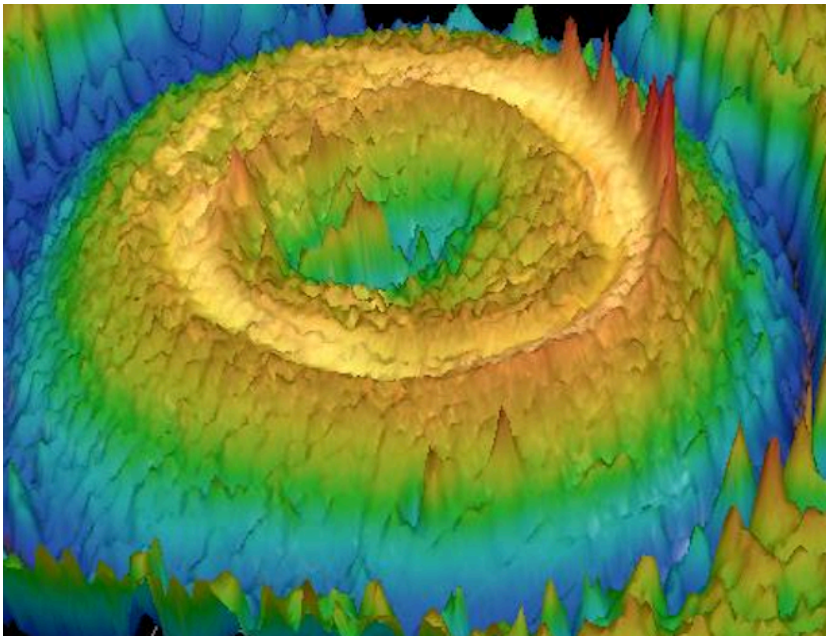

Figure 5-13: Detailed close-up view of the patterned feature.

Deviation from nominal values is shown in Figure 5-14 for the SLM produced reflector for the following dimensions B, C, and resultant of F dimension acquired from insert dimensions. Four average deviation values are recorded for dimension B, -0.0004 mm, -0.258 mm, -0.211 mm, and 0.135 mm, deviation is accepted to be within the tolerance range of $\pm$ 0.3 mm. Average value recorded for deviation from C dimension is -0.498 mm crossing over the accepted tolerance range of $\pm$ 0.2 mm. This increased deviation is a result of shrinkage during the SLM-fabrication process resulting in shrinkage in overall length of the injected reflector. As for deviation values measured from the patterned feature on the internal surface of the reflector, two values were recorded within the accepted tolerance range of $\pm$ 0.4 mm, these values are 0.2527 mm and 0.3106 mm.

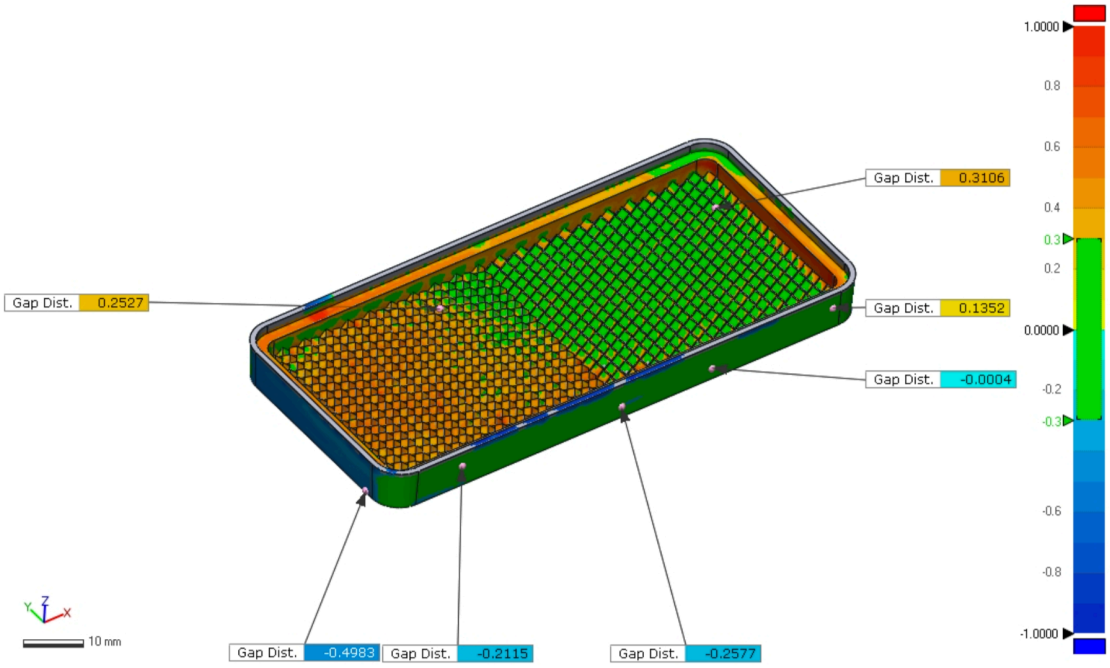

Figure 5-14 Deviation analysis of the produced SLM sample

It should be highlighted that overall, the resulting dimensional measurements of the SLM reflector have minimal deviation in comparison with the CNC reflector. This phenomenon can be explained due to difficulty in machining the complex surface of the reflector's core insert resulting in increased deviation from nominal.

(iii) Light Reflectivity test

Since the manufactured end-products are vehicle reflectors, measuring the light reflections is an essential parameter that further compares the functionality of both the SLM and CNC processes. No such research on measuring the light reflectivity has yet been reported in the literature to evaluate the end-products performance. The purpose of the test is to display and quantify the intensity of the light reflected from these sample reflectors in order to achieve the desired functional effectiveness.

The experiment was carried out in an optical laboratory where light was controlled at the Department of Electronics at the Arab Academy for Science and Technology and Maritime Transport, Alexandria, Egypt. The experiment consists of an optical source where the light is illuminated, the SLM and CNC-produced samples and an optical power meter to measure the light intensity/power as shown in Figure 5-15.

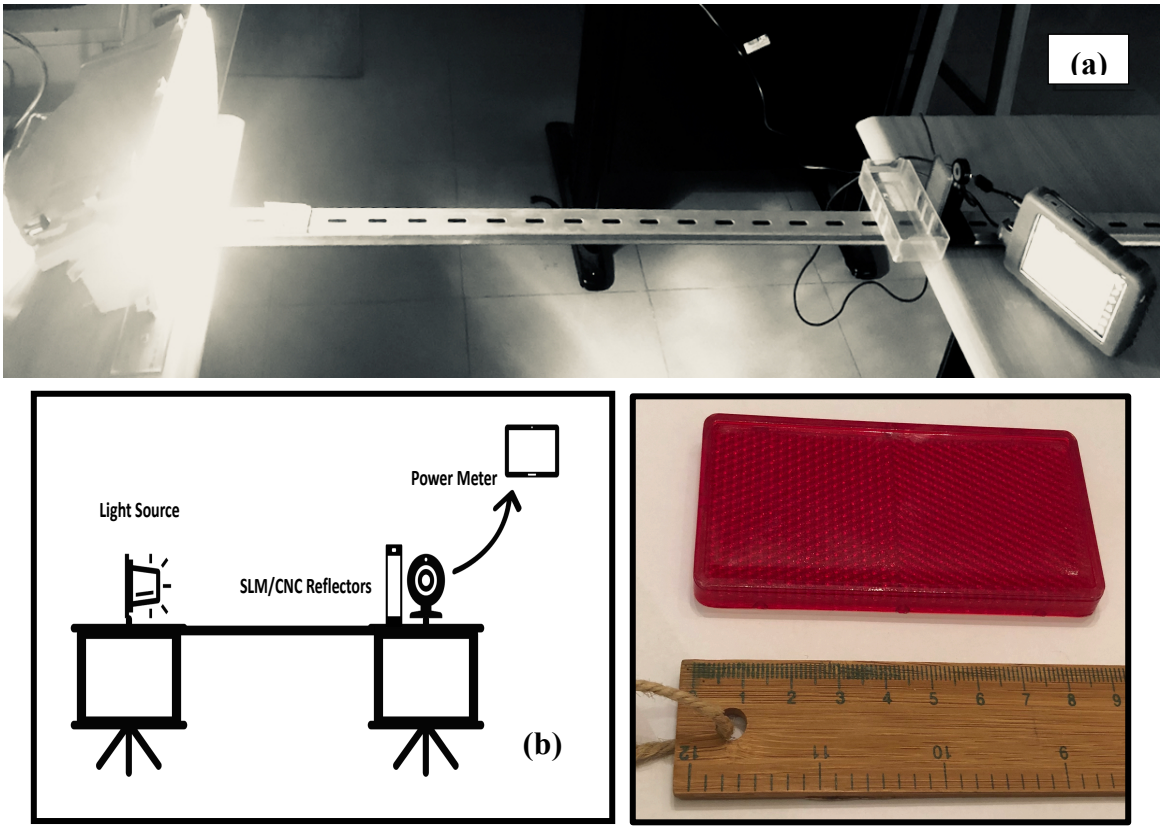

Figure 5-15: (a) Experimental setup to measure light intensity using a PM200 optical power meter. (b) Schematic illustration of the test setup. (c) Injection moulding reflector.

The light source is an automotive headlamp equipped with an H4 12V 130/90W Halogen bulb which transmits light centred at a wavelength of 532 nm and has a bandwidth of 100 KHz. The output light from the source propagates along the channel on the Y axis (with variable distances) until it reaches the produced sample reflector. The distance between the light source and the tested specimens in the X and Z axes are fixed throughout the tests. The amount of light transcending through the reflectors provides an inverse relation to the reflection intensity of the reflectors. The reflected light is diverged in different directions (with different angles) and light is distributed.

In this study light intensity is measured as the light transmitted through the reflector rather than the reflected light from the reflector. In the case of measuring light reflectivity, the power meter will have to be placed in between the power source and the reflector. Hence, causing distortion and error in results due to the absorption of some light from the power meter. For that reason, in this study, the transmitted light through the reflectors are the measured intensity for more efficient and accurate results. The optical power meter used is a Thorlabs PM200 module that can record power up to 150W.

The module has a high sensitivity silicon PIN photodiode (PM16-121C) attached to the meter that covers the visible light wavelengths range (i.e. 400-700μm). It has a response time of less than 1 μs allowing variations of frequencies up to 1 MHz to be measured.

The test is performed in darkness in order to avoid background light and any interference from other sources. Six experiments at different distances were carried out for each specimen to analyse variation in light transmitted through the reflectors. For each experiment (i.e. at each distance), the light is firstly recorded in order to measure the light intensity reaching such a distance with no reflections directly from the light source. The reflector produced from the CNC is then placed at this distance and the transmitted light is recorded to measure reflectivity of the sample. The sample is then replaced by the SLM-produced reflector and the transmitted power is also recorded to compare its functional effectiveness.

At 0.5 m distance, the light power before reflection was measured at 0.968mW. The refracted ray passing through the CNC reflector recorded 66.8% substantial descent in power reading (i.e. 0.321 mW) due to the reflection of light by the vehicle reflector. Similarly, a 76.3% decline in light intensity is recorded using the SLM reflector with power of only 0.229mW. These measurements show that light transmitted through the SLM reflector is less than that of the CNC sample which indicates that the reflectivity of the SLM produced reflector is higher at 13.5 %.

These measurements are repeated at 1m, 1.5m, 2m, 2.5m and 3m and all recorded powers are displayed in Table 5-3. Figure 5-16 demonstrates a graphical illustration of the measured light power transmitted directly from the light source versus the light transmitted through the SLM and CNC reflectors.

Table 5-3: Measurements of the light power readings and percentage decrease in light intensity and improvement in reflectivity.

Distance from light source (m)	Light source power (mW)	Refracted light passing through CNC reflector	Percentage decrease in light intensity from light source (%)	Refracted light passing through SLM reflector	Percentage decrease in light intensity (%)	Percentage of reflectivity improvement of SLM over CNC reflector (%)
0.5	0.968	0.321	66.8%	0.229	76.3%	13.5%
1	0.245	0.070	71.4%	0.057	76.7%	1.4%
1.5	0.108	0.030	72.2%	0.024	77.8%	0.6%
2	0.059	0.018	69.5%	0.012	79.7%	0.6%
2.5	0.038	0.011	71.1%	0.008	78.9%	0.3%
3	0.026	0.01	61.5%	0.006	76.9%	0.4%

A substantial decrease is shown between the first readings at 0.5 m as compared to further readings at other distances. The light intensity was considerably high at 0.5 m and gradually diminished at further distances. Therefore, the percentage in reflectivity improvement of the SLM reflector over its counterpart the CNC reflector was calculated. The highest improvement of 13.5 % was recorded at 0.5 m. The percentage improvements that followed at further distances showed a significant fall in values until 0.4 % improvement in reflectivity was reached for the SLM reflector.

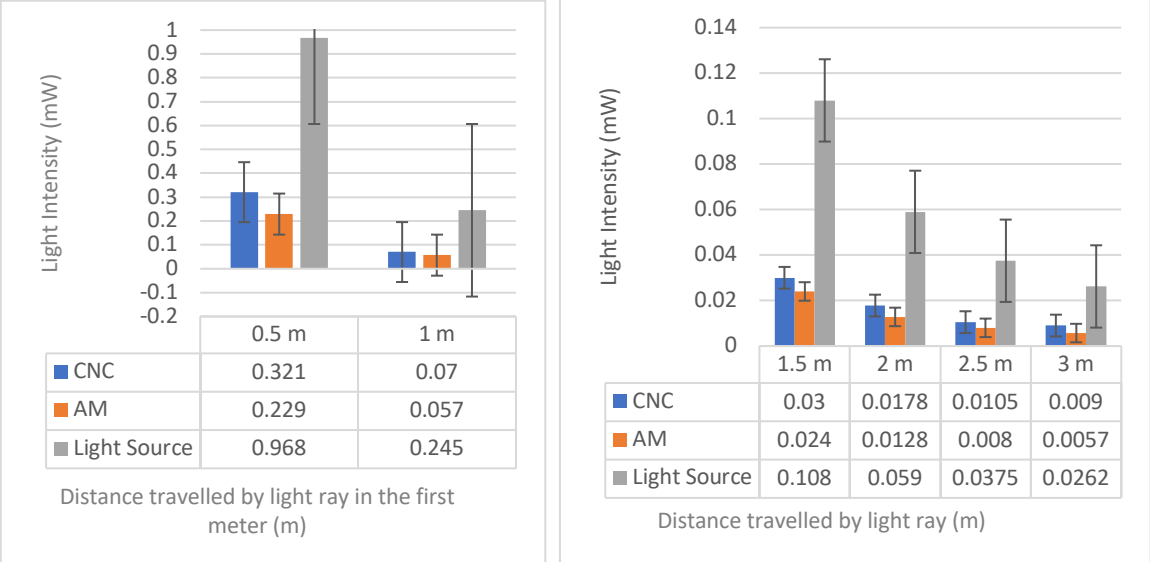

Figure 5-16: Measured light intensities at different distances

It is perceived that a decline in light intensity is notable after the reflectors are placed in front of the power meter. Starting from a distance of 0.5 m until 3 m, the percentage decrease in light power is directly proportional to the distance travelled by the light ray. Figure 5-17 depicts the changes occurring in light intensity as distance varies.

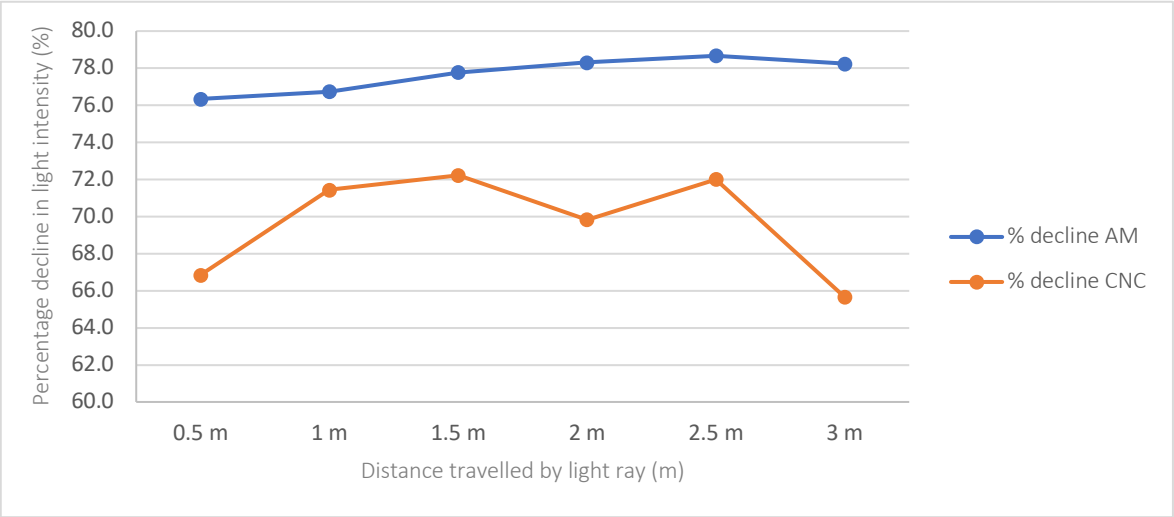

Figure 5-17: Percentage decline in light intensity after placing CNC and SLM produced reflectors at different distances

It was noted that the light power measured after placing the SLM reflector continuously indicated a lower value of transmitted light power, as compared to the light power measured from the CNC reflector. This experiment was determined on verifying reflection competencies of the reflectors. Therefore, if the value of the measured light power of a certain reflector for a given distance is higher than the value of the other reflector, then it proves that the reflector with the higher light power shows less reflection capabilities. For all the established trials, the CNC produced reflector produced the higher light power as opposed to its counterpart the SLM reflector. Therefore, the SLM produced reflector demonstrates enhanced reflection capabilities.

5.4 Summary

In the reflector study, CNC machining and SLM manufacturing techniques were successfully used for the production of a vehicle reflector's tool insert. SLM proved to be advantageous when dealing with fabrication of complex geometries attaining required geometries, surface roughness, and maintaining dimensional accuracy. In terms of surface

roughness, it was concluded that the SLM-fabricated inserts and hence the SLM-produced inserts proved to have relatively lower values of surface roughness in comparison to their CNC counterparts. The optical test performed verified that the reflectors are fully functional. The SLM reflector reflectivity improvement surpassed that of the CNC reflector, with a maximum improvement of 13.5 % at 0.5 m and 0.4 % at 3 m. As a result, due to higher geometrical accuracy of the SLM-produced reflector, reflection capabilities surpass those of the CNC-produced reflector. Therefore, this study recommends that selective laser melting is the processing approach to be adopted for fabricating the reflector.

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6 Assessment of Design-Feature Limitations and Complexities

This chapter presents design limitations and complexities that manufacturers of injection moulding tool inserts are faced with when manufacturing tool inserts for the aftermarket automotive sector. Three studies are discussed in this chapter. The purpose of the studies presented is to distinguish limitations in design that can have an impact on the manufacturability of injection moulding tool insert sets. Therefore, the studies presented in this chapter are following the guidelines set by the manufacturing framework of this research.

For each tool insert, two design approaches were adopted: Design for Additive Manufacturing (DFAM) and Design for Subtractive Manufacturing (DFSM) to investigate the outcome of the produced tool inserts. The use of three different tool inserts in this study was to explore a wide range of design features that have a direct impact on manufacturability. After developing the CAD model designs, the tool inserts were manufactured using two significant manufacturing methods, additive and subtractive manufacturing. The AM method adopted was SLM. As for the subtractive manufactured tool inserts, due to the complexity of the parts design, more than one technique was adopted; CNC milling, turning, wire EDM, and die-sink EDM.

6.1 Tool Design

Three studies were selected for investigation in this chapter. The purpose for selecting each of these studies was to provide a comprehensive understanding of the design limitations that can be found when manufacturing an injection moulding tool insert. These studies are similar in demonstrating feature complexities; however, each study reveals variations in the feature complexities. For each study, an injection moulding tool insert for an automotive spare part was selected. The three tool insert sets defined in the three studies are named for simplicity: plug A, plug B, and plug C tool inserts.

6.1.1 Plug A tool inserts

The tool insert for plug A is for a spare part component that is assembled as a fixture plug in a vehicle's headlight. The purpose for choosing this component is to explore the

complexity of the part due to the presence of multiple features in a relatively small cross section. Figure 6-1 is a schematic CAD model illustration of a sectioned view for the entire tool insert for plug A and for an exploded view see Figure 1-1.

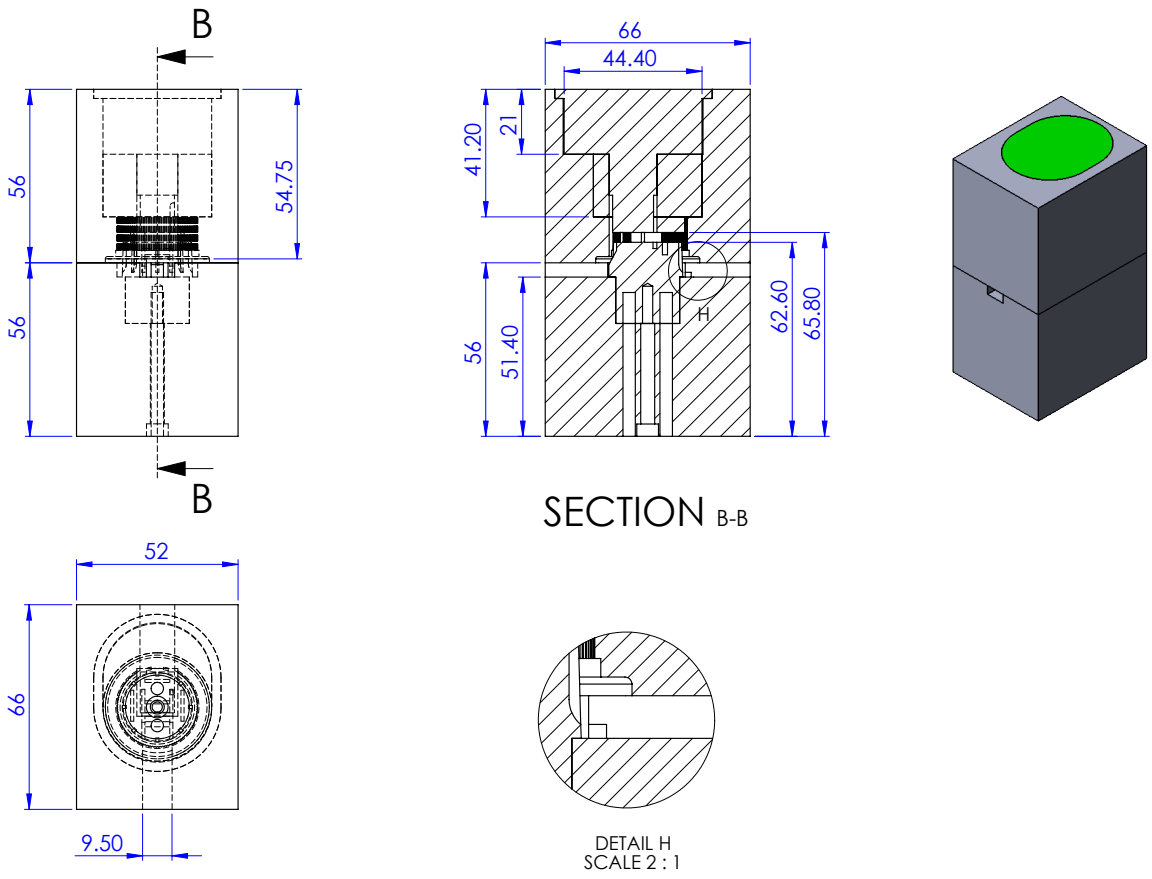


Figure 6-1: Schematic 2D view of plug A tool insert, dimensions in mm..

In the design phase, it is essential to be attentive to the design goals and limitations that may have an impact on the manufacturing process. Therefore, the tool insert was designed with a notion to determine potential complications during the design stage, and eventually increase product quality and decrease manufacturing lead-time and cost.

In the design stage of this study, two approaches were adopted when considering the design of plug A, DFSM and DFAM. The methodology embraced for approaching each design tactic was different. When applying DFSM, each of the core and cavity inserts had to be separated into six components with different geometries that were further assembled to construct the whole of the core and cavity inserts. As can be seen in Figure 6-2, the individual components contain features that may have limitations with some

subtractive methods of manufacturing. Some of these features that can detected are sharp-edged corners, fine holes, fine slots, and internal freeform-pattern designs. The separation process of the components was required to facilitate the process of manufacturing the components due to the presence of complexities that complicate manufacturing the core and cavity inserts as a whole part. Figure 6-2 is an illustration of the separated components of the core and cavity inserts of plug A.

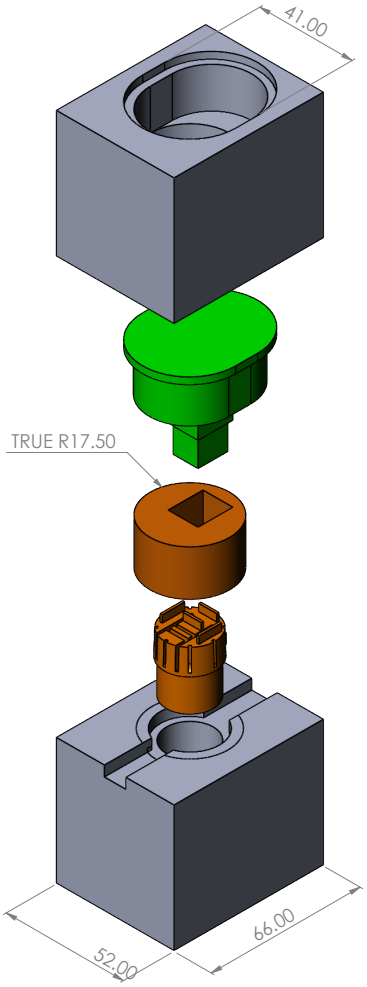


Figure 6-2: DFSM separated components of the core and cavity inserts of plug A, dimensions in mm.

DFAM was a design approach that required knowledge of the limitations and capabilities of the technology that is being utilised. The CAD model design for the tool inserts of plug B were generated from the same CAD model designed for subtractive manufacturing. Nonetheless, the separated components of each of the core and cavity inserts were assembled and treated as a whole entity and the model then converted to a

*.STL file for the SLM fabrication process. Figure 6-3 demonstrates the generated CAD model design for the core and cavity inserts of plug A that was used for the SLM process.

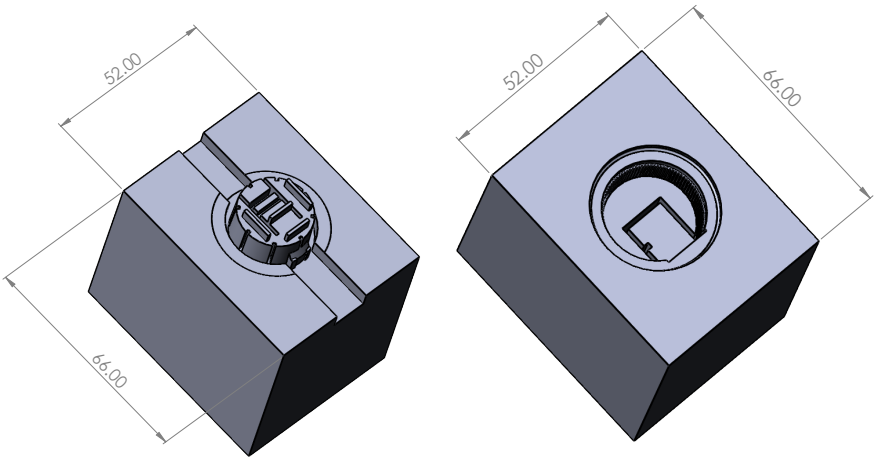


Figure 6-3: DFAM core and cavity inserts for plug A, dimensions in mm.

6.1.2 Plug B tool inserts

Plug B is another plug type component that is assembled in a vehicle's headlight. Features are explored in this study to realise the range of complexities that exist in a tool insert of an automotive spare part. Figure 6-4 is a schematic 2D CAD model illustration of a sectioned view for the entire tool insert of plug B and for an exploded view see Figure 6-5.

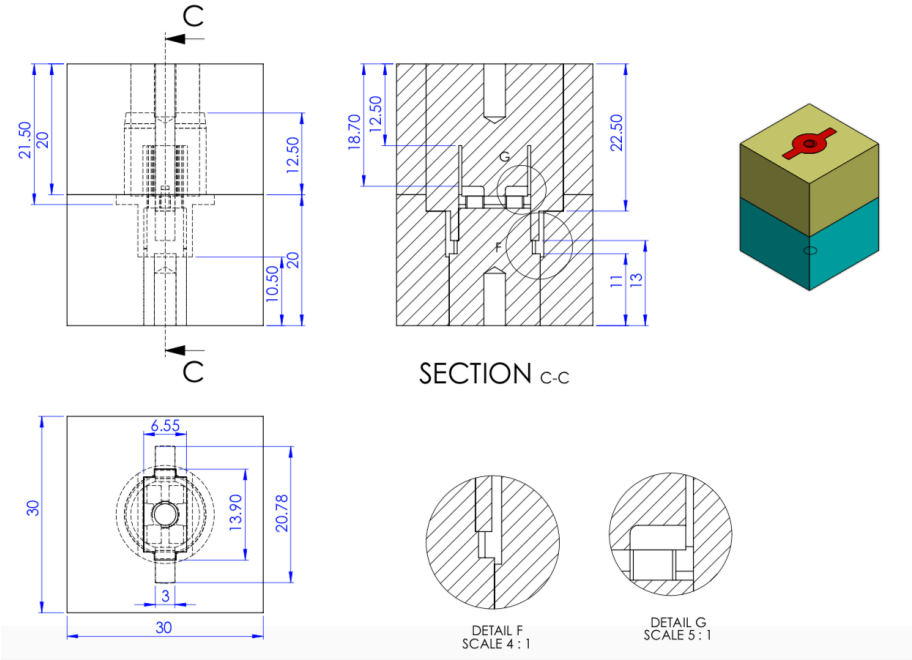


Figure 6-4: Schematic 2D drawing of plug B tool insert, dimensions in mm..

Due to the complexity of the part geometry, DFSM and DFAM were the two approaches adopted for designing the CAD model of plug B tool insert. The DFSM was perceived in the same method that was assumed for the tool insert of plug A. The core and cavity inserts were separated into four components with different geometries that were later assembled to create the core and cavity inserts. Each of the separated components hold features that may be of restrictive nature to some of the adopted subtractive methods of manufacturing. Examples of the detected features are sharp-edged corners and fine hole design features. It was necessary to create separate components when designing for subtractive manufacturing to simplify the process of manufacturing the components without encountering complications. Figure 6-5 demonstrates the separation of components of the core and cavity inserts of plug B.

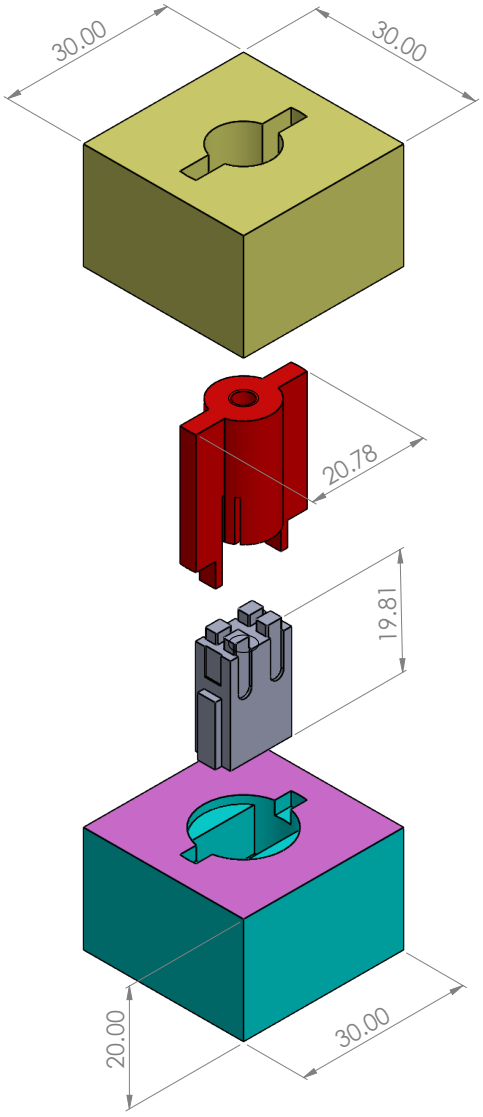


Figure 6-5: DFSM model for plug B core and cavity inserts, dimensions in mm..

The DFAM for plug B core and cavity inserts was generated from the same CAD model designed for subtractive manufacturing, however, the detached components were later assembled and built into the core and cavity inserts. Subsequently, the *.STL file of the CAD model was generated for SLM fabrication. Figure 6-6 illustrates the different components of each of the core and cavity inserts for plug B.

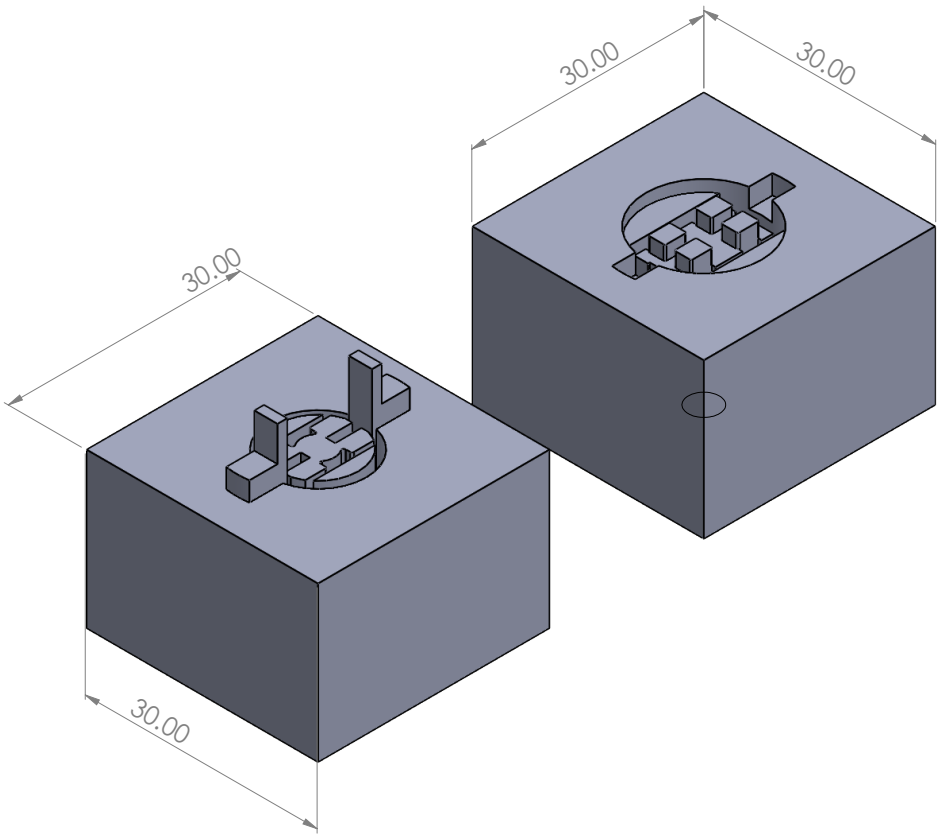


Figure 6-6: DFAM CAD model of plug B core and cavity inserts, dimensions in mm..

6.1.3 Plug C tool inserts

The tool insert of plug C is for another plug type component that is assembled in a vehicle's headlight. The purpose for choosing this component was due to the presence of multiple features with a range of complexities in the geometry of plug C's tool insert. The following figure, Figure 6-7 is a CAD model illustration of a sectioned view for the entire tool insert of plug C and for an exploded view see Figure 6-8.

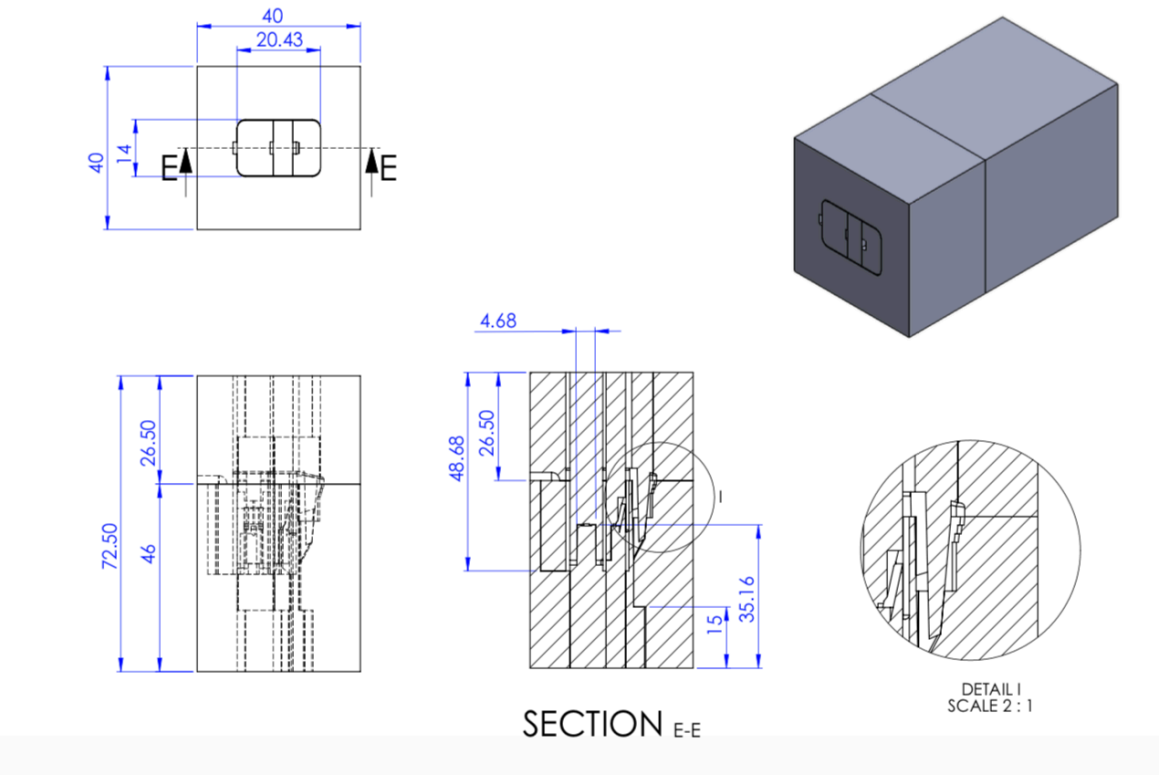


Figure 6-7: Schematic 2D drawing of plug C, dimensions in mm..

In this study, the same method of DFSM and DFAM was embraced for creating the CAD model of plug C tool insert. Due to complexities in design, the DFSM was perceived in the same method that was assumed for the tool insert of plugs A and B. Nine separate components were created with different geometries for the core and cavity inserts, those components were separated to ease the manufacturing processes. Examples of features that may cause limitation to manufacturability are sharp-edged corners and fine hole design features. These features may limit some subtractive methods of manufacturing.

After manufacturing the parts, they were assembled together to constitute the core and cavity inserts of plug B. Figure 6-8 demonstrates the separation of components of the core and cavity inserts of plug B.

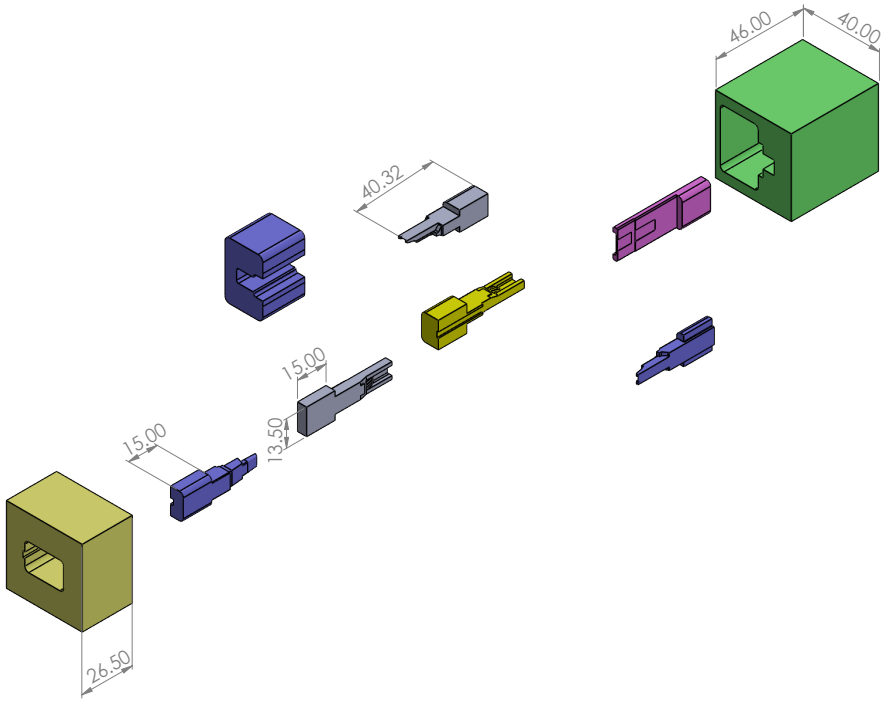


Figure 6-8: DFSM CAD model design for plug C core and cavity, dimensions in mm..

DFAM was employed in the same manner as the previous studies for plug A and B. Sufficient knowledge of the limitations and capabilities of SLM technology was essential. The CAD model design for the core and cavity of plug C tool inserts was generated from the same CAD model designed for the subtractive manufacturing approach, however, the unconnected components were combined to construct the core and cavity inserts. Figure 6-9 demonstrates the CAD model design generated for the core and cavity inserts for plug C that was used for the SLM process.

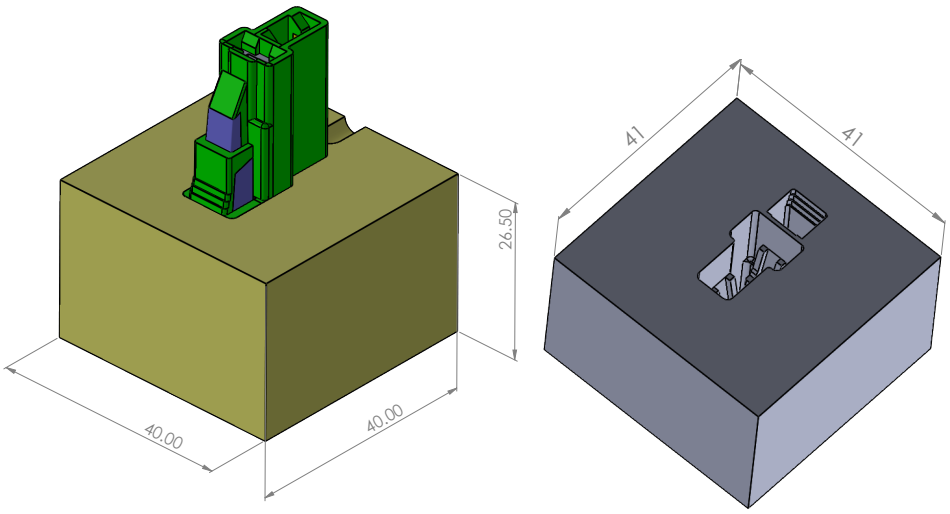


Figure 6-9: DFAM of plug C core and cavity inserts, dimensions in mm..

6.2 Tool Inserts Manufacturing

As with the previous studies, all tool inserts requiring the use of subtractive manufacturing techniques are successfully executed at Al Fouad Co. for Automotive Spare Parts (Alexandria, Egypt). SLM-fabricated tool inserts were fabricated at Croft Additive Manufacturing Ltd (Warrington, UK). The machine used for fabricating the core and cavity inserts was a ReaLizer SLM 250 with a laser power of 164 W. The build layer thickness was 50 μm. During the SLM-fabrication process, the hatch X and Y distance is set at 70μm. Parts were scaled in the CAD model to compensate for allowances caused by shrinkage during cooling of the injected products. Tumbling was used to remove the excess powder after the fabrication process.

6.3 Tool Insert SLM and SM Fabrication of Plug A

In this study, a spare part component produced for the aftermarket automotive industry was investigated to produce its tooling insert. The AM method adopted was SLM. For the subtractive manufactured tool insert, due to the complexity of the part, more than one technique was adopted, CNC milling, turning, wire EDM, and die-sink EDM.

6.3.1 Subtractive manufacturing

The CAD design adopted for both tool inserts was different due to the complexity of the part design that led to different design approaches. For the subtractive tool insert, the tool was designed as multiple individual inserts that were further assembled after manufacturing to constitute the whole of the core and cavity of the tool insert set. Depending on the geometrical features of the part, dimensions, and level of complexity CNC machining, wire EDM, or die-sink EDM was selected. Figure 6-10 Is a schematic illustration of the exploded CAD design of the individual inserts of the core and cavity for the plug A tool insert set.

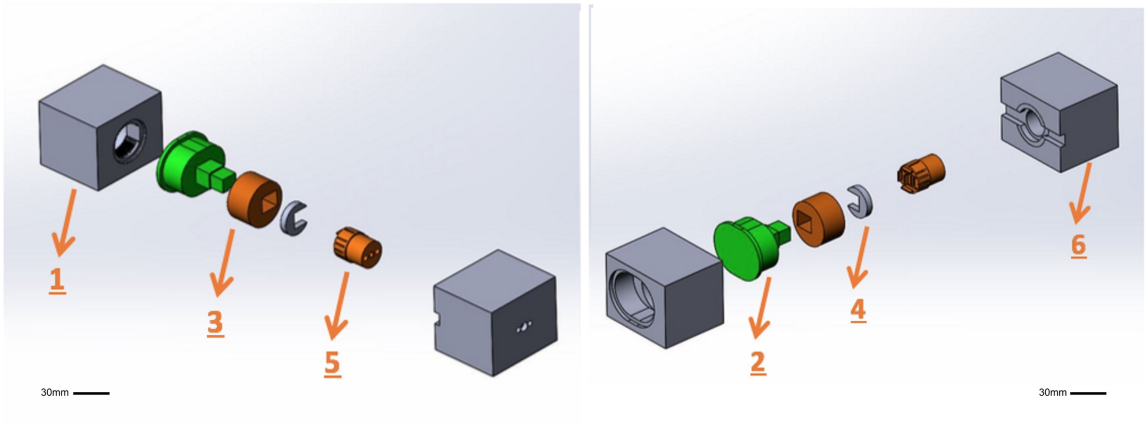


Figure 6-10: Exploded view of Plug A tool insert with individual assembled units.

3-axis First V 700 machines with maximum spindle motor power of 5.5-7.5 KW and 4,000-8,000 RPM was used to manufacture the tool insert. End mill carbide tools of shank diameters 4 and 8 mm were used. Additionally, An HCM-H36 die-sink EDM that provides 50 Ampere and the wire EDM machine used was an Accute X-500i with power of 50-60 HZ and wire diameter range of 0.15-0.33 mm.

Figure 6-10 shows the exploded view of the individual components of the tool insert. Each component was manufactured using a different set of manufacturing techniques. First, for component 1 the part is machined using CNC milling to produce the external shape. To create the internal through-hole geometry with the different features on the surface, a hole is machined using CNC milling to act as an entry point to further machine the part using wire EDM to create the internal vertical freeform-pattern design. CNC milling was the only manufacturing approach employed for manufacturing component 2. As for component 3, initially the part is machined using a turning process and additional milling machining was adopted to create a through square-cross section that is further machined using wire EDM to create the sharp-edged corners. Component 4 was entirely manufactured using wire EDM to create the internal sharp-edged corners of the C-shaped component. Component 5 was initially machined using turning, electrode cutters were machined using CNC milling that were subsequently used to generate the sharp-edged slots surrounding the component using die-sink EDM. Finally, component 6 was entirely machined using CNC milling. Figure 6-11 demonstrates the core and cavity for plug A after assembly and mounting on the bolster.

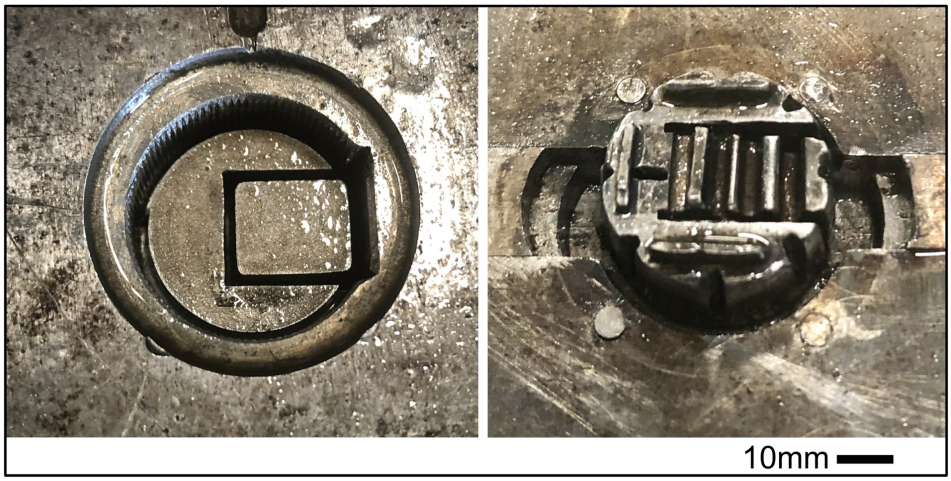


Figure 6-11: Assembled core (left) and cavity (right) of plug A tool insert.

6.3.2 SLM fabrication

The maximum part dimensions were 66mm x 52mm x 112mm with given consideration to shrinkage allowance of 1.5% of the injected polypropylene. Tumbling was used as a post processing technique to remove the excess powder after the fabrication process. Figure 6-12 demonstrates the SLM-fabricated tool insert core and cavity for plug A.

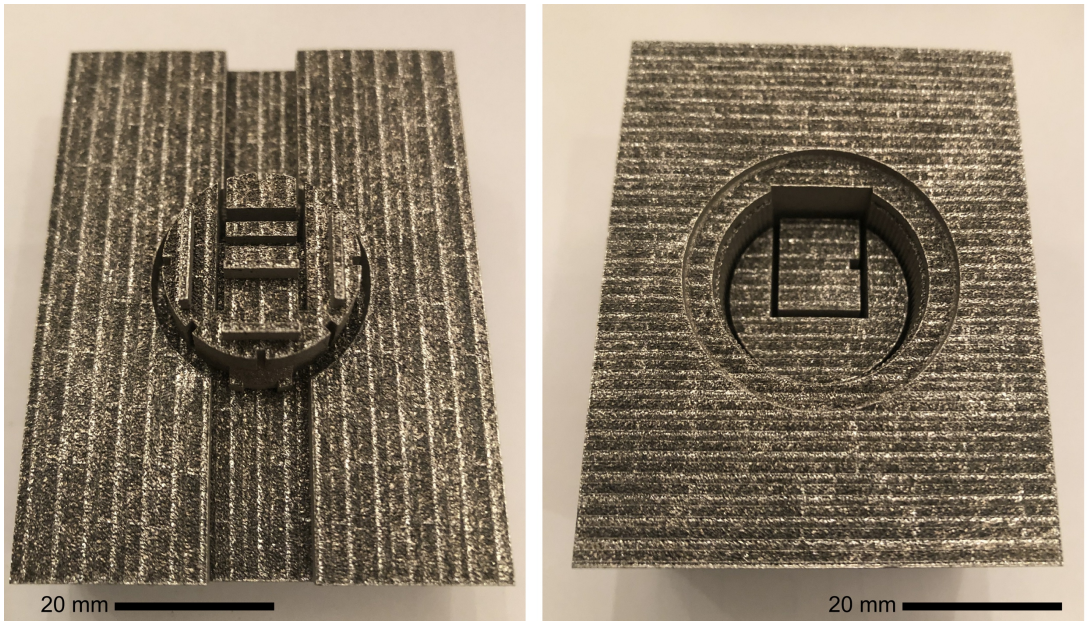


Figure 6-12: SLM fabricated core and cavity for Plug A.

6.4 Tool Insert Fabrication of Plug B

Plug B is a spare part component produced for the aftermarket automotive industry that is being assembled as part of a vehicle's lighting unit. The component was investigated and analysed to establish producing its tooling insert. The same procedure that was implemented for manufacturing the tooling inserts of plug A was adopted for producing the tool inserts of plug B. SLM was the adopted fabrication technique for AM while CNC milling, wire EDM, and die-sink EDM were the main methods of manufacturing.

6.4.1 Subtractive manufacturing

Due to the complexity of the tool insert's geometry, it was necessary to use different approaches to design to eliminate limitations in the execution process of manufacturing the parts. The CAD design involved in the subtractive manufacturing varies from the SLM tool insert's CAD design. For SLM-fabrication, the core and cavity were fabricated as an undivided part. Moreover, DFSM was utilised as individual parts to assemble to construct the whole core and cavity inserts after manufacturing. The constitutions of features in the part geometry strongly affect the use of a certain manufacturing approach. Therefore, CNC machining, wire EDM, and die-sink EDM were selected. Figure 6-13 is a schematic illustration of the CAD design of the individual inserts of the core and cavity of the plug B tool insert set.

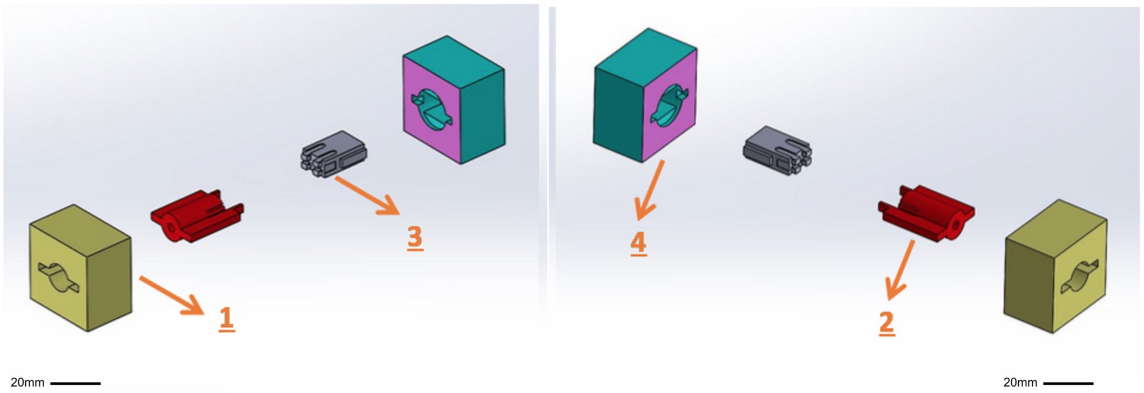


Figure 6-13: Exploded view of the individual assembled components of plug B tool insert.

The machines used for manufacturing the tool inserts were 3-axis First V 700 with maximum spindle motor power of 5.5-7.5 KW and 5,000-10,000 RPM. End mill carbide tools of shank diameters of 3, 4 and 8 mm were used respectively. An HCM-H36 die sink

EDM that provides 50 Ampere and the wire EDM machine used was an Accute X-500i with power of 50-60 HZ and wire diameter range of 0.15-0.33 mm.

The four components of plug B tool insert shown in Figure 6-13 employed multiple operations to manufacture the individual parts. In some instances, more than one operational technique was used to produce a single component. Each component was manufactured using a different set of manufacturing techniques. Component 1 required four manufacturing processes to produce the part. The first of the four processes was milling the part to its external shape and then fabricate the cutting electrodes that will be subsequently used in the die sink process. The third process is wire EDM to create the internal shape of the component. The last process was die-sink EDM to develop the sharp-edged features of the component. Component 2 was manufactured using wire EDM and die-sink EDM to create the sharp-edged corners of the component and the fine through-hole that runs in the middle of the component. Cutting electrodes were manufactured using CNC milling to provide the necessary features of the component. Component 3 is similar to component 2 in the sequence of operations executed and the nature of the processing techniques. First wire EDM process is executed, followed by CNC machining of the cutting electrodes to use them for the die-sink EDM process. Finally, the last component (component 4) requires the use of CNC milling to develop the external shape of the component and to create the sharp-edged corners of the external pockets. The internal features were initially processed using CNC milling and further machined using wire EDM. Figure 6-14 is an illustration of all the components assembled and mounted on the bolster for plug B tool insert.

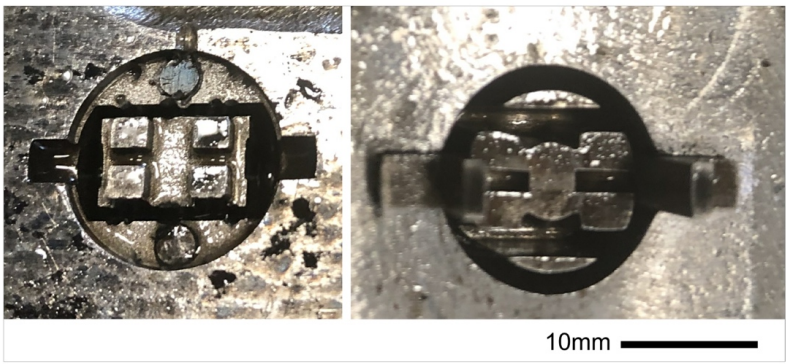


Figure 6-14: Assembled tool insert of plug B.

6.4.2 SLM fabrication

The maximum part dimensions for each core and cavity were 30mm x 30mm x 40mm with given consideration to shrinkage allowance of 1.5% of the injected polypropylene. After the parts were fabricated, post-processing technique in the form of tumbling was used to remove the excess powder after the fabrication process. Figure 6-15 demonstrates the SLM fabricated tool insert core and cavity for plug B.

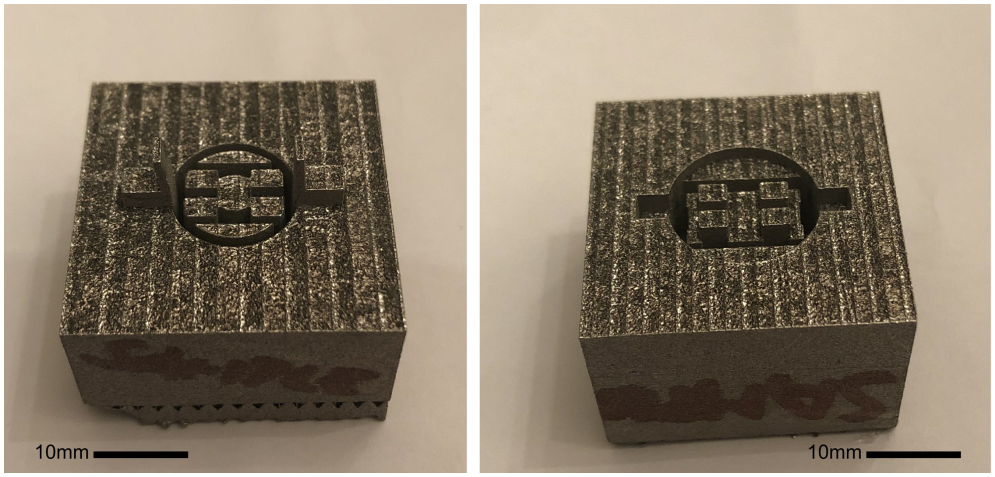


Figure 6-15: SLM fabricated core and cavity for plug B.

6.5 Tool Insert Fabrication of Plug C

Plug C is the third spare part component produced for the aftermarket automotive industry that is a part of a vehicle's lighting unit. Due to the complexity and the size of the part, it has been investigated to produce its tooling insert. In the same sense, the study has been executed as per the previous studies. The tool inserts were manufactured using SLM and as for the subtractive methods of manufacturing the tool insert was manufactured using CNC milling, wire EDM, and die-sink EDM.

6.5.1 Subtractive manufacturing

The small geometry of the part features hinders the use of certain manufacturing techniques. For subtractive manufacturing, for each of the core and cavity inserts designers were forced to modify the inserts into subassemblies that are later assembled to comprise the whole of the core and cavity inserts. Relying on the geometrical features of the part, dimensions, and level of complexity CNC machining, wire EDM, or die-sink EDM is selected. For AM, the core and cavity inserts were manufactured as whole parts

with no need for assembly. Therefore, the CAD design used for execution on the SLM machine differs from the one used for the subtractive manufacturing methods. Figure 6-16 Is a schematic illustration of the CAD design of the individual inserts of the core and cavity of the plug C tool insert set.

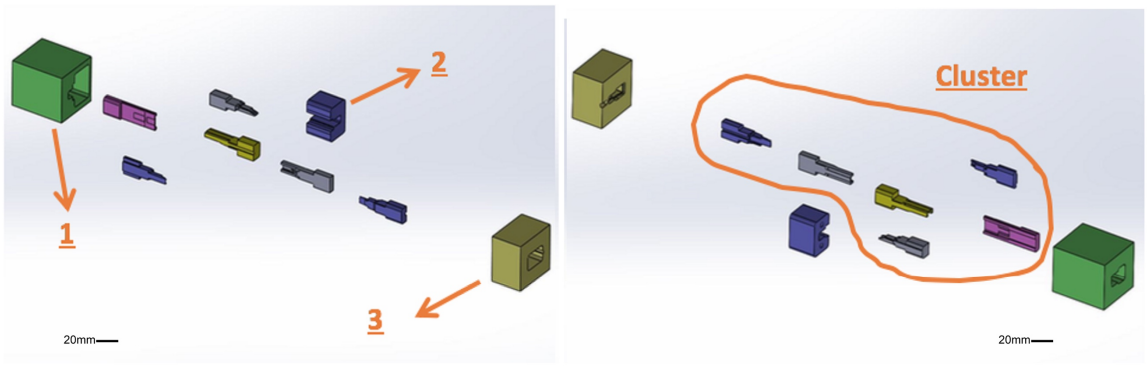


Figure 6-16: Exploded view of individual components of plug C tool insert.

The machines used were 3-axis First V 700 with maximum spindle motor power of 5.5-7.5 KW and 10,000 RPM. The cutting tools used for the milling process were end mill carbide tools of shank diameters of 2, 3, and 4 mm. An HCM-H36 die-sink EDM that provides 50 Ampere and the wire EDM machine used was an Accute X-500i with power of 50-60 HZ and wire diameter range of 0.15-0.33 mm.

The tool insert for plug C was separated to multiple individual components to facilitate the manufacturing process of the tool insert as shown in Figure 6-16. Component 1 was initially CNC machined using a milling process, further processing of the internal features of the components were executed using wire EDM process to create the sharp-edged corners of the internal pocket. Component 2 required only one processing method of wire EDM to create the sharp-edged corners on the open pocket feature. As for component 3, it was machined using a milling process to develop the external features as well as creating cutting electrodes that were used later in the die-sink EDM process to create the sharp-edged corners and the fine fillet radii. The rest of the components referred to as the cluster in Figure 6-17 were all processed in a similar mode. All six components were wire cut using wire EDM, cutting electrodes were CNC machined and subsequently used in the die-sink EDM process to create the sharp-edged features of the various internal and external pockets on the surface of the components. Figure 6-17 shows the tool insert of plug C after assembly and mounting of the core and cavity.

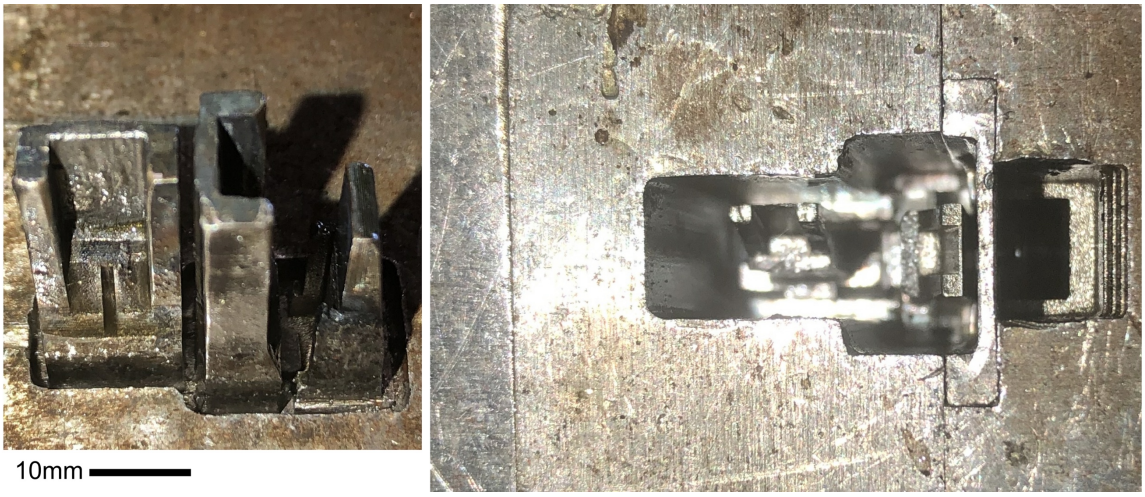


Figure 6-17: Assembly of core and cavity of plug C tool insert.

6.5.2 SLM fabrication

The maximum part dimensions were 40mm x 40mm x 72.5mm and scaling the parts in the CAD model was necessary to compensate for allowances caused by shrinkage during cooling of the injected products. After the fabrication process, the core and cavity were post processed using tumbling to remove the excess powder. Figure 6-18 shows the SLM fabricated tool insert core and cavity for plug C.

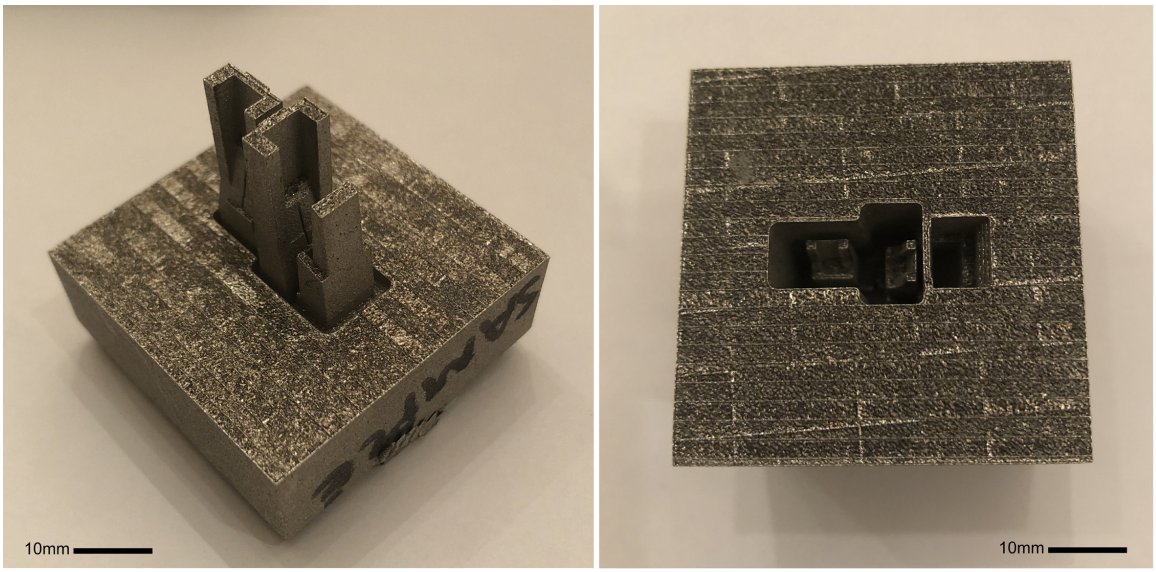


Figure 6-18: SLM fabricated core and cavity of plug C.

6.6 Summary

Plug A, B and C studies provided this research with a perception on how the same tool insert can be developed with a differential point of view during the design stage. It was proven that the approach adopted when applying DFSM rules was contradictory to that of DFAM. However, DFAM was generated after the DFSM was accomplished. First, for both the core and cavity, each separate component was created individually as a solid part and those parts are grouped and assembled to create the core or cavity insert. For DFSM, the parts are defined separately, as for DFAM the part is viewed as a whole entity that cannot be separated. When the geometrical complexities in design of DFSM and DFAM were taken into account, the distinguishing areas were shown to be highly complex. In this way, it is possible to identify the advantageous points for each design approach. Incorporating the combined approaches of additive and subtractive technologies is capable of providing a valuable insight that can improve manufacturability. In a proposed hybrid approach, the inserts are perceived as geometrical features that are analysed according to their complexity level, and the best manufacturing process is selected for each area.

As shown from the three studies of the tool insert plugs, it is proven that integrating additive and subtractive technologies (SLM, CNC machining, turning, die sink and wire EDM) promises to overcome limitations, providing solutions to existing manufacturing issues of the respective methods of manufacturing. Th freedom of design presented by SLM allows for the production of parts with high complexity, internal features, and hard to reach features. The possibility of achieving those features is attainable despite whether a subtractive method is also employed. However, as seen in the plug studies, the SLM-fabricated parts required further post-processing following the fabrication process even though tumbling was completed. The fabricated tool inserts required further polishing and finishing to attain the desired surface finish that is expected to avoid any consequences that might hinder the production process. On the other hand, the employed subtractive methods of manufacturing were able to produce components with high surface finish and dimensional accuracy, but each insert had to be separated into multiple components and each component required multiple processing techniques. In addition to that, highly skilled personnel is a requirement when dealing with subtractive manufacturing, as well as limitations to tool accessibility is still relatively challenging to

accomplish complex geometries, such as internal structures, undercuts, and sharp-edged features. Therefore, as a result integrating additive and subtractive manufacturing technologies in a consecutive or simultaneous approach is considered a likely solution that consolidates the benefit and reduce the limitations faced by each technology independently.

Therefore, it is noted that proposing a manufacturability feature assessment system aims to benefit from the advantages of each of the SLM and subtractive methods of manufacturing. By applying such a system, the areas on the tool inserts that hold the most geometrical complexities to manufacture are focused on while defining design limitations of each manufacturing method. Therefore, a feature-based system was developed to evaluate the geometrical features of tool inserts to assist designers in selecting the most suitable manufacturing methodology whether SLM or subtractive manufacturing.

7 Developing a Feature-Based Manufacturability Assessment System (FBMAS)

It is essential to obtain a detailed insight to the tool insert and recognise limitations and complexities at the design stage in order to decide on prospective manufacturing techniques that could or should be deployed. In this chapter, the development of a feature-based manufacturability assessment system (FBMAS) is presented to demonstrate the feasibility of integrating SLM technology with subtractive manufacturing for any given part. The chapter commences by describing the design features that the FBMAS was focused on and thereby defining them. Subsequently, a general overview is outlined for the system's specification and identifying the objectives and limitations of the system. The chapter completes by describing the structural approach used for developing the FBMAS Graphical user interface (GUI) and explaining how this can be operated effectively by the user.

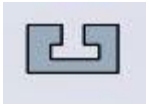
7.1 Defining Design Features

Design and manufacturing are the key considerations for developing a product and recently, combining additive and subtractive technologies has gained attention. In the design process, design rules are set and defined to take account of manufacturing constraints.

Different definitions have been recommended by previous research for machining features with different viewpoints. Başak and Gülesin (2004) reviewed earlier studies that concluding that a feature-based design involves defining all the necessary information in a database regarding part geometry, surface topology, dimensioning and tolerances. Other studies considered a feature used in CAD as a geometric shape, and based on the type of application it can be defined as geometric, manufacturing or an assembly feature. Sormaz and Khoshnevis (2000) defined that a machining feature is a volumetric feature that is machinable in a single operation and expressed concerns due to restricting the definition to removal of material volume. Wang (2015) proposed a machining feature definition that entails surface features, geometrical features, and volumetric features. Givehchi *et al* (2015) added to the definition the state of the feature boundary representation. Finally, Le *et al* (2017) adopted the definition that describes a machining

feature as a geometrical shape with a set of specifications that can be acknowledged by at least one machining process. Zhang *et al* (2016) proposed a definition of AM features in the same manner as machining features for which at least one AM process is known. The definition is based on the characterisation of AM processes that has an impact on build orientation and PBF in particular which can manifest important effects on surface roughness and mechanical properties. Therefore, in this work, manufacturing feature definition is adopted from the work of Le *et al* (2018) and refers to both AM and machining features. For the purposes of this research, design features with relevance to the scope of work for additive and subtractive manufacturing technologies were defined and are presented in Table 7-1 ('Solidworks Essential Manual', 2012; LaCourse, 2017; Thornton, 2017).

Table 7-1: Feature definitions and illustrations.

Design-Feature	Illustration	Definition
Hole		A hole feature originates from a rounded profile. Hole types include 'through', 'blind' and 'tapered'.
Slot		A slot is a perimeter that has a constant centerline and width. Slot types include 'blind' that are contoured with two ends and 'through' that pass completely through the part.
Pocket		A pocket is a feature with an open or a closed perimeter often called an open pocket or a closed pocket. Pocket types include 'through' and 'blind'.
Boss-Extrude		A boss-extrude feature adds to the area of the surface through extrudes above the planar surface.
Freeform-Pattern		Any feature that has multiples that can be grouped together to create a pattern design. They can be machined as individual features or as a pattern.
Fillet		Fillets are rounded corners. A curve created at the intersection of two or more faces.
Sharp-Edge		A sharp edge on the external side of a body.
Undercut		An undercut refers to a feature that is described as a non-visible recessed surface that is inaccessible using a straight tool.
Tapping		Tapping is responsible for creating screw threads in a hole.
Negative draft		In a part viewed from a plan view, the side walls are tapered towards the bottom; the internal dimension at the bottom will have a larger dimension compared to the top.

This aspect of the research focuses on developing a FBMAS that recommends to the users the most appropriate and advantageous manufacturing technique, be that SLM, subtractive manufacturing or the integration of both based on a set of design rules. This system could provide valuable insight for combining additive and subtractive processes.

7.2 System Development

Knowledge based expert systems (KBS) or expert systems as sometimes referred to, are interactive systems that require expertise knowledge. KBS are computer systems that are capable of imitating intelligent human behavior in problem solving (Kumar, 2018). Complex problems in expert systems are solved with minimal help from experts. The knowledge of an expert system is accumulated through the collective input of experience and expertise from numerous individual experts. Therefore, the collective experience of experts provides users with valued decision recommendations that can assist them in the decision-making processes. Expert systems are considered as one type of KBS that denotes information in the form of If-Then statements until a certain conclusion is reached (Chen *et al.*, 2012). Başak and Gülesin (2004). stated that previous research determined that expert systems enhance quality and productivity and decrease costs. Furthermore, it is understandable that these types of systems are formulated in a step-by-step structure, where the user is led through the sequence of steps to reach a certain decision, while also comprehending how the decision has been made.

Therefore, as part of this research the purpose was to develop a knowledge-based system. That system contains expert data regarding the selection process that provides the user with decision-making recommendations for manufacturing an injection moulding tool insert for the aftermarket automotive sector.

The core structure of the FBMAS is demonstrated in Figure 7-1. During the design stage, the designer is free to explore different “design for manufacturing” approaches, DFSM, and DFAM given that access to the manufacturing systems is available. Therefore, the first step after the CAD design of a tool insert is developed, is for the designer to analyse the manufacturability of the tool inserts CAD model. The main features that critically affect the decision for part manufacturability were identified in section 7.1 of this chapter.

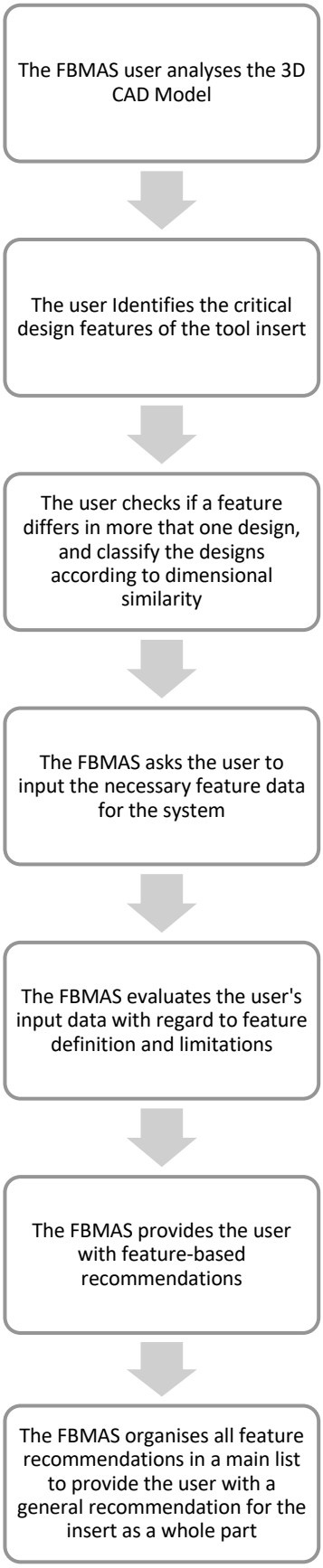


Figure 7-1: General framework of the FBMAS system structure.

When developing the FBMAS, the following specifications and limitations were considered before developing the Graphical user interface (GUI).

7.2.1 Recognising system specifications and limitations

The following are the targeted system specifications:

- Applying the feature-based system to assist users in defining and evaluating manufacturability limitations of a given tool insert based on a set of predetermined feature criteria;
- The system is feature-based, evaluating the tool insert as multiple features and providing recommendations according to rules in "IF-THEN" format that are constructed in the knowledge base. The "IF" part includes the condition clauses and the "THEN" part includes the resulting sentences;
- Feature specifications of diameter to length ratios are derived from SECO (2019a) and SECO (2019b) and shown in Appendix D and Appendix E;
- The separate feature recommendations are processed to provide the user with a generic part recommendation;
- The system is interactive in assisting the user to assess the feature-based manufacturability limitations and provide recommendations for which manufacturing technique to use.

The main limitations set for the developed feature-based system were:

- The technologies that the FBMAS can only be applied (i.e. will be limited) to are SLM for additive manufacturing, CNC machining, die sink EDM, and wire EDM for subtractive manufacturing;
- The rules set for the system were constructed on the basis of individualisation of features, with overlapping features being outside the scope of this research;
- The maximum part size allowed for this system is associated with the maximum volume of commercially acknowledged SLM machine systems (SLM Solutions, 2017), 500 mm, 280 mm, and 850 mm respectively. Build platform wall allowance is understood based on technical user experience.

- The identified critical features for this study are limited to hole, slot, pocket, boss-extrude and freeform pattern;
- The maximum number of different design groups of a feature allowed for this system is five designs. This rule applies to each of the features individually.
- Economic cost factors are omitted in this research. For example, SLM is a technology that is scarcely found in Egypt (where the application of this research has been focused) either in academic or for industrial use. All SLM parts developed for this research were manufactured in the UK and all CNC machined parts were manufactured in Egypt. Therefore, cost association and direct comparison is unreliable in this case.

7.2.2 Graphical User Interface

The FBMAS architecture is a fixed-inflexible system that can only provide the user with what the developer has predetermined for the system. The system was developed using Matlab (MathWorks, Matlab academic version R2017a). The logic of the system is comprised of fixed rules that define the design constraints provided by human experts. The programming code is shown in Appendix F. Those design rules are set for SLM and the subtractive manufacturing methods as focused by the FBMAS and outlined in a flowchart shown in Appendix G. Figure 7-2 provides a schematic illustration of the FBMAS overall structure.

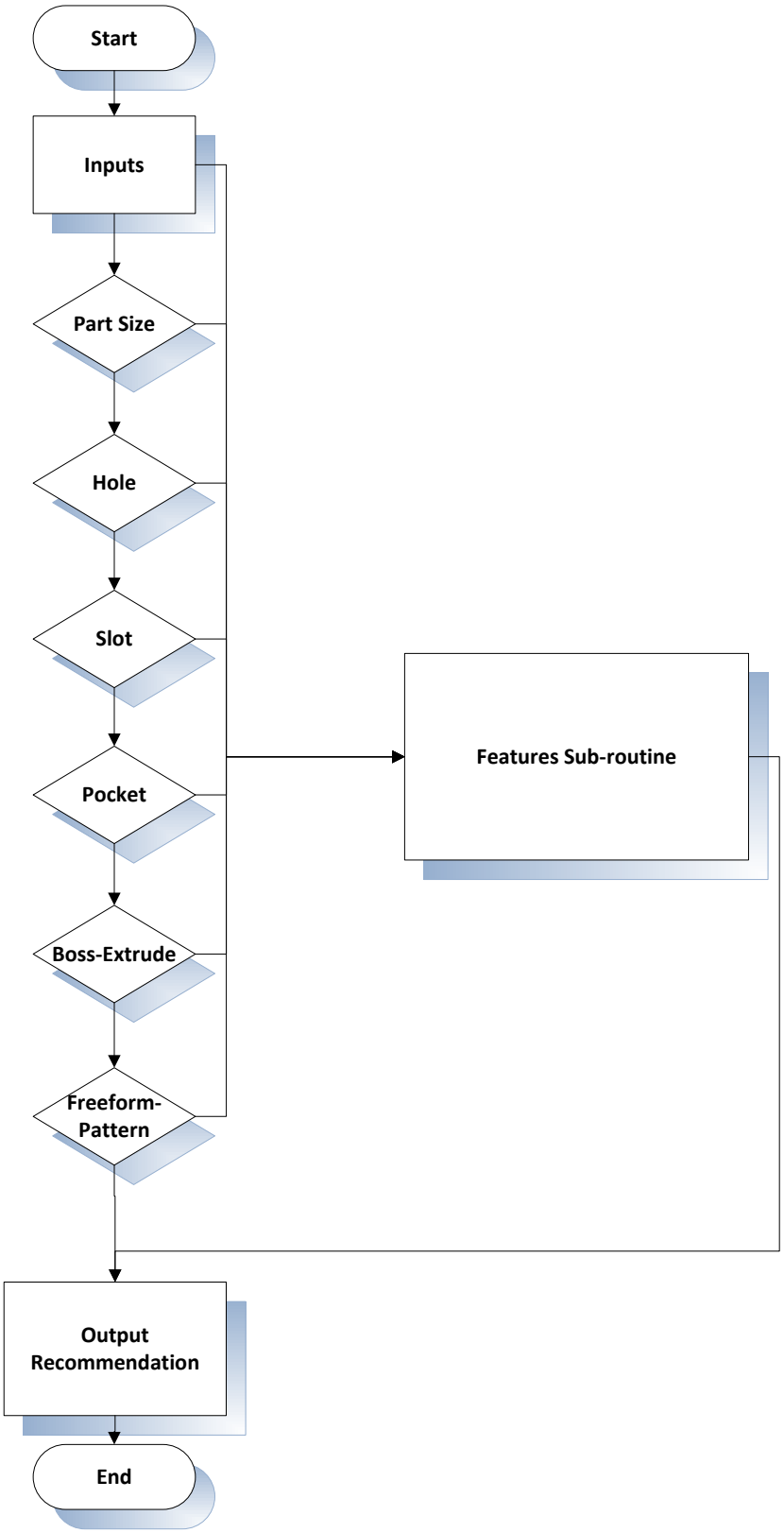


Figure 7-2: Schematic diagram of the FBMAS broad structure.

The user is required to input the necessary information for each feature in the form of queries in the GUI for the different defined feature designs. The system then formulates the information and returns an output to the user with the decision-recommendation for each feature design. After all identified features are assessed, the FBMAS displays a list of the individual feature decision recommendations and the overall recommendation for part manufacturing. Figure 7-3 displays a graphical illustration of the FBMAS from the initialisation stage to displaying of recommendations.

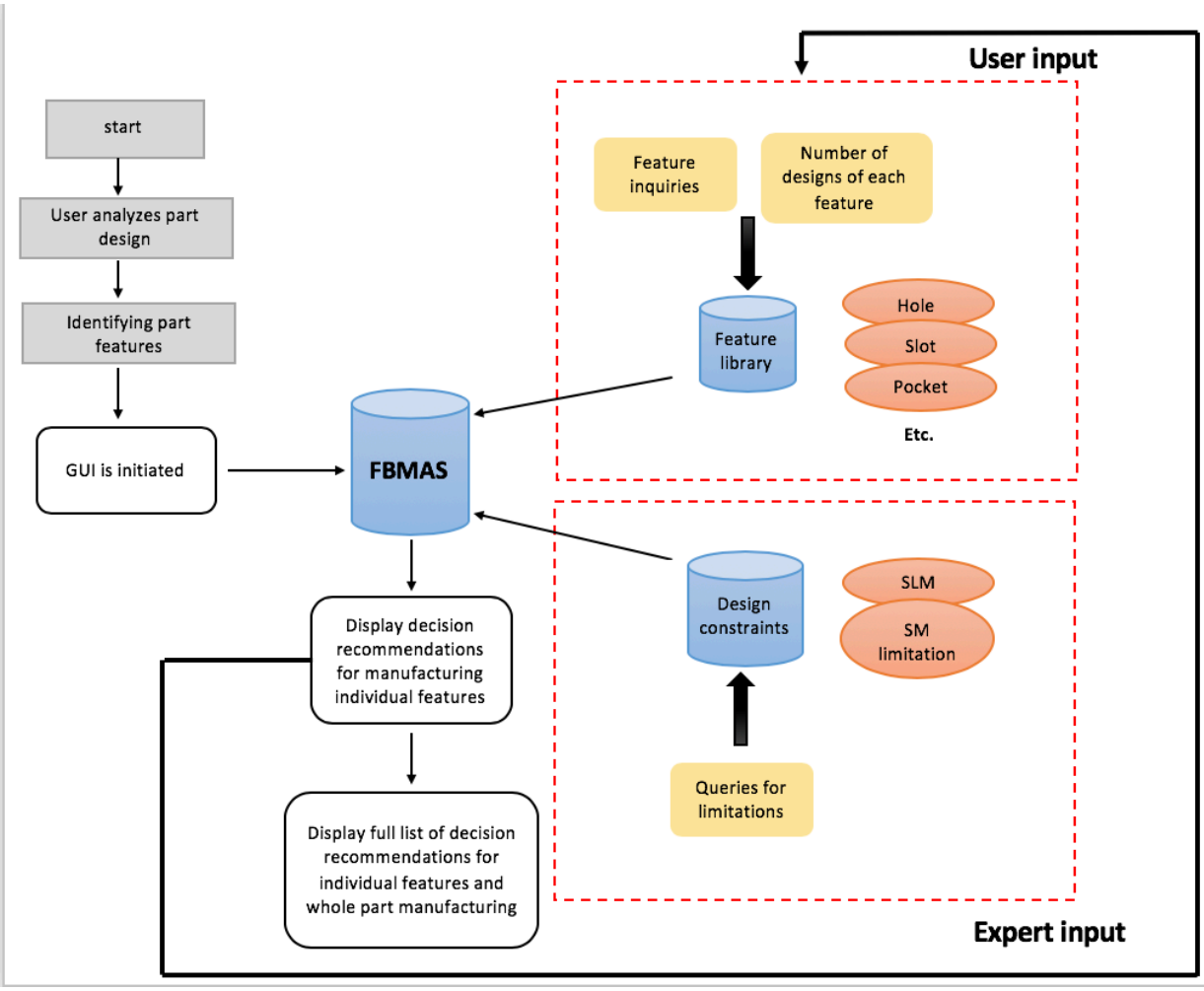


Figure 7-3: Graphical illustration of the FBMAS from initialisation stage to displaying of recommendations.

(i) FBMAS initialisation

Figure 7-4 illustrates the primary screen that appears to the user when the FBMAS is initialised. In the first screen, there are two main panels and the user is requested to input the necessary information for all fields in the three panels.

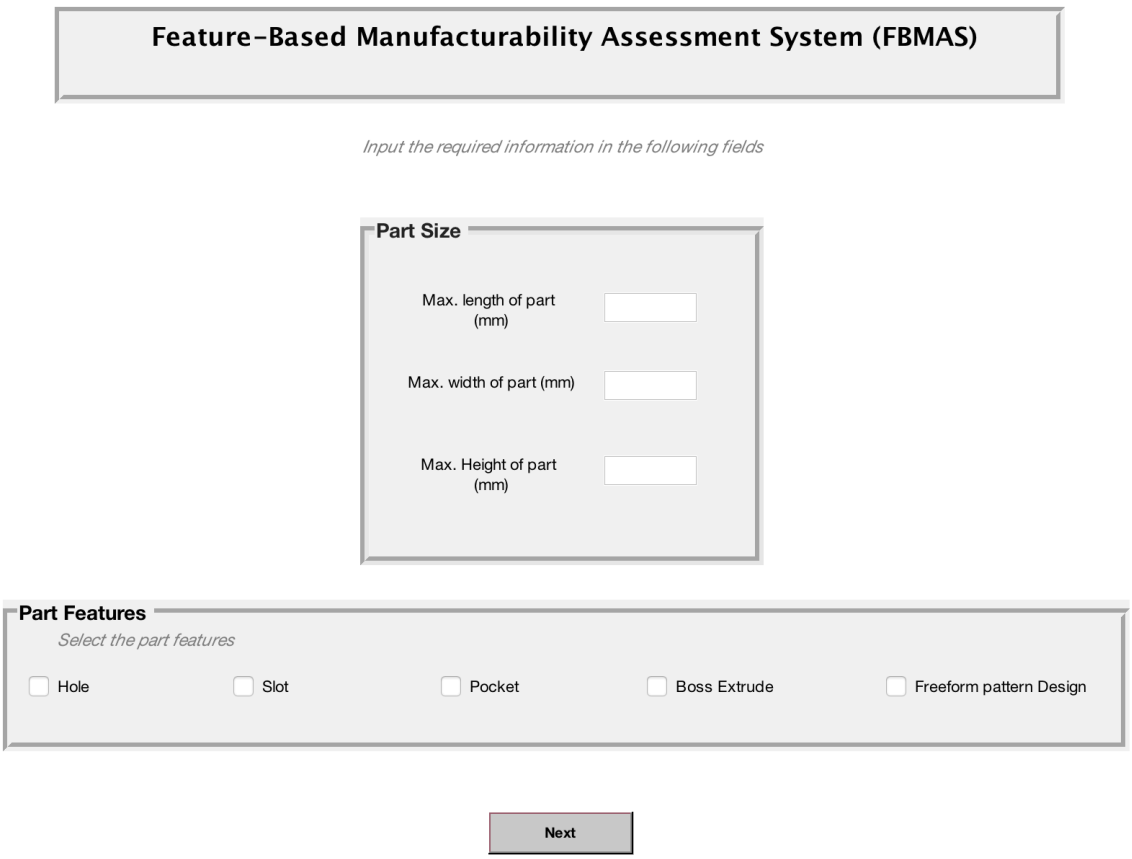


Figure 7-4: Initial screen of the FBMAS.

The first panel comprises inquiries about the main part sizes. The maximum part length, width, and height were set at 500 mm, 280 mm and 850 mm respectively. The maximum part dimensions specified in this research were based on the maximum featured commercial SLM system in the market that is capable of efficiently producing large volumetric sized metal parts. The user must enter values for the three dimensions as shown in the codes of Figure 7-5. Variable “aa” is defined for part length, variable “cc” for part width, and variable “dd” is defined for part height.

```
aa = str2num(char(get(handles.edit1,'String')));
cc = str2num(char(get(handles.edit2,'String')));
dd = str2num(char(get(handles.edit5,'String')));

if isempty(aa)==1 || aa<1
    msgbox('Input part length!')
elseif isempty(cc)==1 || cc<1
    msgbox('Input part width!')
elseif isempty(dd)==1 || dd<1
    msgbox('Input part height')
end
```

Figure 7-5: Size constraint.

Depending on the rules and the constraints set for the maximum part size, the returned queries will be checked with the design constraints as shown in the system logic in Figure 7-6. A decision recommendation will be fed to the designer for the insert to be manufactured using subtractive technologies in the occasion that the insert cannot be separated into smaller modules. If the insert design can be separated into individual modules, the user is recommended to separate the part into modules before any further evaluation is conducted. After the recommendation message is displayed the system terminates and each evaluated module is treated as a separate entity.

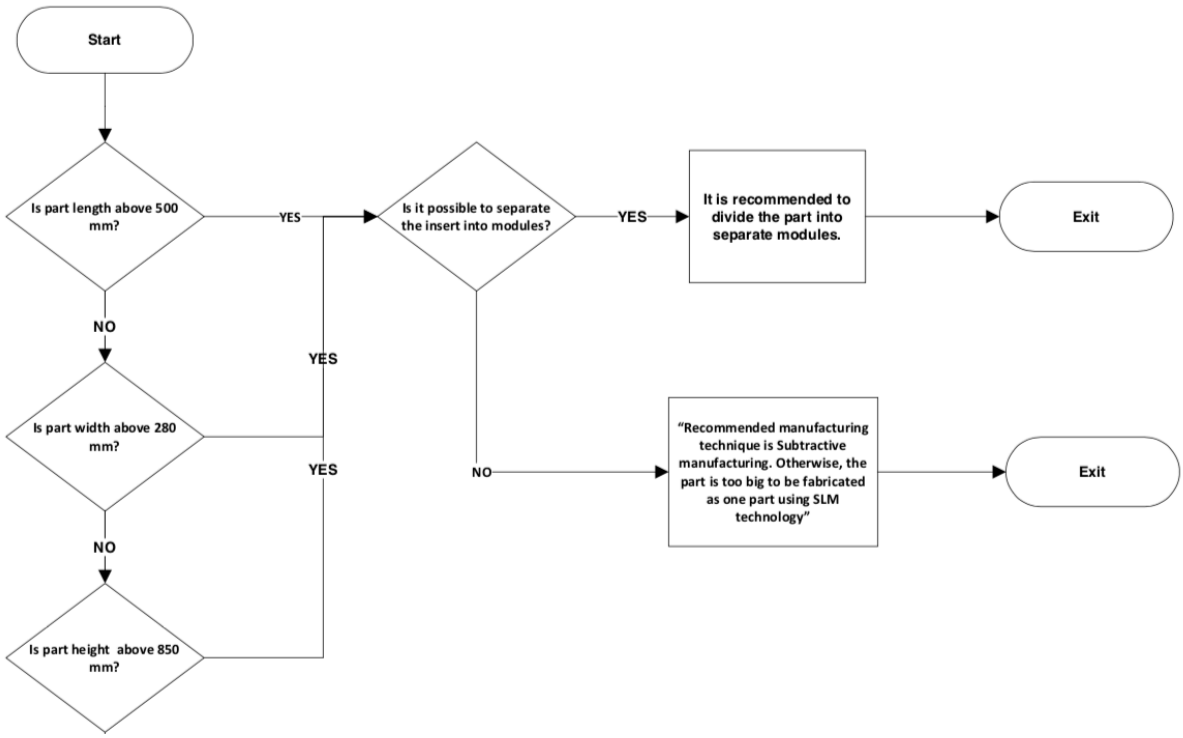


Figure 7-6: Size constraints flowchart.

As for the second panel, the user is obligated to specify the features that are identified for the given insert. After the features are selected, the designated feature screens are activated for the user. At this stage, pushing the next button activates the system to screen the constraints and in case one of the constraints is met, the user is provided with a valid recommendation on how the insert should be manufactured. Otherwise, the next button activates the subsequent screens relying on the features selected from the second panel.

(ii) Hole feature

In the likely event of a hole feature being selected, the user is approached with multiple inquiries. First, in a separate page the user is prompted to input the number of different hole designs as shown in Figure 7-7. The maximum number of a given group of feature designs allowed for this system is five. For example, the maximum number of different design groups for a hole feature is five as shown by the codes in Figure 7-8 where global variable “number” is defined as the number of design groups, the same rule applies to all features of the FBMAS.

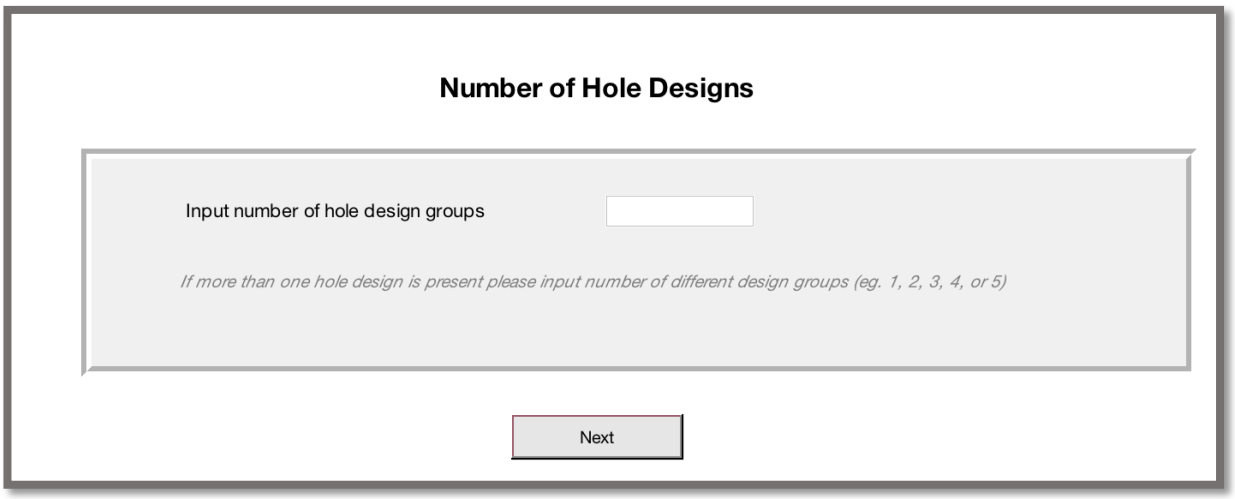


Figure 7-7: The user is prompted to enter the number of hole design groups.

```
h1=isempty(number);
if number<=0
    msgbox('Please input the number of designs!')
    elseif h1==1
    msgbox('Please input the number of designs!')
elseif number>5
    msgbox('Input a valid number of designs!')
end
```

Figure 7-8: Number of design group constraint.

After the user inputs the number of hole designs, they are driven through a sequence of questions to identify the feature's criteria and limitations. Those limitations are gauged through a set of logical rules that have an impact on the choice of manufacturing technology. The resulting recommendation decision for the hole feature page is saved, to be displayed in the recommendation list page. The recommendation list page is displayed at the end of the system after all the features of the insert are evaluated. If the user identified that there is more than one hole design, then the system is prompted to open the same number of design pages as specified by the user. Figure 7-9 displays the hole feature design page that appears to the user when a hole feature is selected in the initial page.

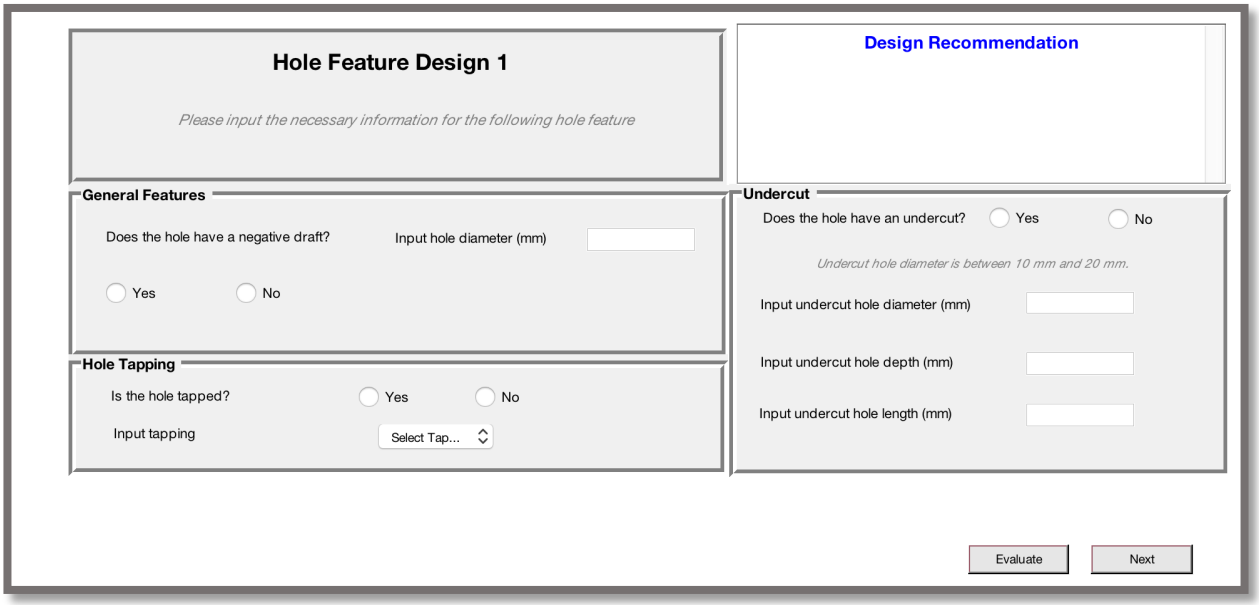


Figure 7-9: Hole feature main page displayed for the FBMAS.

A set of questions are listed in the page and the user has to provide an answer to each question. The questions generated are the result of the compiled design information obtained from inquiries and investigations done with experts in the automotive industry. First, the user is questioned to determine whether the hole has a negative draft. Therefore, if the user identifies that there is in fact a negative draft, a decision recommendation is displayed for the hole feature. Figure 7-10 illustrates the negative draft logic which the user is guided through for the hole feature.

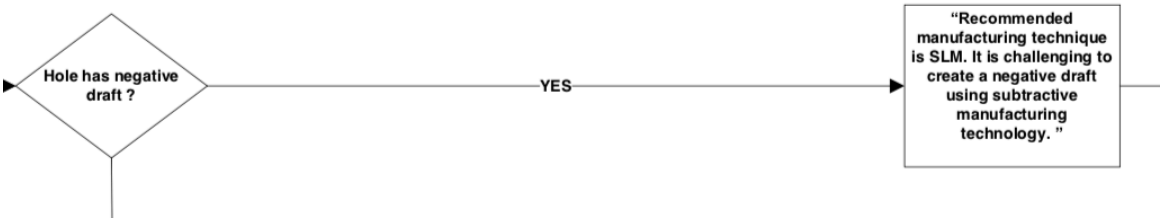


Figure 7-10: Hole negative draft logic.

At this point, evaluating the rest of the feature criteria after a decision recommendation is made is unnecessary, because the outcome from the evaluation dominates any other outcome that will follow. If the user acknowledges this feature criterion, then a decision recommendation is displayed to indicate that a negative draft is not achievable using any subtractive method of manufacturing. Figure 7-11 is an example of the decision recommendation displayed.

Figure 7-11: Example of a displayed design feature recommendation.

However, if the above-mentioned feature criterion is not present, then the logical flow of the system continues to evaluate the rest of the feature criteria. Further on, the user is required to answer a set of questions that inquire whether there is an undercut feature or not; if the user agrees that there is in fact an undercut feature, more questions have to be answered. First the user is required to input the undercut hole diameter, followed by the

undercut depth, and finally the length of the undercut feature as shown in .Figure 7-12 Where, variable “c” is defined as the hole diameter in which an undercut feature exists, variable “a” is hole depth, and variable “e” hole length.

```
elseif get(handles.radiobutton21,'Value')~=0
    if isempty(c)==1 || c<10
        msgbox('Input a valid undercut hole diameter!')
    elseif isempty(a)==1 || a<1
        msgbox('Input a valid undercut hole depth!')
    elseif isempty(e)==1 || e<1
        msgbox('Input a valid undercut hole length!')
```

Figure 7-12: Input undercut hole dimensions.

Certain design limitations must be taken into account; for this, FBMAS design rules for SLM and subtractive technologies were the founding base for the selection system. It was found that the minimum diameter that SLM technology can accomplish for an open feature is 1 mm (EPMA, 2013; Diegel *et al*, 2017; Renishaw plc, 2017). For subtractive technology, design guidelines were acquired and validated through experts in the automotive industry for the production of injection moulding tool inserts (Drake Jr., 1999; Henzold, 2006). To create an undercut feature requires the use of a t-slot cutting tool with specific diameters as shown in Figure 7-13. The minimum hole diameter recommended is 10 mm or greater to correspond with the minimum diameter of the cutter. The maximum hole diameter is 20 mm, otherwise it will be considered a pocket. If the user inputs a value less than 10 mm or above 20 mm a message will appear to direct them to input a valid undercut hole diameter. The length L of undercut varies relying on the diameter to length ratio that corresponds with the minimum permissible length of the t-slot cutting tool. The depth of undercut is derived from Equation 4, Where Dc is the derived diameter from the cutter diameter. And Dm is the derived diameter from the tool shank diameter.

Equation 4: Undercut depth

$$Undercut\ depth = \frac{(Dc - Dm)}{2}$$

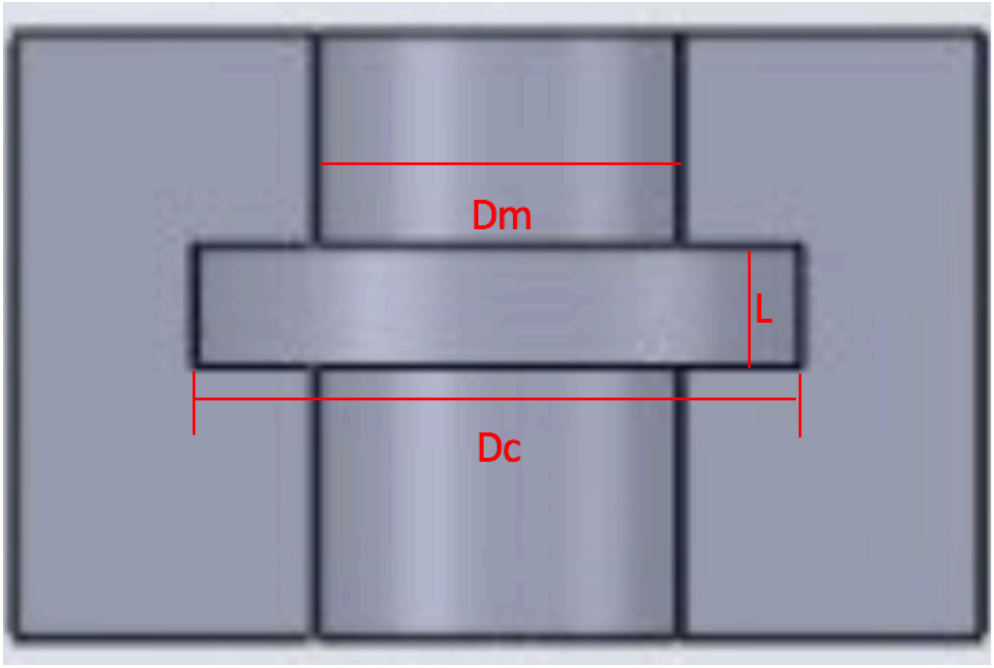


Figure 7-13: Illustrative undercut diagram for a hole feature.

Therefore, if the user assumes that there is an undercut feature and the required information is entered, then the system proceeds to analyse and assess the design rules that are defined for the undercut feature. Furthermore, a decision recommendation is displayed for the user identifying the proper manufacturing technology to seek. Figure 7-14 illustrates a section of the undercut logical questions.

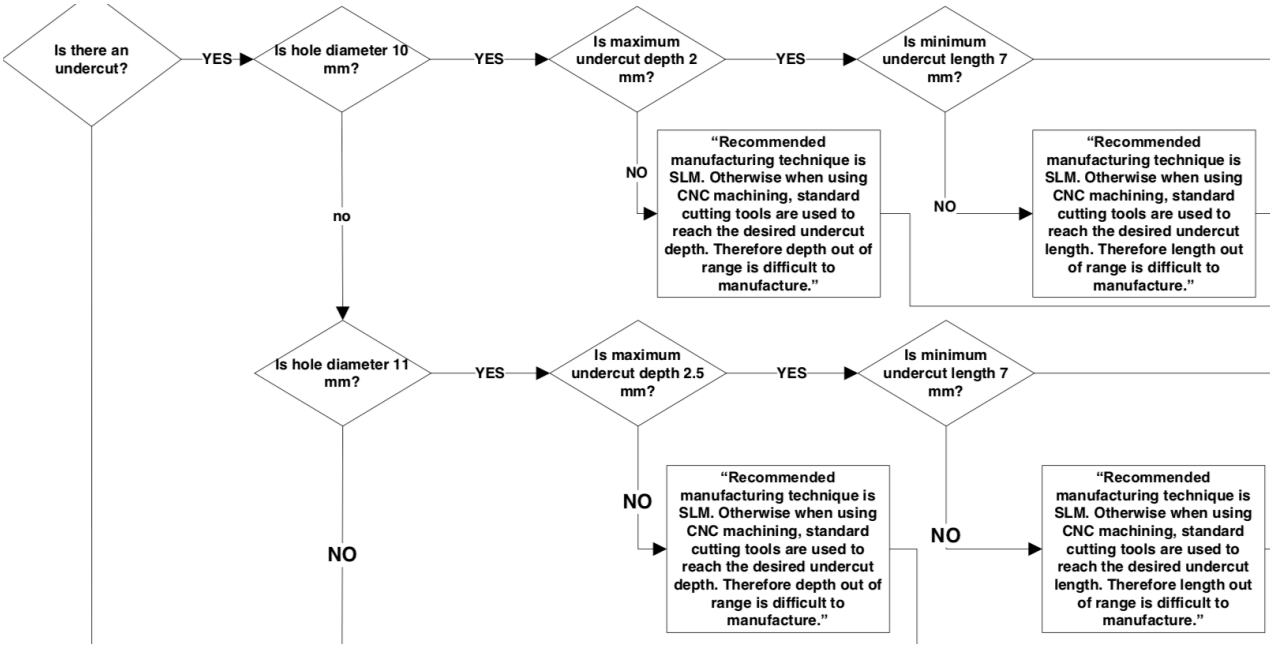


Figure 7-14: Undercut logical guidelines.

The system proceeds to enquire about other hole feature limitations. If no undercut is detected, the user is queried for the existence of hole tapping. If the user affirms, the following question examines the tapping size as shown in Figure 7-15 and Figure 7-16. According to the user's response, a decision recommendation is displayed if a limitation is detected, otherwise the system resumes to enquire about additional limitations.

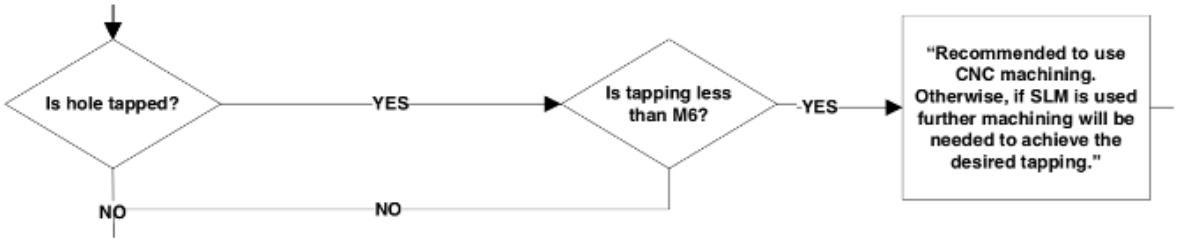


Figure 7-15: Hole Tapping logic.

```
contents=get(handles.popupmenu9,'String')
popupmenu9value=contents{get(handles.popupmenu9,'Value')}
switch popupmenu9value
    case 'Select Tapping'
        msgbox('Select tapping!')
    case 'M2'
```

Figure 7-16: Tapping code.

At this point, if none of the previous hole features presented a defined limitation, the decision system proceeds to enquire about the hole diameter. As mentioned in 7.2.2 (ii), the minimum open feature diameter that can be accomplished by SLM technology is 1 mm. However, for subtractive manufacturing hole diameter and depth are associated with the cutting tool dimensions, therefore, it is important to signify the ratio of hole diameter to depth as a design limitation. Hole diameter ranges are illustrated in Figure 7-17 with the corresponding ratios to hole depth. The minimum permissible hole diameter is 1 mm and the maximum is 20 mm. if the user enters a value outside the permissible range, a message

appears to alert the user to input a valid hole diameter. If hole diameter exceeds 20 mm, a message is displayed for the user to refer to the pocket feature.

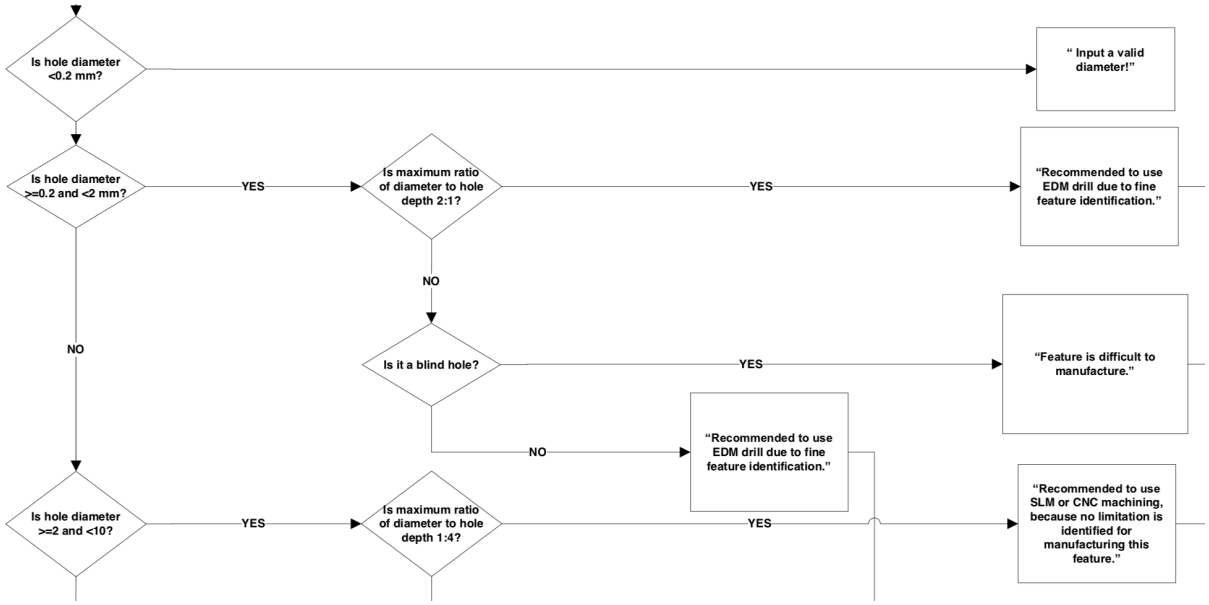


Figure 7-17: Logical guidelines for hole diameter.

The user is required to enter the hole diameter and the FBMAS system is responsible for assessing the entered information. Figure 7-18is an example of the programming code for hole diameter between 0.2 mm and 2 mm. Depending on the value submitted for diameter, the system prompts the user to answer a question. For example, if the user enters a value of 1 mm for the hole diameter, the system proceeds to enquire whether the ratio of diameter to length is 2:1. If 'yes', a decision recommendation is displayed, but if 'no', another question appears to check if it's a blind hole. Figure 7-19 displays the prompted questions.

```
if d<0.2
    msgbox('Input a valid hole diameter!')
elseif d>=0.2 && d<2
    qqq=questdlg('Is maximum ratio of hole diameter to hole length 2:1?', ...
        'Question', ...
        'Yes','No','NO');
```

```
switch qqq
    case 'Yes'
        set(handles.edit9, 'String', 'Recommended to use EDM drill due to fine feature identification.')
    case 'No'
        qqq=questdlg('Is it a blind hole?', ...
            'Question', ...
            'Yes','No','NO');
        switch qqq
            case 'Yes'
                set(handles.edit9, 'String', 'Feature is difficult to manufacture.')
            case 'No'
                set(handles.edit9, 'String', 'Recommended to use EDM drill due to fine feature identification.')
```

Figure 7-18: An example of programming code of prompted questions.

Figure 7-19: Example of questions prompted by the system.

After the FBMAS enquiries about all the defined hole feature's limitations for each of the identified hole designs, the decision system proceeds to enquire about limitations that are detected in the subsequent design features in the same manner as the hole feature. The logical sequence in which the questions are arranged are dependent on the significance of each feature criteria to the decision-making process. The slot feature is the next in the main logical flowchart.

(iii) Slot feature

The slot feature is the next in the main logical flowchart. To initiate the slot feature design page, the user has to select that there is a slot feature in the main initialisation page. First, the user is prompted to enter the number of different slot design groups, then the slot design pages are activated. The same logic as for the hole feature is executed for the slot feature but with some variations to the design rules. Figure 7-20 displays the page that is displayed to the user when a slot feature is selected.

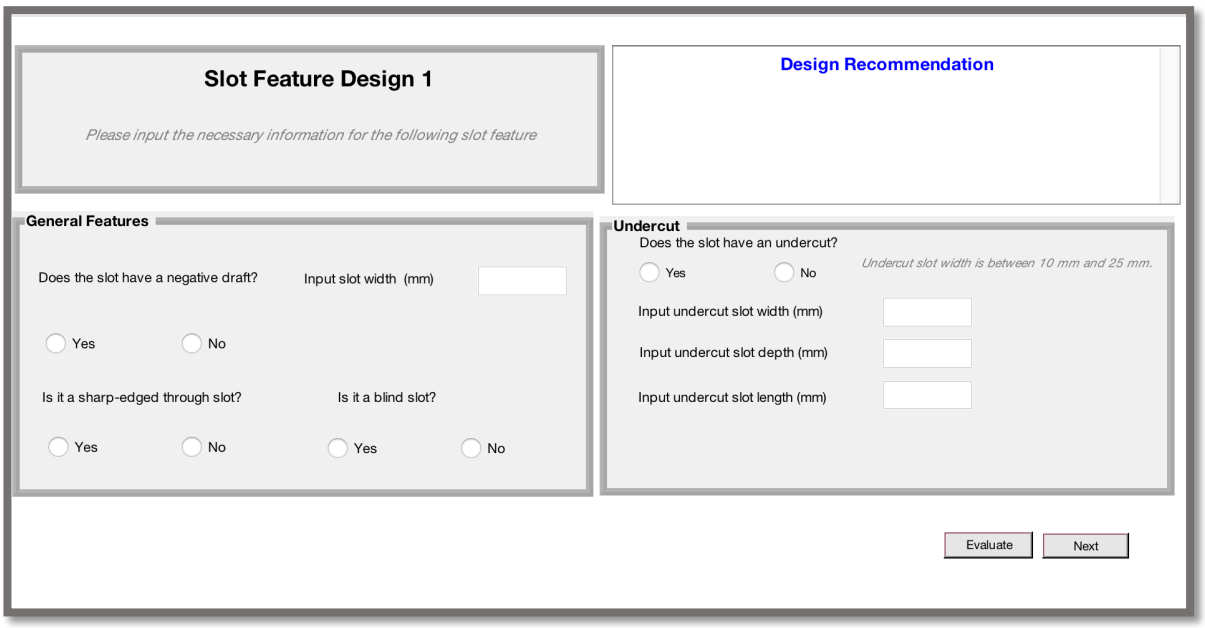


Figure 7-20: Slot feature design page displayed for the FBMAS.

The logical sequence in which the questions are arranged are dependent on the significance of each feature criteria to the decision-making process. The user is obligated to fill in all the fields of the page. The first question is a yes/no enquiry if the slot has a negative draft. A negative draft is a critical constraint for subtractive manufacturing. Therefore, if the user determines that there is in fact a negative draft then the system automatically concludes that this feature has to be fabricated using SLM technology. Moreover, if there is no negative draft the system is guided to follow the logical flowchart to detect further constraints.

During investigations for this research, it was shown that injection moulding tool inserts for automotive applications are most likely complex in design. In definition, the term complex means that multiple features are mutually integrated in one component requiring the use of multiple manufacturing methods to achieve the desired design. Referring back to the slot feature design page, the user is asked whether the slot feature has sharp-edged corners. To create a sharp-edged corner, the user can either select a SLM technology or a subtractive manufacturing approach. To establish which subtractive manufacturing approach to use, the user has to determine whether the slot is through or blind. In all circumstances CNC machining is not possible to create a sharp-edged corner, therefore EDM methods are attempted. Depending on the type of slot, for example if it is through, then wire EDM is recommended, otherwise if the slot is blind, conventional die-sink EDM is recommended.

Consecutively, the system is guided to question the presence of an undercut in the slot feature. In the event that there is in fact an undercut feature, the user is obligated to input the undercut slot diameter, undercut depth, and finally the length of the undercut feature. As defined previously in the hole feature, certain design limitations must be taken into account. The slot feature follows the same design rules as the hole feature design. Moreover, the maximum undercut slot diameter is 25 mm, otherwise the user is advised to refer to the pocket feature. Figure 7-21 presents the undercut panel in the slot feature design page.

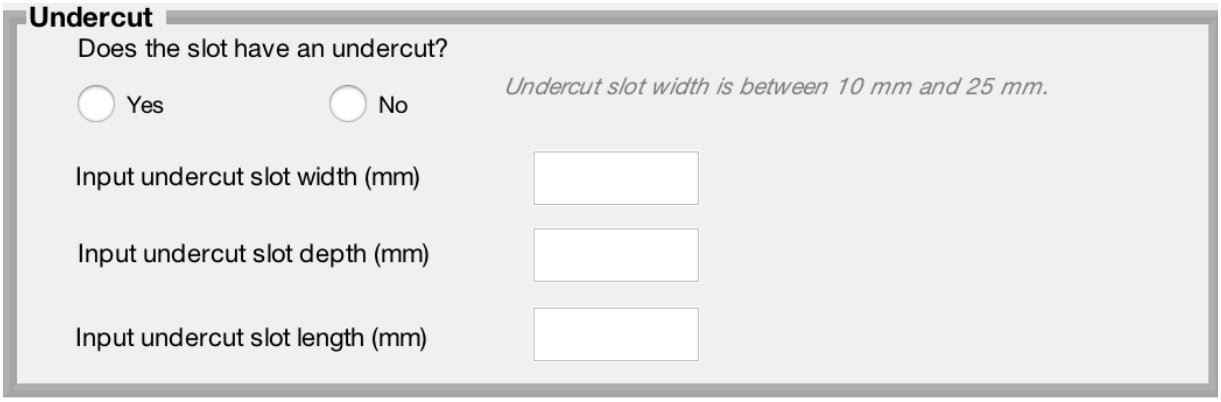


Figure 7-21: Undercut panel of the Slot feature design page.

At this point if no constraints were found, the FBMAS proceeds to enquire about the slot width. Previously noted, the minimum open feature diameter that can be accomplished by SLM technology is 1 mm. Yet, slot width is associated to slot depth for subtractive machining methods, therefore, indicating the significance of slot width to depth ratio as a design rule is important. Slot width ratios are similarly categorised as hole diameter ranges in the previous hole feature section. The minimum accepted slot width is 1 mm and the maximum is 25 mm. If a value is entered below the accepted range, the user is asked to enter a valid value, otherwise, if the entered value exceeds the maximum range, the user is advised to refer to the pocket feature or re-enter the value.

Once all the slot feature criteria are assessed for limitations, the FBMAS decision system progresses to enquire about further limitations that are identified for pocket features.

(iv) Pocket feature

The pocket feature is the third that the user is asked about for the given tool insert design. To display the pocket feature design page, the user has to originally select the pocket feature from the feature list in the main initialisation page. Henceforth, the system is executed to assess the pocket feature design limitations in accordance with the information that is entered by the user. Figure 7-22 displays an image of the pocket feature design page.

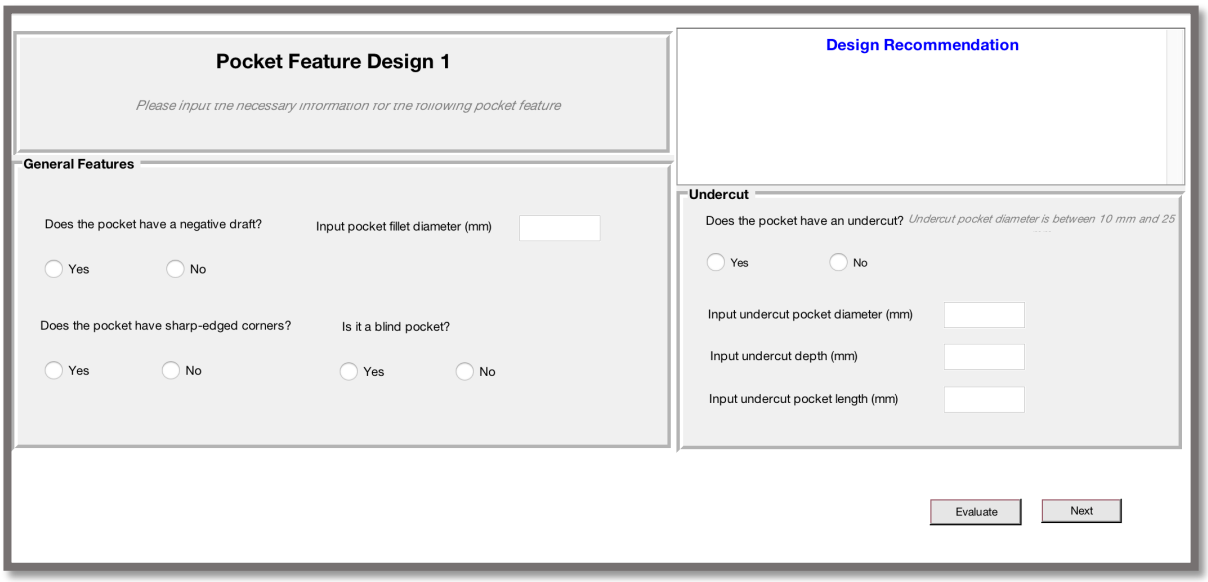


Figure 7-22: Displayed Pocket feature design page.

Initially, the user is required to enter the number of different pocket design groups. Depending on the number of design groups entered, a series of design pages are displayed subsequent to the previous design pages. As with the previous design features, the user has to input whether there is a negative draft and sharp-edged corners. The logical sequence the system executes is relevant to the set design constraints.

Further on if no constraints are met at this point, the FBMAS system continues to question the presence of an undercut in the pocket feature. As with the previous features, the user is required to enter the undercut pocket diameter, undercut depth, and finally the length of the undercut feature. The pocket feature follows the same design rules set for the previously discussed hole and slot features.

Finally, at the end of the pocket feature enquiries, the FBMAS proceeds to ask about the pocket fillet diameter. As formerly highlighted, the minimum open feature

diameter that can be accomplished by SLM technology is 1 mm. Moreover, for pocket features the pocket fillet diameter is directly associated with the pocket depth. Therefore, it is imperative to distinguish the cutting tool ratio in use for manufacturing the desired pocket feature to achieve accurate dimensions. The minimum accepted pocket fillet diameter is 0.2 mm. If a value is entered below the accepted range, the user is asked to enter a valid value. The system assesses the response to whether there is a pocket fillet of diameter between 0.2 and 2 mm. The decision recommendation is conditional; if the pocket is blind, the decision recommendation for the pocket feature is to use EDM, otherwise, a fillet feature that is less than 1 mm in diameter is difficult to manufacture using CNC machining. Moreover, if it's a through pocket feature, wire EDM is recommended otherwise it is impossible to create a fillet feature that is less than 1 mm in diameter using CNC machining.

After the pocket feature design constraints are assessed for limitations, the FBMAS decision system proceeds to investigate more design limitations that are recognised in the following boss-extrude feature.

(v) Boss-extrude feature

The fourth feature in the FBMAS is the boss-extrude feature. After the user selects the boss-extrude feature from the main initialisation page, the feature design page is prompted as shown in Figure 7-23. The FBMAS is executed to assess feature design limitations depending on the information entered by the user. First, the user is requested to enter the number of different boss-extrude feature design groups. According to the number of designs entered, design pages are opened subsequently. For each design page, the user is asked to fill out the enquiry fields. The user is asked whether there are sharp edged corners or corner fillets less than 1 mm in diameter.

Figure 7-23: Boss-extrude feature design page.

If no constraints are met, the FBMAS enquires about the spacing between the boss-extrude feature and the nearest wall. Corresponding with this, constraint limits the use of CNC machining approach of manufacturing. Furthermore, the FBMAS checks if the height to width ratio of the boss-extrude feature id more than 8:1; if the user confirms, then SLM technology is disqualified as a potential manufacturing technique.

The boss-extrude feature criteria are assessed for limitations and the FBMAS decision system progresses to enquire about further limitations that are identified in the succeeding freeform-patterned feature.

(vi) Freeform-patterned feature

A freeform-pattern feature is simply multiple repetitions of an individual design feature. Significantly, the feature diameter is the key design criteria to query so as to assess design limitations for a freeform pattern feature; Figure 7-24 shows the displayed design page for the freeform-pattern feature design.

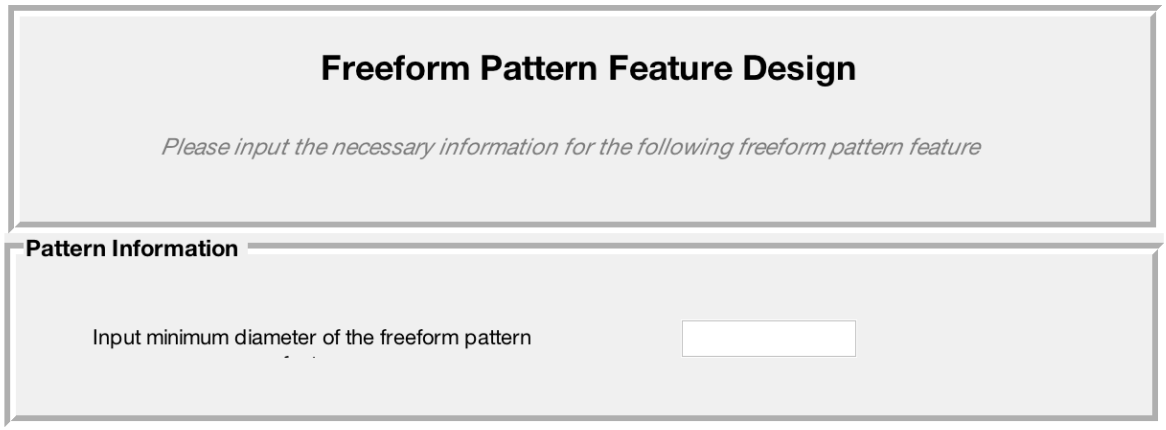


Figure 7-24: Freeform-pattern feature GUI page.

First, the user is asked about the number of freeform-pattern design groups. The same design rules set for a feature diameter query was followed in this sub-chapter. The pattern diameter is directly associated to the feature's depth. Therefore, the design ratios were followed by the FBMAS to assess the adequate manufacturing technique for implementation. The minimum permissible diameter for CNC machining a freeform pattern design is 0.25 mm. The user is required to enter the diameter and the system is responsible for assessing the input as shown in the logical guidelines in Figure 7-25. Depending on the value submitted for diameter, the system prompts the user to answer a question about the ratio and according to the answer a decision recommendation is displayed. If the user enters a value outside the permissible range, a message appears to alert the user to input a valid diameter.

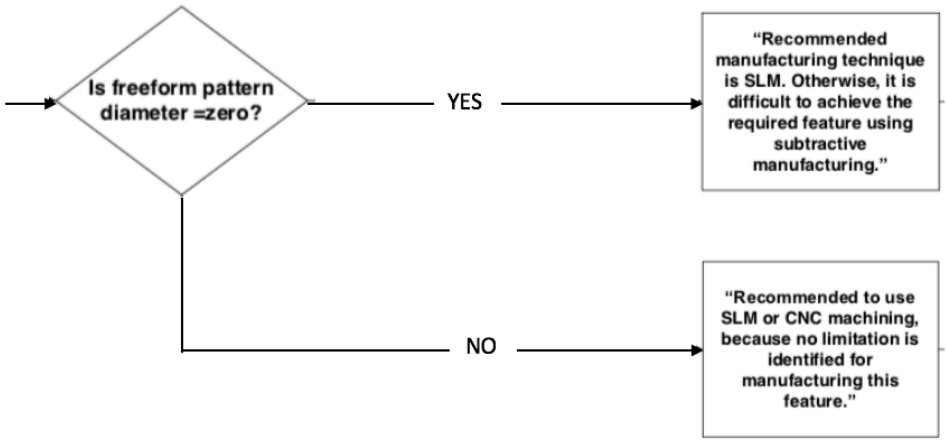


Figure 7-25: Freeform-pattern design constraints.

(vii) Feature and part decision recommendations

The decision recommendation page is the last stage of the FBMAS. At this point, the user has initiated all the necessary feature design pages that are of relevance to the part under consideration. In the recommendation page, each feature is displayed in the upper tabs menu. When the user presses on one of the feature tabs, a display of the identified design groups of a given feature are displayed. For each design group specified by the user, a decision recommendation for the manufacturability of the given feature is presented along with an explanation of limitations. Figure 7-26 shows the recommended decision for five hole feature design groups. These recommendations provide the user with an insight into the different capabilities and limitations of the defined manufacturing technologies in this system when it comes to design feature manufacturability.

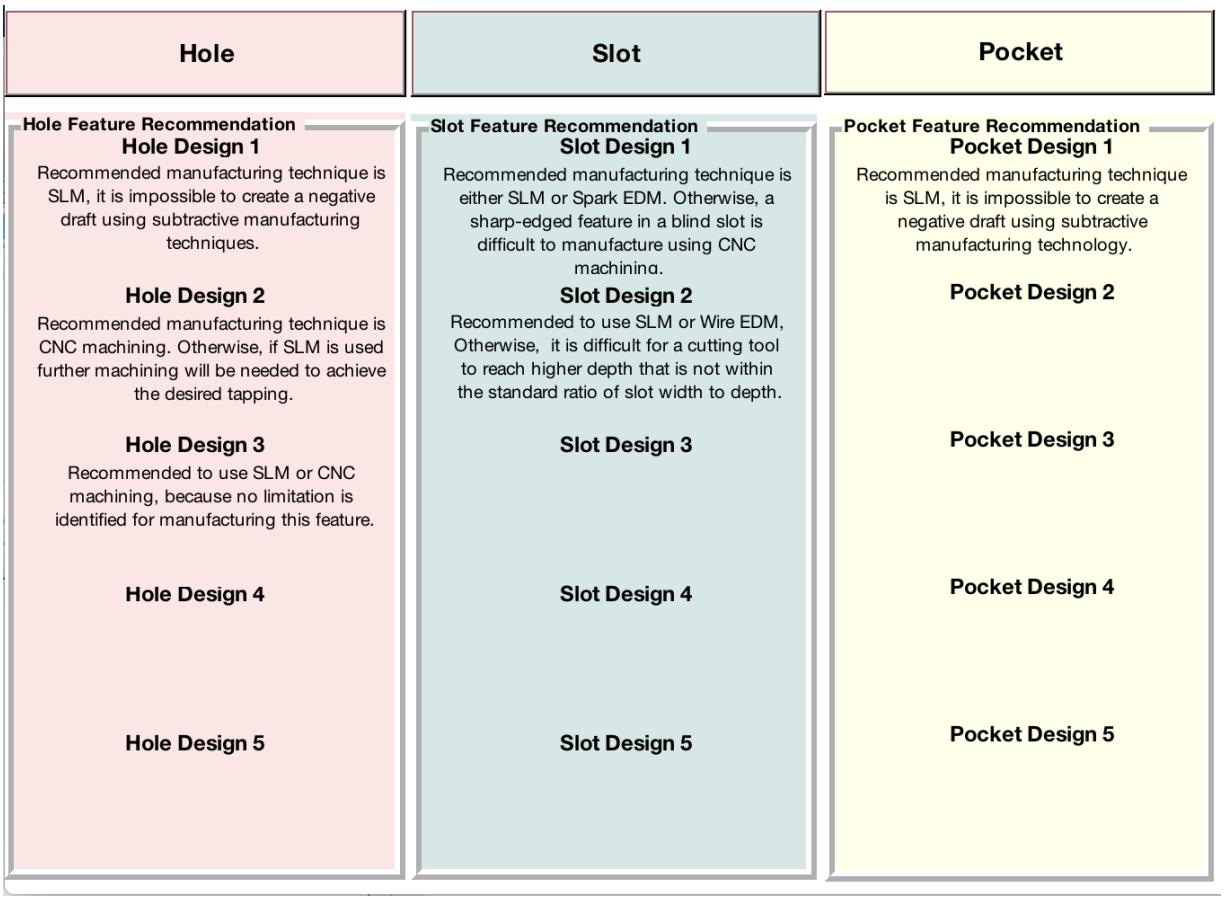


Figure 7-26: Design recommendation page of the FBMAS.

7.3 Summary

This chapter has discussed the systematic approach for developing the Feature-Based Manufacturability Assessment System. The features for a given CAD model design for additive and subtractive manufacturing technologies that are relevant to the scope of this research work were defined and presented. Moreover, the methodical description of the systems logical operations was clearly recognised through the presented segments of the flowchart and applied through the GUI. The main logic which the system follow is “IF-THEN” rules used to define design limitations that assist users in determining the proper manufacturing method for the tool insert under consideration. The conditions of the “IF-THEN” are based on constraints set by the operations of SLM technology and the defined methods of subtractive manufacturing in the system. The system focuses on identifying the outcome through decision recommendations for the individual design features.

8 System Verification and Validation

This chapter presents the verification and validation of the developed FBMAS. Verifying the system was established through inspecting the logic of the developed FBMAS. to validate the system for the purpose of supporting fabrication of injection moulding tool inserts for the automotive industry, six tool inserts were selected for validation. The validation process for the case studies was conducted in consultation with a stakeholder from industry. In addition, the method employed for investigating the tool inserts prior to feeding inputs to the FBMAS was similar for all the defined case studies. The output decision recommendations of the FBMAS were compared with actual decisions made by the experts consulted to assess how well the system works.

8.1 Verification and Validation

Considering how verification and validation are related to the development process of the FBMAS, Figure 8-1 displays the modelling paradigm. The paradigm is adopted from the simplified version illustrated by Sargent (2011) for verification and validation of simulation models. The principal knowledge was captured to correspond with the need of this study. The real-life design evaluation process is the problem entity that needs to be modelled. The logical depiction of the system is the conceptual model, and the programming of the conceptual model is the computerised model. To develop the conceptual model, extensive analysis and flowchart modelling is carried out to validate compliance with the actual system. Verifying the computerised model makes sure that the computer programming and implementation is done with no faults. Operational validation is carrying out sufficient experimentation to ensure that the system's outcome is providing accurate results as intended in actual situations. Finally, in this work, data validity throughout all stages of the verification and validation process is performed to ensure that the design feature limitations are correctly defined and represented.

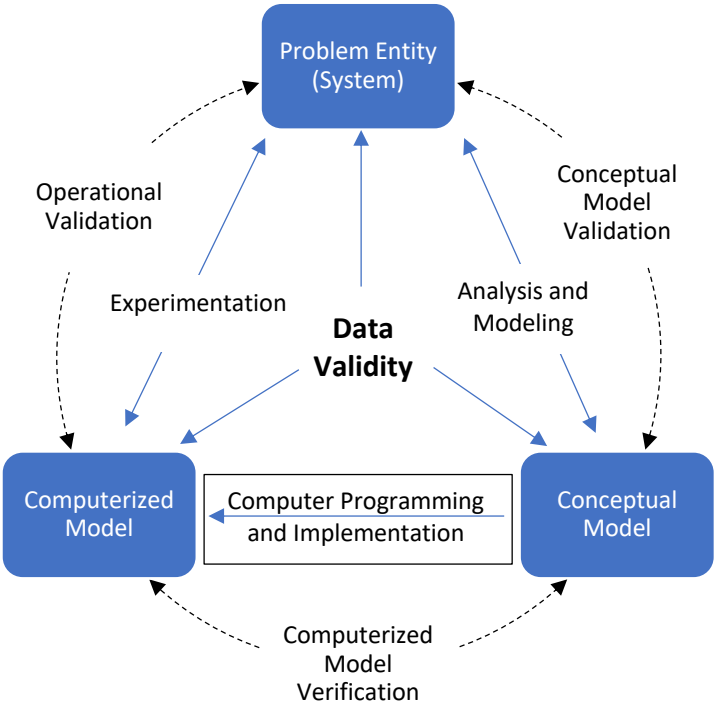


Figure 8-1: FBMAS verification and validation paradigm (Sargent, 2011).

The two main verification and validation techniques acquired in this work are event and extreme condition tests. In the "event" test, the system is run to depict similarities with the real-life system. As for the "extreme condition" test, the outcome should be perceived as acceptable regardless of the extreme inputs to the system (Sargent, 2011).

8.2 System Verification

Prior to utilising the developed FBMAS, the system had to be examined to verify that it operates accurately. The verification process was executed at several stages. Initially, the logic and interface of the system was verified through the different stages of system development. Furthermore, after completion of the system development, it was examined as a whole to ensure that it works properly.

Different scenarios were established to examine the systems performance when subjected to different inputs and the effect of these variations on the system's outputs. Input variations were mainly set to part size and presence of a given feature. To test the systems operation, variations to part size and feature existence were determined for the FBMAS to

acquire the expected output. To verify the accuracy of the system's performance, the same criteria were tested manually to compare and hence ensure that the same results are acquired.

As an example to the verification process, the system was tested through various scenarios of entering different values of part size. Firstly, the system as tested under extreme conditions where the input data provide plausible outputs for unlikely extreme conditions. For example, if part size in any of the X, Y, and Z directions is zero, a message is displayed to state that a valid part size must be entered. Other event scenarios are carried out with part sizes above and below the SLM design limitations of 500 mm, 280 mm, and 850 mm respectively. The results retrieved from the FBMAS were similar to those results determined from manually processing the system. Changing the inputs results in correspondingly altered outputs.

This method of system verification was carried out multiple times to ensure the reliability of the FBMAS in accurately following the programmed logical design rules. Additionally, the same verification approach to test for feature manufacturability evaluation was used. Extreme conditions of feeding the system with the presence of all design features and the lack of all, henceforth, providing the decision recommendation of the outcome. Another event scenario is the system being fed with inputs that are known to provide a decision recommendation for manufacturability using SLM technology and the output is checked for providing an accurate outcome. This method is followed to trace all the possible logical approaches of providing numerous inputs to the FBMAS and retrieve plausible outputs. Comparing the outputs retrieved through the verification process of the FBMAS with the manual process was conducted at various stages through the development of the FBMAS. In continuously seeking to verify the system at all stages, errors are effortlessly detected and corrected instantaneously.

8.3 System Validation

The primary purpose for validating the FBMAS was to ensure that the system provides realistically feasible outcomes, assisting users in evaluating manufacturability of design features of tool inserts for the aftermarket spare parts automotive industry. This approach ensures that the knowledge of experts for SLM technology and subtractive manufacturing

techniques were accurately captured and constructed within the structure of the developed FBMAS. Design constraints were set to outline limitations that exist for the defined methods of manufacturing. Those constraints were defined by industrial experts and conform to the design constraints that do actually exist and cause manufacturing restrictions. Six industrial injection moulding core or cavity inserts were selected from industry to validate the system. Three of the selected inserts were manufactured using both SLM technology and subtractive manufacturing methods. The remaining three core and cavity inserts were manufactured using subtractive manufacturing methods only. The case studies were selected by the experts to test the systems decision outcomes with the actual outcomes due to challenging limitations faced during manufacturing. The selection of the case studies was done under supervision and consultation of the industrial experts that have hands-on experience of the manufacturing of injection moulding tool inserts for the aftermarket automotive industry.

8.3.1 Headlamp cover study

The headlamp cover is a component that is fitted over the headlamp after the headlamp is assembled to the vehicle to cover the space between the headlamp and the vehicles body. The component size is to be considered for validation by the FBMAS. Figure 8-2 displays the headlamp cover end product.

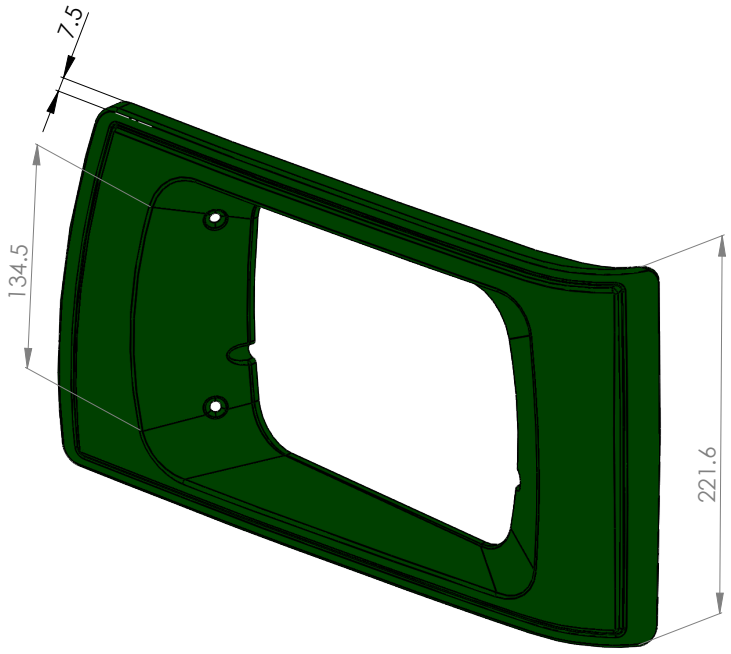


Figure 8-2: Headlamp cover product, dimensions in mm.

Figure 8-3 demonstrates the 3D CAD model for the headlamp's cover tool inserts. the CAD model was generated for the tool insert prior to a decision is taken to which manufacturing approach is used.

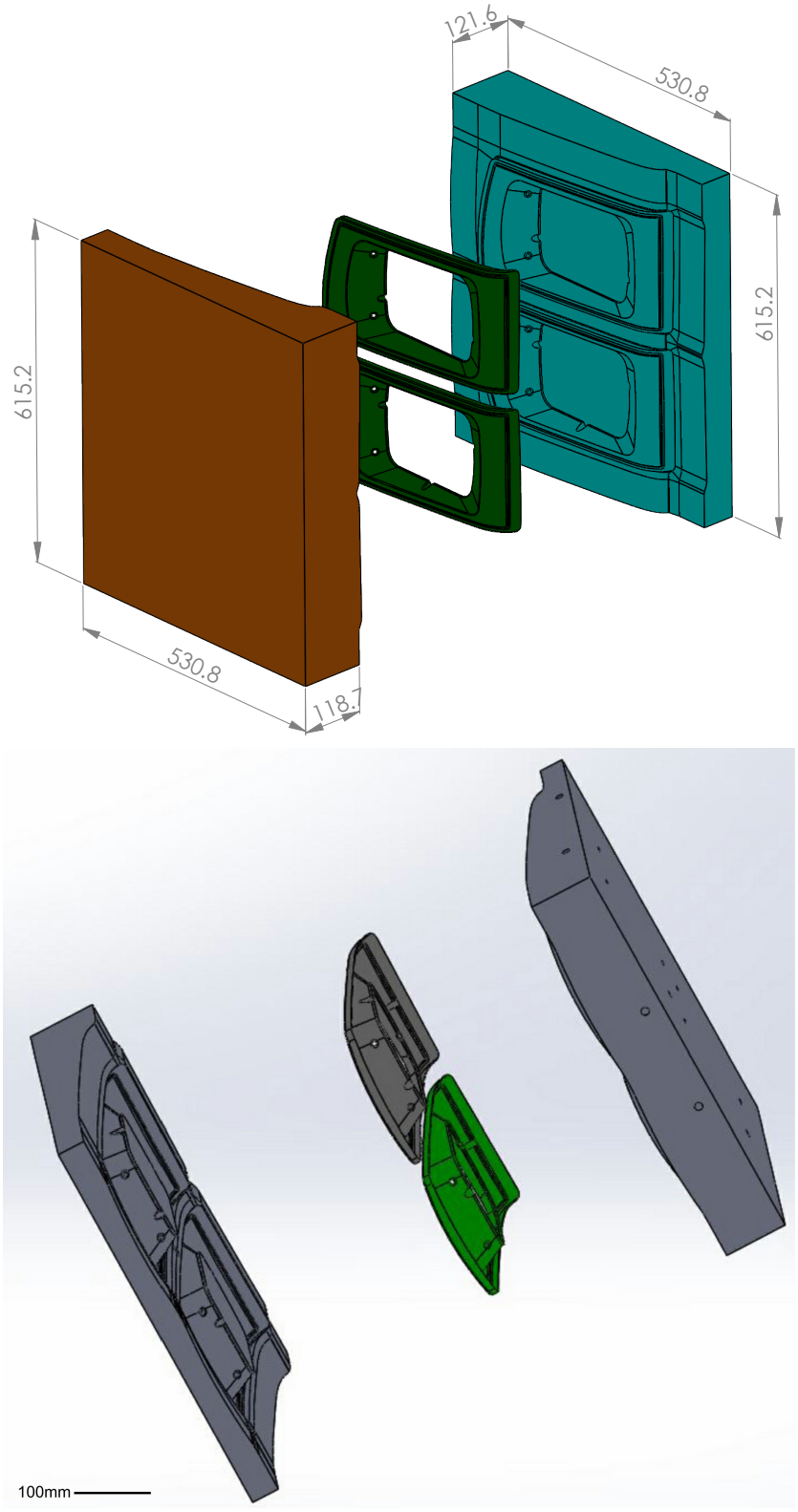


Figure 8-3: Headlamp's cover 3D CAD model, dimensions in mm.

(i) Manufacturability assessment of core tool insert

The core tool insert of the headlamp cover was manufactured using subtractive manufacturing methods. In this study, only the size of the tool insert is considered for evaluation. The dimensions of the core insert are 307.58 x 530.82 mm. The core insert was successfully manufactured as one part on CNC milling machines at Al Fouad Co. for Automotive Spare Parts (Alexandria, Egypt). Design experts decided on manufacturing the core insert using CNC machining knowing that it is not recommended to separate the core insert into separate modules. To validate the FBMAS, the part information was fed to the system to achieve the necessary decision recommendations for the part under consideration.

(ii) Core insert features' evaluation using FBMAS

The core insert dimensional specifications were fed to the system and the decision recommendations were compared to real-life decisions provided by design experts. The dimensional specifications recorded for the given core insert for the part length, width and height are 307.58 x 530.82 x 121.6 mm respectively.

After the part dimensions are entered, the system displays a message to the user enquiring whether it is possible to separate the part into modules. If the user responds with affirmation, then the system asks the user to proceed in separating the part into modules and then evaluate each individual part as a separate entity. If the user responds negatively to separating the part into modules, then the system recommends that the user proceed to manufacturing the part using subtractive methods otherwise the part cannot be fabricated using SLM technology. Figure 8-4 displays the user query and systems recommendation. The FBMAS system recommends that the core insert is manufactured using CNC machining conforming with the recommendations given by the consulted experts in the field.

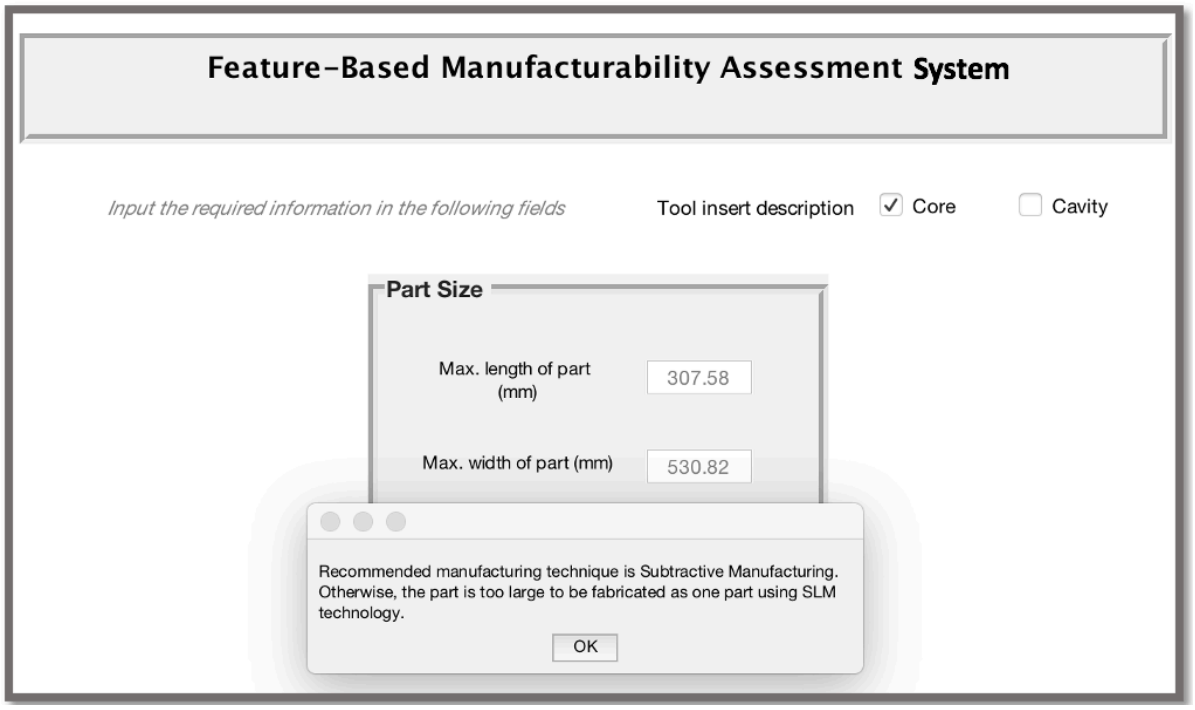


Figure 8-4: Headlamp's cover core insert recommendation.

8.3.2 Plug A study

Plug A is a plug component that is assembled to the housing of a vehicle's headlamp and from one side copper wires are assembled to the plug and the other side is where the bulb is placed. this component constitutes a number of features that are closely interlinked increasing the complexity of the part and difficulty in manufacturing, therefore it was carefully considered for validation. Figure 8-5 displays the end product plug A.

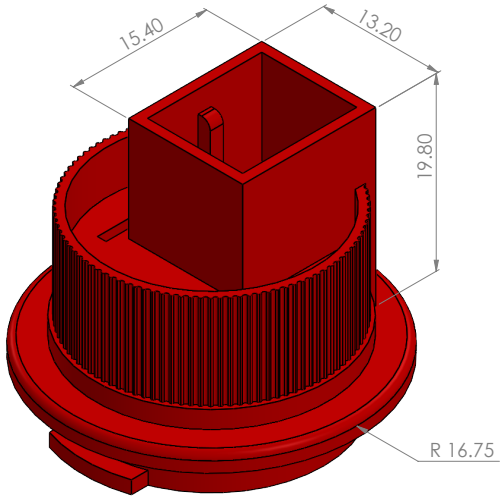


Figure 8-5: Plug A component.

Figure 8-6 illustrates the 3D CAD model for the core and cavity of the component's tool insert that was prepared as an initial step before a decision is taken to which manufacturing approach is used.

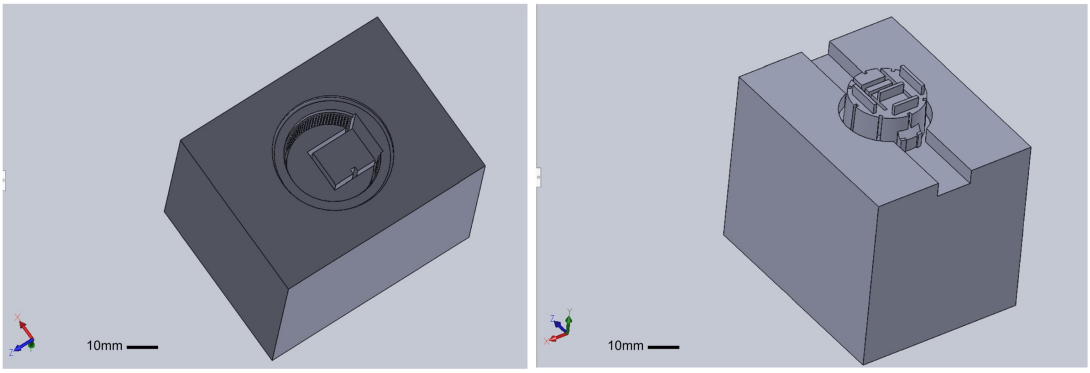


Figure 8-6: Core and cavity insert of plug A.

(i) Manufacturability assessment of core and cavity tool inserts

The tool insert for Plug A was initially manufactured using subtractive methods. To be able to machine the core and cavity inserts, they had to be divided into separate parts to be manufactured independently using CNC machining, die-sink or wire EDM at Al Fouad Co. for Automotive Spare Parts (Alexandria, Egypt). Chapter 6 Figure 6-10 displays the individual components of the core and cavity inserts.

The individual components were manufactured using different techniques. Part 1 was CNC machined using a milling process to create the external shape of the component. Constructing the internal through hole geometry was achieved at two stages, first a hole is machined using CNC milling to craft an entry point for wire EDM to create the internal vertical freeform-pattern design. Part 2 was CNC machined using a milling process. Part 3 was manufacturing at three stages. Initially, the part was machined using a turning process, then additional milling machining was implemented to produce an entry point for wire EDM to create a through square-cross section with sharp-edged corners. Part 4 was manufactured using wire EDM to create the internal sharp-edged corners of the c-shaped component. Part 5 was manufactured at two stages. Firstly, the part was CNC machined using a turning process, then electrode cutters were machined using CNC milling that were later used to

generate the sharp-edged slots surrounding the component using die-sink EDM. Finally, part 6 was manufactured using CNC milling.

After the individual parts are manufactured, they are assembled together to establish the core or cavity of the tool insert. Manufacturing each of the core and cavity inserts as one part is possible using die-sink EDM, but the results would not confirm to the quality standards required. However, the approach of dividing the insert was conducted to facilitate the manufacturing of the inserts due to evident limitations to the use of variable manufacturing technologies at the factory where the parts were manufactured. Manufacturing the core and cavity inserts using subtractive methods did not present highly satisfactory results in accordance to accuracy and quality measures of the end product required by the user. Even though, the designers decided to manufacture the core and cavity components as separate parts instead of one whole insert to avoid difficulty in manufacturing, as the assembly process proved constricting in achieving superior results. Furthermore, design experts confirm that designs of the same nature prove to be difficult to manufacture using solely CNC machining and rely more on EDM technology.

Additionally, using the same 3D CAD model, the tool insert's core and cavity were fabricated on a Realizer 250 selective laser melting (SLM) technology machine at Croft Additive Manufacturing Ltd (Warrington, UK) in Stainless Steel 316L. Unlike the approach used for subtractive manufacturing, each of the core and cavity inserts were fabricated as a complete part with no need to divide the insert into sub-components. The core and cavity inserts were successfully manufactured based on the quality and accuracy required. However, after fabrication it was evident that post-processing was needed to improve surface finish. After achieving the accepted surface finish, the design experts verified that SLM was able to accomplish the required design features with no apparent limitations.

In this study, the core and cavity of the tool insert are viewed as two separate entities, with each part evaluated individually to assess the enclosed features. Henceforth, to validate the FBMAS, the information concerning the core and cavity inserts were fed to the system to achieve the necessary decision recommendations for each given part.

(ii) Core insert features' evaluation using FBMAS

The design features' information was fed to the FBMAS and the output results in the form of decision recommendations were compared to real-life decisions provided by design experts. The design features recognised for the given core insert are illustrated in Table 8-1.

Table 8-1: Core insert feature specifications.

Part Size	**66 X 52 X 56 mm**
Slot Feature Design Group 1	
Negative draft	Yes
Sharp Edge	Yes, blind slot
Width	1 X 4.69 mm
Slot Feature Design Group 2	
Negative draft	Yes
Sharp Edge	Yes, blind slot
Width	1 X 9.7 mm
Slot Feature Design Group 3	
Sharp Edge	Yes, blind slot
Width	1 X 2 mm
Pocket Feature Design Group 1	
Sharp Edge	Yes, blind pocket
Diameter	11.2 X 4.6 mm
Pocket Feature Design Group 2	
Sharp Edge	Yes, blind pocket
Diameter	1.65 X 4 mm
Pocket Feature Design Group 3	
Sharp Edge	Yes, blind pocket
Diameter	4 X 4.6 mm
Boss-Extrude Feature Design Group 1	
Ratio of height to width	4.2:1
Sharp edge	Yes

After the system is fed with the part information as shown in Figure 8-7, design pages of slot, pocket, and boss extrude features are displayed for the user to respond to the queries. The user answers the questions as displayed in Figure 8-8. For the slot feature, after all slot feature design groups are evaluated subsequently after the next button is pressed, the pocket feature design page is displayed. The user continues to respond to the enquiries of all the pocket feature design groups.

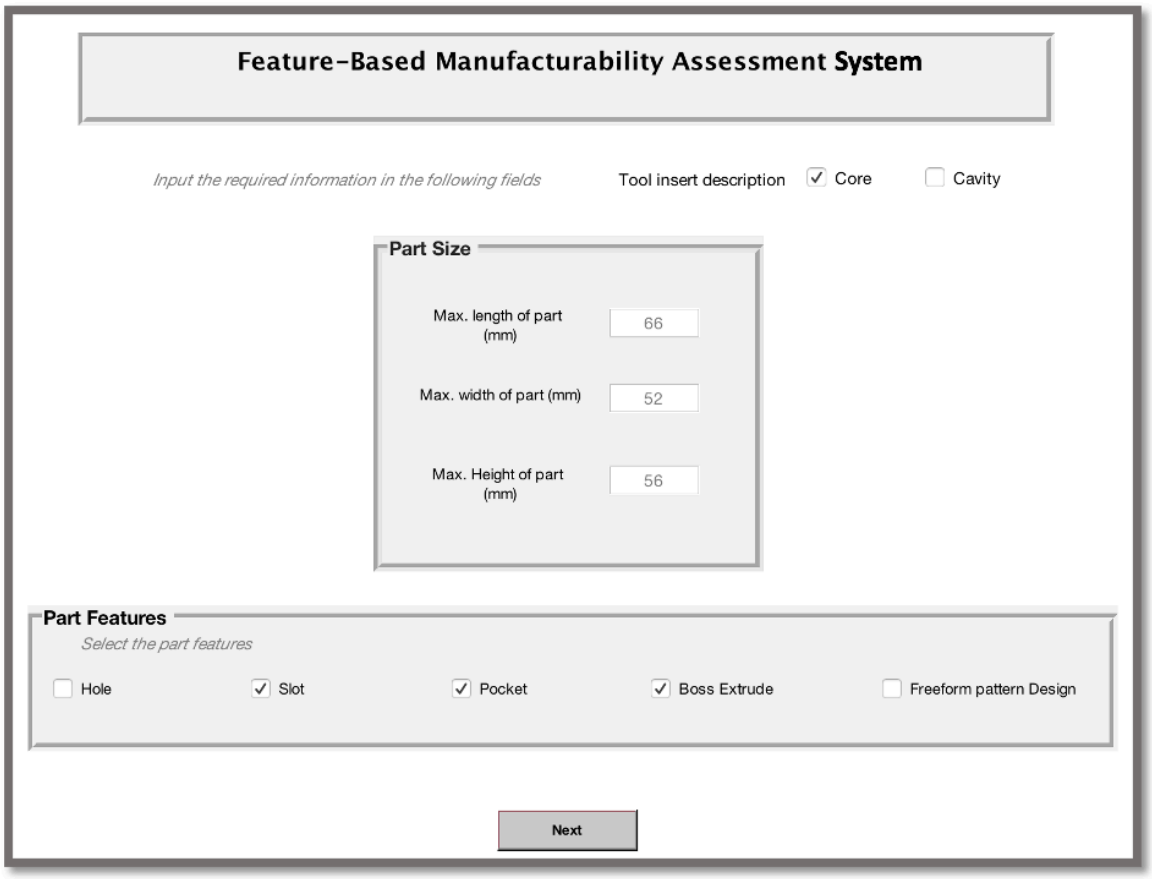


Figure 8-7: Core information fed to the FBMAS initial page.

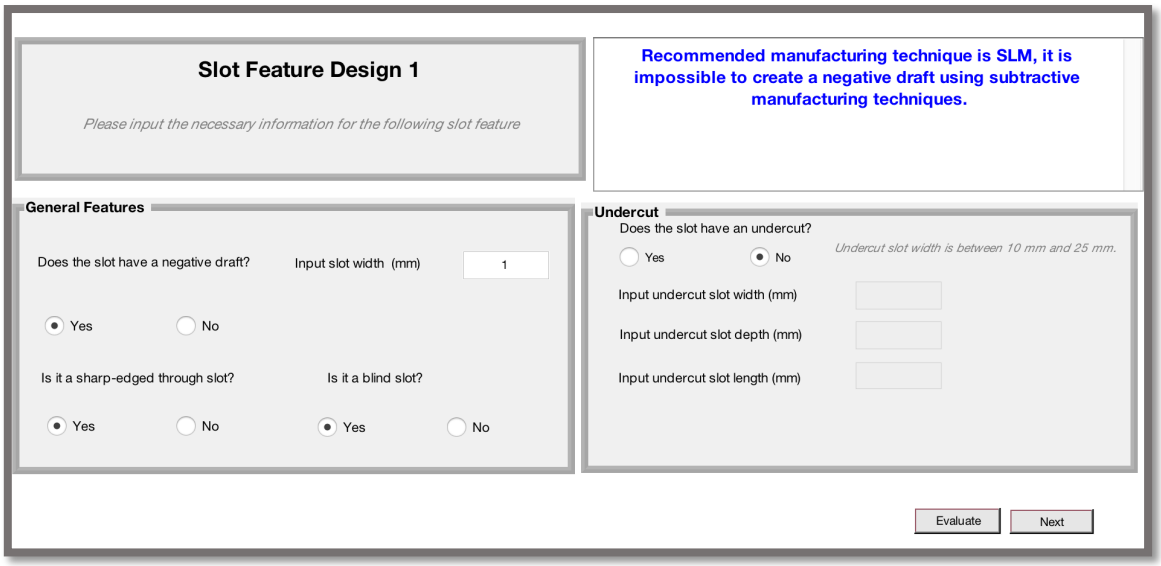


Figure 8-8: Slot feature design group 1 page.

Finally, as demonstrated in Figure 8-9, the decision recommendations displayed for Plug A core insert addresses the following conclusions; after each individual feature has

been evaluated for its manufacturability limitation, the user is provided with a recommendation to either use SLM Or die-sink EDM approaches for manufacturing the slot, pocket, and boss-extrude features of the given insert. The recommendations given by the FBMAS conforms with the recommendations given by the consulted experts in the field. The recommended approach to manufacture the core tool insert is SLM or die-sink EDM given the availability of the selected approach.

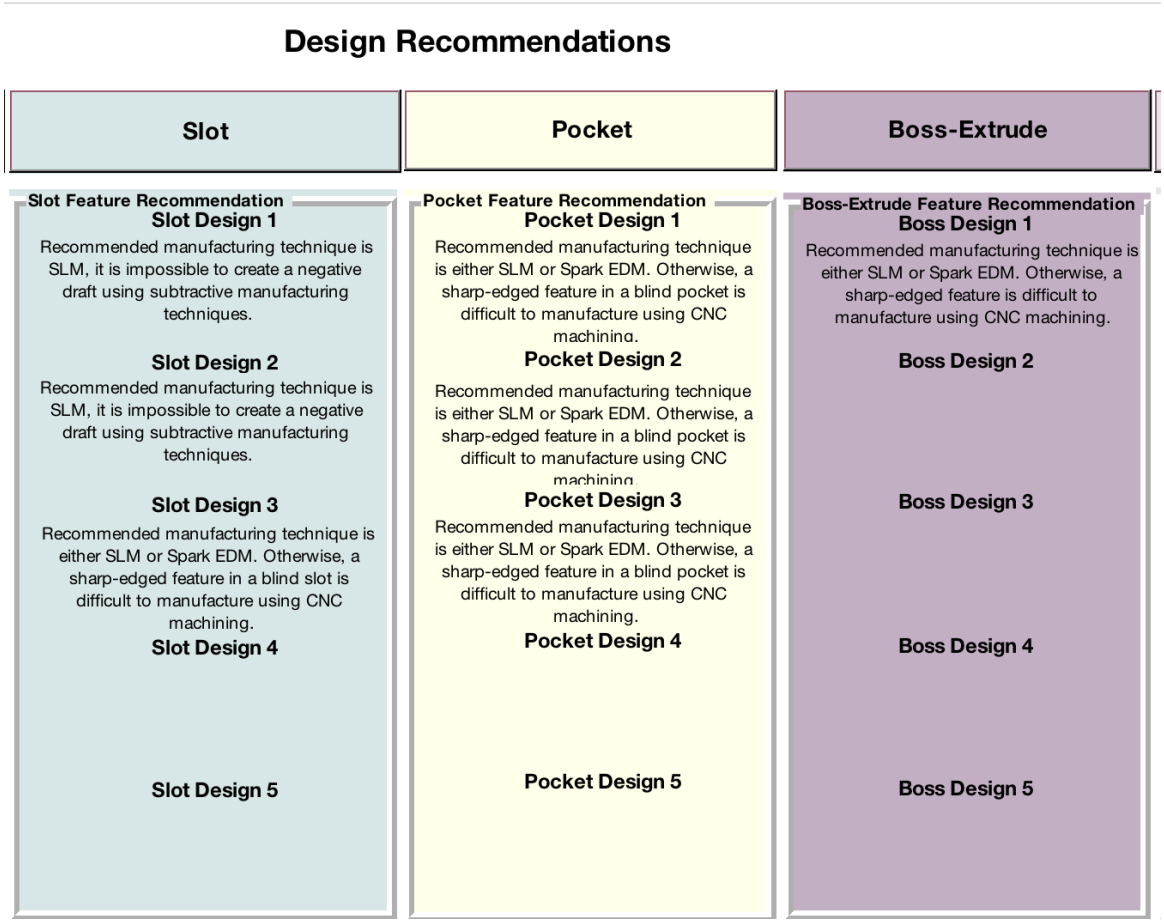


Figure 8-9: Plug A core insert decision recommendation page.

(iii) Cavity insert features' evaluation using FBMAS

The cavity's feature specifications were fed to the system and the FBMAS retrieved the possible decision recommendations for each feature. The identified design features fed to the system are illustrated in Table 8-2.

Table 8-2: Cavity insert feature specifications.

Part Size	**66 X 52 X 56 mm**
Slot Feature Design Group 1	
Negative draft	Yes
Sharp Edge	Yes, blind slot
Width	1.5 X 9.5 mm
Pocket Feature Design Group 1	
Diameter	33.5 X 2 mm, blind pocket
Pocket Feature Design Group 2	
Diameter	1.1 X 12 mm, blind pocket
Pocket Feature Design Group 3	
Sharp Edge	Yes, blind pocket
Diameter	26.8 X 14.8 mm
Freeform-Pattern Feature Design Group 1	
Diameter	0.5 mm

When the system identifies the input feature information, the slot, pocket, and freeform pattern design pages are displayed. Firstly, the user responds to the enquires in the slot feature design page. Afterwards, the user presses on the next button to proceed to the next pocket feature design pages. The user continues to the next design feature, the freeform pattern design. Finally, the decision recommendation page is displayed to list all the possible recommendations for each design feature as shown in Figure 8-10. The slot feature is recommended to be manufactured using SLM technology due to the negative draft of the feature. As for the first pocket design group, it is recommended to manufacture the round pocket using SLM technology or CNC machining as there seems to be no limitations for manufacturing. The second and third pocket design groups are recommended to be manufactured using SLM or die-sink EDM due to the blind sharp edge corner pocket features, which are impossible to manufacture using machining methods. For the freeform-pattern design as an individual feature, it is recommended to be manufactured using SLM or CNC machining as it appears to have no visible constraint in manufacturing the pattern feature. Moreover, the recommended approach to manufacture the cavity insert is SLM technology as it appeared in all feature recommendations for the given part. The recommendations

retrieved from the FBMAS corresponds with the recommendations given by the consulted design experts.

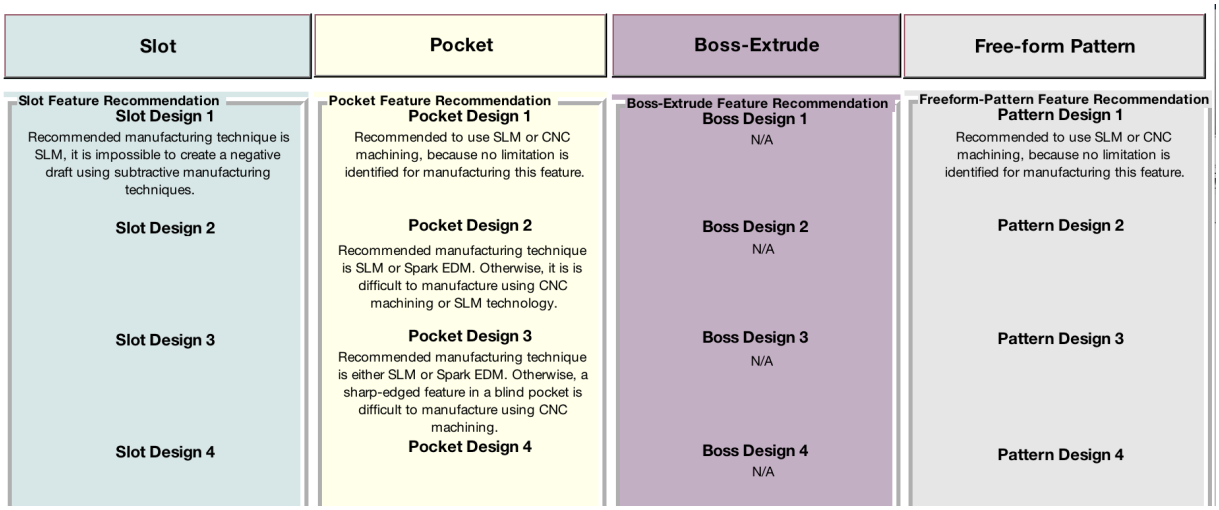


Figure 8-10: Decision recommendation for Plug A cavity insert.

8.3.3 Reflector study

The second study is for a headlamp reflector. The reflector is a stand-alone part that is not assembled to any other component. Figure 8-11 displays the produced end product.

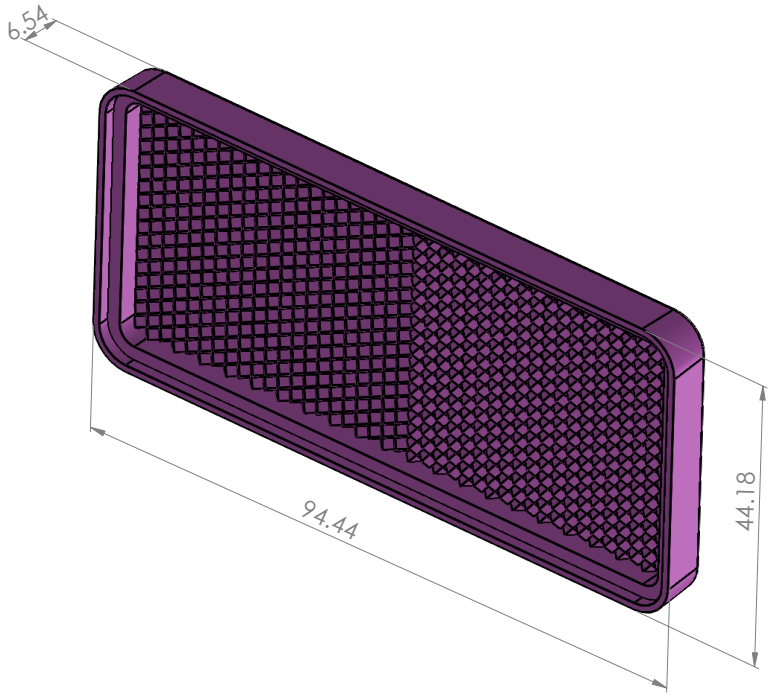


Figure 8-11: Reflector product, dimensions in mm.

(i) Manufacturability assessment of core insert

The core tool insert for the reflector product was manufactured using two approaches, both subtractive and AM. Initially, the 3D CAD as shown in Figure 8-12 was prepared and the core insert was CNC machined using a tapered end mill of diameter 0.25 mm and shank diameter of 3 mm to achieve the required sharp-edged freeform pattern design, although the required tip diameter was set to be sharp edged.

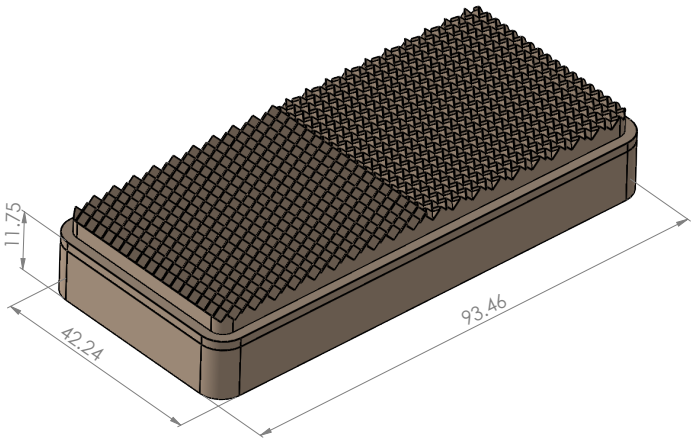


Figure 8-12: Reflector's core tool insert, dimensions in mm.

Figure 8-13 (a) and (b) demonstrate a simplified design of the repetitive pattern of the core insert. Acquiring a tapered end mill with zero diameter was impossible. Therefore, the CNC machined insert did not deliver the stipulated results in accordance to part quality and accuracy. Furthermore, experts confirmed that if only subtractive methods are targeted, using die-sink EDM manufacturing techniques will deliver more satisfactory results.

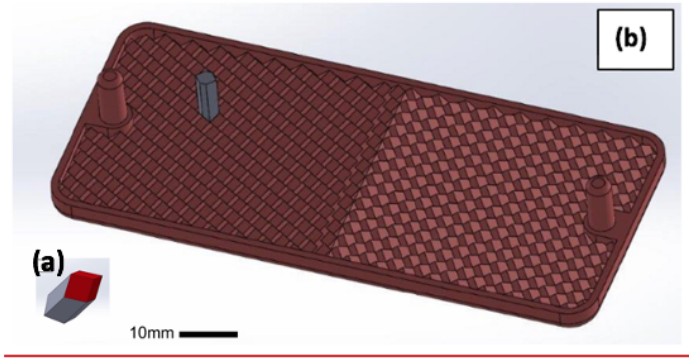


Figure 8-13: (a) A simplified view of the repetitive pattern of the core insert (b) The reflector product with a view of the simplified view of the repetitive pattern attached to the core.

The second approach for manufacturing was to use SLM technology. The core insert was successfully fabricated as one whole part conforming to the necessary quality and accuracy measures. Moreover, minor post-processing was required to achieve the desired surface finish. It was confirmed by experts that SLM offered positive results in fabricating the identified design features with no limitations.

(ii) Core insert features' evaluation using FBMAS

The core's feature specifications were fed to the system and the possible decision recommendations were processed and displayed by the FBMAS. The acknowledged design features fed to the FBMAS were the minimum freeform pattern diameter. The identified pattern design requires that the base is a sharp edge feature as shown in Figure 8-14.

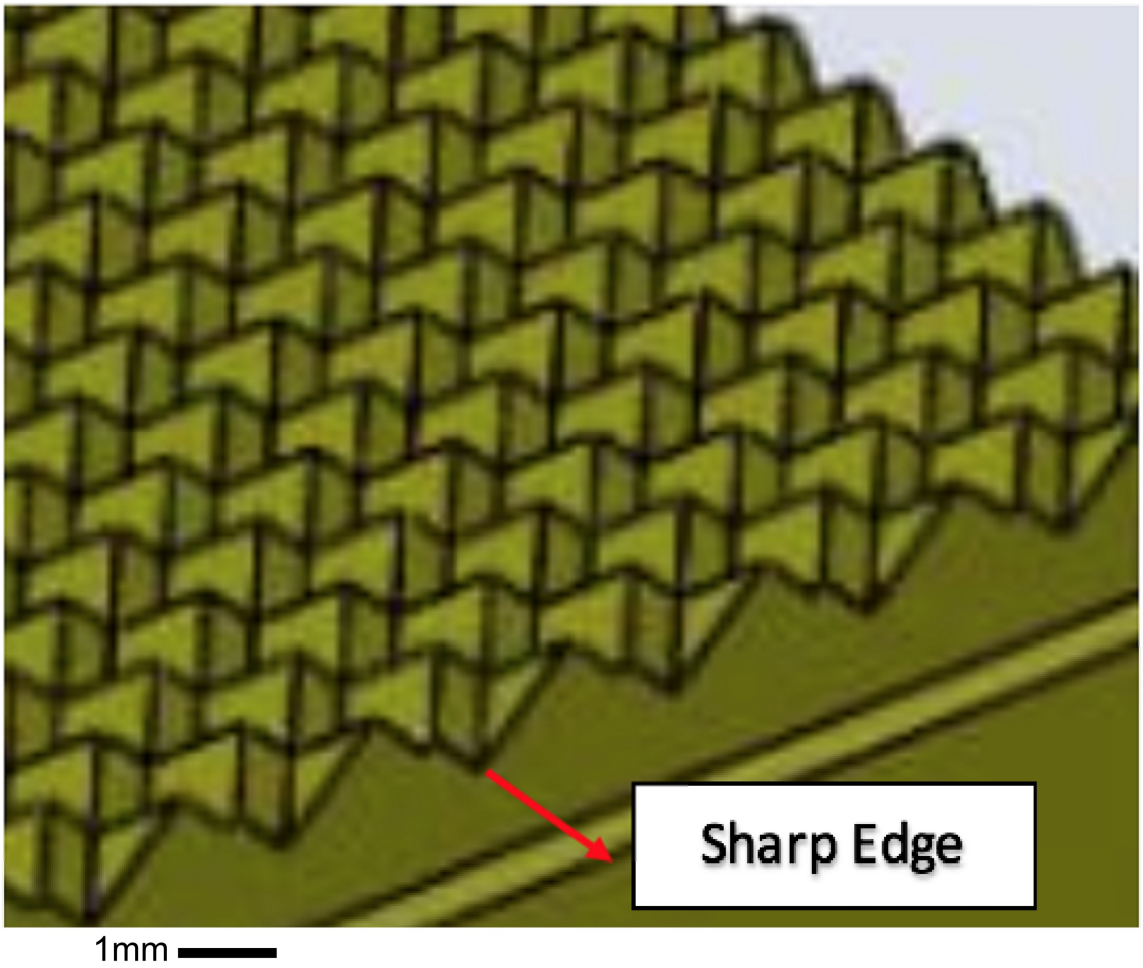


Figure 8-14: Detailed view of core insert.

The user entered the identified features and the freeform-pattern design page was displayed. The user inputs the required information and presses the next button to

display the decision recommendations as shown in Figure 8-15. The FBMAS states that to manufacture the freeform pattern design of core insert, it is recommended to use SLM technology as the ideal manufacturing technique, as opposed to subtractive manufacturing. The FBMAS recommendations conformed with the recommendations indicated by the consulted experts given the availability of the manufacturing systems.

Figure 8-15: Reflector's decision recommendation.

8.3.4 Sign base study

The sign headlamp is a component that is mounted on the side of overhaul trucks. In this study, the base component of the sign headlamp is evaluated to manufacture the tool insert that produces the component using injection moulding process. Figure 8-16 displays the sign base component under consideration. A number of features are identified and discussed in this section that determine difficulty in manufacturing. Therefore, the study was taken into consideration for validation.

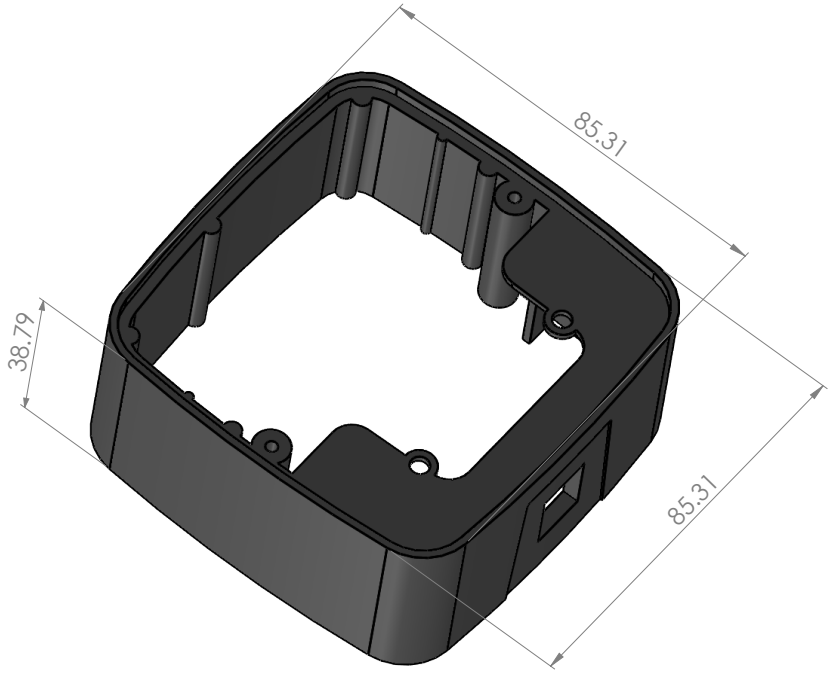


Figure 8-16: Sign base component, dimensions in mm.

Figure 8-17 illustrates the 3D CAD model for the core and cavity of the base sign tool insert prepared for manufacturing the parts using subtractive methods.

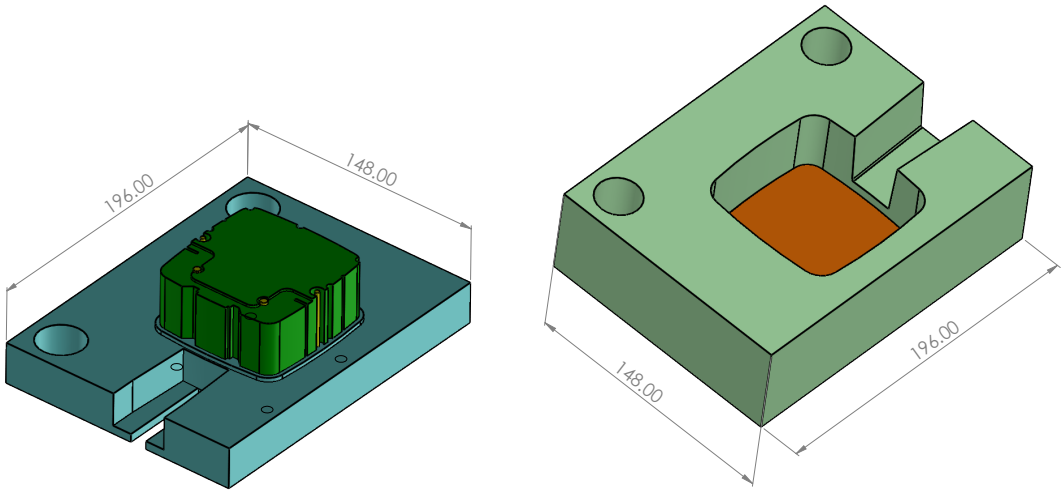


Figure 8-17: Core and cavity insert of sign base, dimensions in mm.

(i) Manufacturability assessment of core and cavity inserts

The tool insert of the base sign was only manufactured using subtractive methods. in order to manufacture the core and cavity inserts, each had to be split into individual component to allow ease in accessibility during the manufacturing process. The manufacturing processes employed were CNC machining, die-sink and wire EDM. Manufacturing processes were performed at Al Fouad Co. for Automotive Spare Parts (Alexandria, Egypt). Figure 8-18 shows the individual sub-components of the core and cavity inserts that form the sign base component.

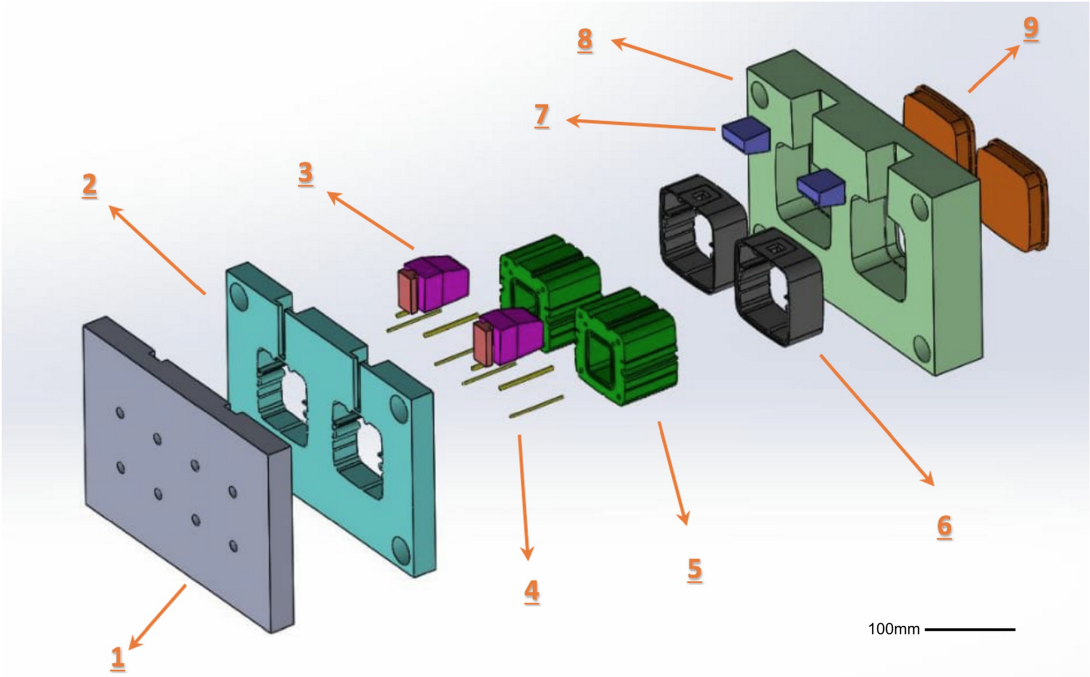


Figure 8-18: Exploded view of the base sign complete injection tool.

Each component was manufactured using a different technique. Looking at the individual components in Figure 8-18 from left to right shows that the fixing plate (1) where the cooling channels are found, is manufactured using CNC milling. The following plate is the base plate for the core insert (2). Initially the plate is CNC machined to achieve the required shape and further wire EDM was accomplished as a necessity to create the fine detailed features of the two cavities of the base plate. The following parts are the sliders (3) that are responsible for generating the side mechanism that creates the side cavity in the end product. The sliders are CNC machined as individual components of the tool. As for the forming pins

(4), they are outsourced standard parts. The core insert (5) is completely generated using wire EDM. The next part demonstrated (6) is the end-product. Following is the base of the slider mechanism (7) that is CNC machined. The cavity plate (8) is entirely CNC machined and the last component is the base attached to the cavity plate (9).

Once the individual parts were manufactured, they were assembled as one part to form the core or cavity inserts. It is possible to manufacture the core and cavity inserts as one part, but the design experts at the company consider other aspects of manufacturing in their evaluation before manufacturing a tool insert. Some of the critical factors considered are quality, lead-time, cost, and availability for use of machine tools. In this case, the approach of splitting the inserts into individual parts was conducted to facilitate the manufacturing of the inserts due to evident feature limitations. Manufacturing the core and cavity inserts using subtractive methods presented satisfactory results in accordance with accuracy and quality measures of the end product required by the user. Furthermore, design experts confirm that such designs prove to be difficult to manufacture using solely CNC machining and rely more on EDM technology.

(ii) Core insert features' evaluation using FBMAS

The design features of the given core insert were fed to the FBMAS and the outcome decision recommendations were compared to the decisions confirmed by the field experts. The identified design features for the core insert are displayed in Table 8-3.

Table 8-3: Feature specifications for sign base core insert.

Part Size	**77.31 X 77.31 X 88.28 mm**
Hole Feature Design Group 1	
Diameter	4.02 X 59.77 mm, blind hole
Slot Feature Design Group 1	
Width	1.5 X 59.77 mm, open blind slot
Pocket Feature Design Group 1	
Sharp Edge	Yes, blind pocket
Pocket Feature Design Group 2	
Diameter	5.03 X 1.51, blind pocket
Pocket Feature Design Group 3	
Diameter	3.92 X 61.28 mm, blind pocket
Pocket Feature Design Group 4	
Diameter	1.01 X 61.28 mm, blind pocket

After initiating the FBMAS and the feature information is entered, the hole and pocket design pages are displayed consecutively. Firstly, the hole design pages are displayed for the user depending on the number of hole design groups determined. The user is required to respond to the defined queries. Consequently, the next button is pressed to display the slot feature design pages and the user continues to respond to the enquiries. After the slot queries are completed, the user is prompted to identify pocket limitations through the pocket feature design pages. Lastly, the decision recommendations page is displayed as shown in Figure 8-19 for the user demonstrating the evaluation for each of the addressed feature manufacturability limitations. Firstly, for the hole feature the FBMAS displayed that it is recommended to manufacture this feature using SLM or die-sink EDM technology. The same recommendation was returned for the slot feature. As for the pocket features, three of the pocket feature design groups were recommended to be manufactured using SLM or die-sink EDM, however, one pocket feature displayed no apparent limitation to be manufactured using CNC machining or SLM technology. Therefore, the user is offered a recommendation to preferably use SLM technology as was shown in the recommendation list that SLM technology

was displayed as the recommended approach for all evaluated features. As a second alternative manufacturing approach, die-sink EDM is a recommended approach for the core of the sign base component. The recommendations retrieved by the FBMAS corresponds with the recommendations given by the consulted experts in the field. The recommended approach to manufacture the core tool insert is SLM or die-sink EDM, given the availability of the selected approach.

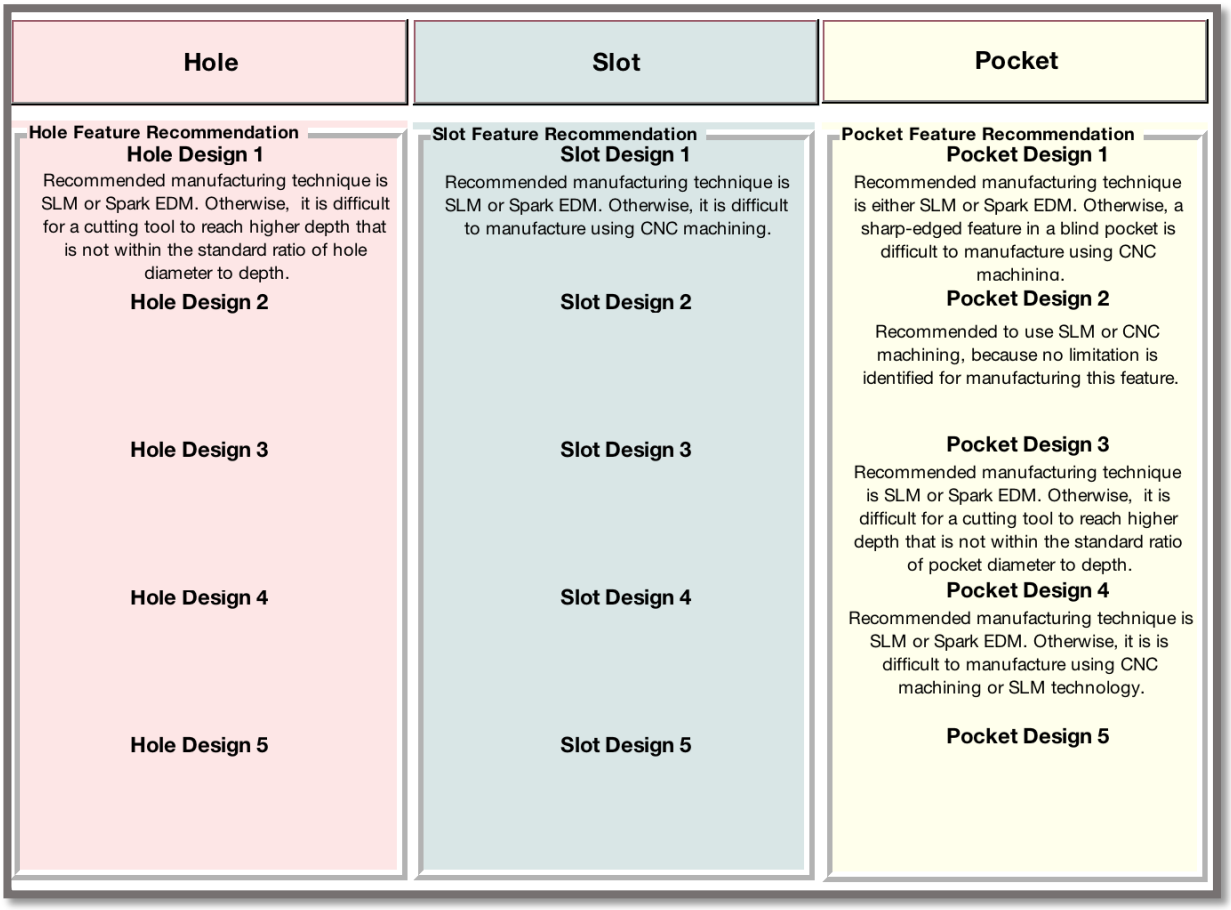


Figure 8-19: Decision recommendation for sign base core insert.

(iii) Cavity insert features' evaluation using FBMAS

The cavity features were entered into the system and the decision recommendation were retrieved by the FBMAS. The defined design features fed to the system are shown in Table 8-4.

Table 8-4: Feature specifications for sign base cavity insert.

Part Size	**85.31 X 85.31 X 55.5 mm**
Pocket Feature Design Group 1	
Diameter	12.06 X 38.76 mm, blind pocket

The input features' information is identified by the system and the pocket design pages are displayed. The user responds to the enquires displayed in the pocket feature page. Subsequently, the next button is pressed by the user and the decision recommendation page is displayed as shown in Figure 8-20 to demonstrate the possible design recommendations. Moreover, the recommended approach to manufacture the cavity insert is SLM or die-sink EDM depending on the availability of the manufacturing system. The recommendations retrieved from the FBMAS corresponds with the recommendations given by the consulted design experts.

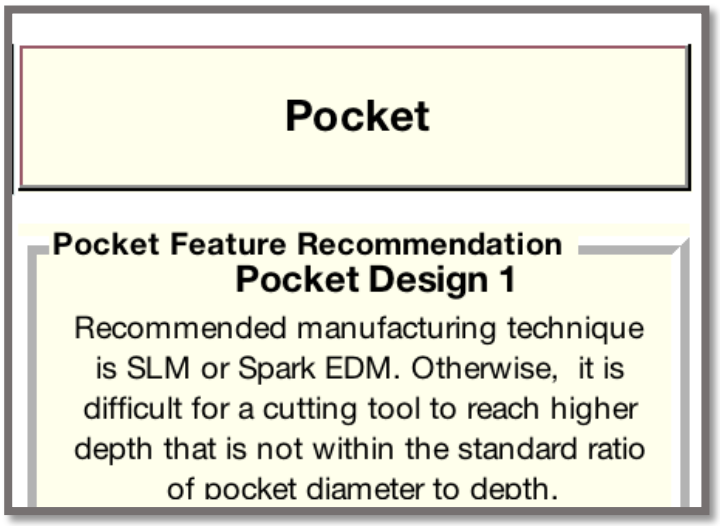


Figure 8-20: Decision recommendation for sign base cavity insert.

8.4 Summary

The developed FBMAS has been verified and the system's logic was proven to be accurate when tested. Six inserts were selected to assist in the validation process exhibiting variability in the type of design feature validated for each study. Firstly, the outcome from Plug A core insert demonstrated that for the slot, pocket, and boss extrude features it is recommended

to use SLM or die-sink EDM technology. As for the cavity insert of Plug A, it is recommended to manufacture the slot, pocket, and freeform pattern features using SLM technology. For the reflector's core insert, it was shown that the required base pattern must have a sharp-edge tip, therefore the FBMAS recommended that the core insert to be manufactured using SLM technology. As for the sign base core and cavity inserts, the FBMAS demonstrated recommendations of manufacturing the hole, slot, and pocket features of the core insert using SLM technology. AS for the cavity insert, it is recommended to manufacture the pocket feature using either SLM or die-sink EDM.

Addressing the system's specifications and limitations provided the user with a focused insight on the positive outcomes of evaluating the tool insert's feature manufacturability, although, there are other aspects to consider when selecting the adequate methods of manufacturing a tool insert. The FBMAS decision recommendations proved to be in correspondence with the decision recommendations of the field experts in evaluating feature manufacturability of the appointed tool inserts.

9 Conclusion and Future Work

9.1 Conclusions

Conclusions that have been derived from this research are presented in this chapter as well as suggested future work. The aim of this research focused on testing the use of SLM in fabricating stainless steel 316 L injection moulding tool inserts for medium to high volume production. Furthermore, it aimed to develop a feature-based manufacturability assessment system (FBMAS) that enables engineers to assess and identify the ideal manufacturing technique through applying SLM and subtractive processes for tool insert manufacturing. The manufacturability assessment process is based upon a set of predetermined design criteria that assists users in evaluating manufacturability limitations of the defined features and recommending the ideal manufacturing method.

Experimental work conducted on the tool inserts fabricated using SLM led to the following conclusions:

- The tool inserts were fabricated within the accepted design tolerances with awareness that the SLM-fabricated inserts require further post-processing to improve the surface finish after fabrication.
- SLM-fabricated tool inserts for the headlamp's adjuster clip (chapter 3 and 4) proved to be successful in performance with regard to the injection moulding process.
- Microstructure analysis confirmed the inclusion of high contents of carbides such as Chromium, Nickel and Molybdenum. The existence of carbides detected along the layer boundaries caused by the sintering process resulted in reinforcing some mechanical properties of the specimens produced such as hardness and wear resistance.
- It was concluded that the results from the fatigue test provided correlations between the mechanical properties and injection moulding processing performance of SLM-fabricated stainless steel 316 L tool inserts where no failure occurs for the test specimens after 3.4 million cycles.
- Injection moulding of the adjustor clip tool inserts proved successful. It was established that a minor increase to hardness values occurred after injection

moulding. An example for the hardness test, prior to injection moulding the core and cavity of tool insert 1 have hardness values of 242 HV, after 10,000 injections, the core hardness value increased to 259 HV and the cavity increased to 264 HV. Whereas an evident increase to surface roughness of surfaces B1, B2, and C has been detected after the completion of injection moulding.

- Wear is a result of the progression of the injection moulding process. Alterations to dimensional accuracy verifies that the tool inserts are liable to wear due to successive loads by the injection moulding process. It is concluded that even though wear clearly progresses as the number of injections increase, the end-products are functionally and dimensionally acceptable.
- After the tool inserts proved to be successful in producing thousands of functional products, more production runs were initiated to guarantee longevity of the tool inserts. Injection moulding continued production until 150,000 parts were produced from one tool insert alone. The parts proved to be functional and visually acceptable showing no signs of defects.
- In terms of surface roughness, it was concluded that the SLM-fabricated inserts and hence the SLM-produced parts proved to have relatively lower values of surface roughness in comparison to their CNC counterparts.
- The optical test performed verified that the reflectors are entirely functional as was intended. As a result, due to higher geometrical accuracy of the SLM-produced reflector, reflection capabilities surpass those of the CNC-produced reflector.

SLM proved to be advantageous when dealing with complex geometries attaining the required geometries, the acceptable surface roughness, and maintaining dimensional accuracy.

- The three studies discussed in Chapter 6 justified the use of different design methodologies (DFAM and DFSM) for the same tool insert depending on the manufacturability requirements and limitations. The systematic approach established for this research is successful in capturing the benefits of SLM and subtractive methods of manufacturing. The areas on the tool inserts that hold the most geometrical complexities to manufacture are focused on, whilst defining design limitations of each manufacturing method.

- The developed FBMAS evaluated design features of tool inserts to assist users in determining the most suitable manufacturing methodology whether SLM or subtractive manufacturing. It was noted that the developed FBMAS decision recommendations proved to be in correspondence with the decision recommendations of the field experts in evaluating feature manufacturability of the tool inserts. The developed FBMAS has been self-verified against the criteria set by the field experts. The system's logic was proven to be accurate when tested. Selected tool inserts assisted in the validation process exhibiting variability in the type of design feature validated for each study.

9.2 Future Work

Future work includes:

- Investigating the use of other powder metal materials for SLM tool insert fabrication and a wider range of polymers for the injected products. Stainless steel 316 L is primarily used by the majority of commercial companies for fabricating SLM components.
- After the successful injection moulding of 150,000 functional parts with no signs of failure, the tool insert could be tested for producing multiple hundred thousand of injections or until complete tool failure occurs. time and cost have been critical factors to the success of this research work. Therefore, it was not feasible to continue the production runs after achieving 150,000 successful injections.
- Upgrading the FBMAS to include a decision-making process, where the user is provided with a solution for part manufacturability that integrates the use of SLM and subtractive methods of manufacturing in a hybrid approach.
- Including economical cost factors and process lead-time parameters to the evaluation process. Cost factors and lead-time had to be omitted in this research to avoid inconsistent outcomes as a result of unavailability of SLM technology at the country where the research work has taken place.

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Appendix A.

Kashouty, M. F. El, Rennie, A. E. W. and Ghazy, M. (2015) 'Assessing additive and subtractive manufacturing technologies for the production of tools in the automotive industry', in *Computer Aided Production Engineering (CAPE 23)*. Edinburgh, UK, pp. 1–8.

Assessing additive and subtractive manufacturing technologies for the production of tools in the automotive industry

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Abstract: Tooling is an integral component to the traditional manufacturing cycle, despite the fact that it's both costly and time-consuming to produce. Additive manufacturing (AM) is currently considered viable in certain instances, often competing against subtractive manufacturing in the delivery of tools, on time, with the required quality. This paper considers the use of AM and computer numerical control (CNC) machining to manufacture an insert for the tooling of a vehicle headlight adjuster clip. The proposed methodology for manufacturing the insert is composed of two manufacturing techniques: AM using selective laser melting (SLM) technology and CNC milling. The tool material used to manufacture the inserts in both cases is Stainless Steel 316L, whilst the injected parts are manufactured in polypropylene. Performance tests were applied to each of the two inserts in the context of material chemical composition, microstructure, hardness, surface roughness, and dimensional accuracy. Furthermore, the injected parts produced were tested to determine dimensional accuracy, quality and functionality. Finally, it was concluded that both the SLM insert and CNC machined insert successfully produced functional parts. Moreover, the products from the SLM tool insert were more accurate dimensionally, but in terms of surface finish, the CNC product was perceived to be better quality.

Keywords: Additive Manufacturing, Selective Laser Melting CNC Machining, Injection Mould Tools, Tool Manufacturing, Automotive Industry.

1 Introduction

Regardless of the dynamic technological advancement in product development and manufacturing techniques, tooling is still considered to be essential and irreplaceable. Some applications for high production volumes require tooling despite the fact that in most instances, it is time consuming and costly (Altan *et al.* 2001). As reported by Ilyas *et al.* (2010), Karunakaran *et al.* (2010), Lupeanu *et al. (*2012), Mellor *et al.* (2014), it is well established that additive manufacturing (AM) advantages precede those of subtractive manufacturing in reducing time for the development of new products with the added benefit of customisation. Potentially, AM cuts down manufacturing lead-times resulting in reduced processing costs (Kerbrat *et al.* 2011).

AM processes are now capable of creating functional parts from metallic alloy powder *(e.g. Vayre et al.* 2012) such as with selective laser melting (SLM). It is noted that cost does not fluctuate with the complexity of the design (Cooper *et al.* 2012; Nagahanumaiah *et al.* 2008), although, poor surface finish and dimensional accuracy are two major predicaments when it comes to successful employment of AM (Karunakaran *et al.* 2000; Newman *et al.* 2015). Tay and Haider (2002) were able to improve surface roughness of AM components from 17–19 μm to 2–3 μm through a process of electroless nickel plating without impacting adversely on the final dimensional accuracy.

Previous studies compared traditional tool fabrication methods with Direct Metal Laser Sintering (DMLS) for an automotive company. The results were satisfying, showing a reduction in lead-time

and cost when using AM for tooling. Traditional machining and Electric Discharge Machining (EDM) took twice as long as DMLS, while tolerances and overall quality were considered equivalent (Wohlers 2010). Moreover, (Newman *et al.* (2015) and Swamidass and Winch (2002) state that 70% of manufacturing businesses in the UK and the US adopting CNC machining, produce significant material waste. (Townsend *et al.* 2012) related AM and machining to assess time, money, knowledge limitations, and opportunities while ensuring that the end product accomplishes the goals of the industrial sectors.

This paper considers the techniques employed for tool manufacturing, discussing the different experimentation executed on the tool inserts produced by both SLM and CNC machining, and how these were employed successfully in the injection moulding process.

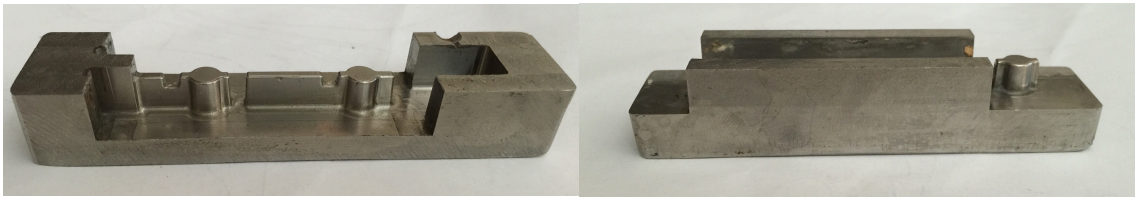
2 Tool Manufacturing

The fabrication of the tool inserts is initiated. Therefore, the CAD design is directed for execution on a CNC milling machine and a SLM machine.

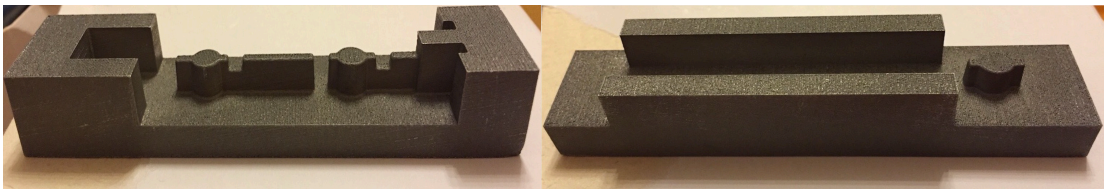
The first set of core and cavity inserts was manufactured at *Al Fouad for Automotive Spare Parts Co*. (Alexandria, Egypt) on two 3-axis First V 700 machines with maximum spindle motor power of 5.5-7.5 KW and 10,000-15,000 RPM. Two End mill carbide tools and one ball nose cutter were used. The diameters for the tool cutter were 4, 16, and 4 mm respectively. The material supplied for manufacturing was Stainless Steel 316L. The approximate time for manufacturing the core and cavity were 12 and 6.5 hours respectively. Cost elements contemplated included labour, conventional and CNC machines depreciation, tooling, energy consumption, and maintenance. The final cost for manufacturing the core and cavity inserts using the conventional subtractive manufacture route was £150.

The second set of parts was built at *Croft Additive Manufacturing Ltd* (Warrington, UK) on a ReaLizer SLM 250 with a laser power of 200 W. The material provided for fabricating the inserts was Stainless Steel 316L powder supplied by LPW Technology Ltd (Runcorn, UK), with particle size nominally in the range 45-150 μm and a layer thickness of 50 μm. The approximate cost of fabricating the parts is 129 Build time for these parts is difficult to define, as the parts are not built individually. Other components were built in the same chamber to maximize the available build area/volume and economies of scale. Furthermore, the cost for fabricating the insert using the SLM process is marginally less than the cost of CNC machining. This might indicate that SLM is more cost effective compared to machining.

Fig. 1 shows the manufactured tool inserts. The first set was CNC machined, while the second set was built using SLM.



CNC machined core **CNC machined cavity**



SLM core **SLM cavity**

Fig. 1 Manufactured tool inserts

3 Experimental Evaluations of the Tool Inserts

Several experiments were executed on the two sets of Stainless Steel 316L inserts. The following experiments were implemented in the sequence below:

- Spectral Analysis Test
- Microscopic Testing
- Hardness Test
- Surface Roughness and Dimensional Accuracy Tests

Spectral Analysis Test

A Spectral Analyzer was used to determine the chemical composition of the material used to manufacture the two sets of inserts. Table 1 shows the standard chemical composition values of Stainless Steel 316L and how this compares with the SLM and CNC machined versions. These were found to be within an acceptable range as compared to the standard composition of Stainless Steel 316L. However, the slightly increased difference between the CNC and SLM inserts is expected to have a direct influence on the performance and hardness of the inserts.

Table 1 Chemical composition (Wt%)

	Wt %								
Sample	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
Standard (AK Steel 2007)	0.035	0.75	2	0.045	0.03	16-18	2-3	10-14	Balance
CNC	0.079	0.411	1.43	0.026	0.017	16.645	2.09	9.9	68.283
SLM	0.071	0.52	1.33	0.045	0.045	16.352	2.02	11.19	67.893

Microscopic Testing

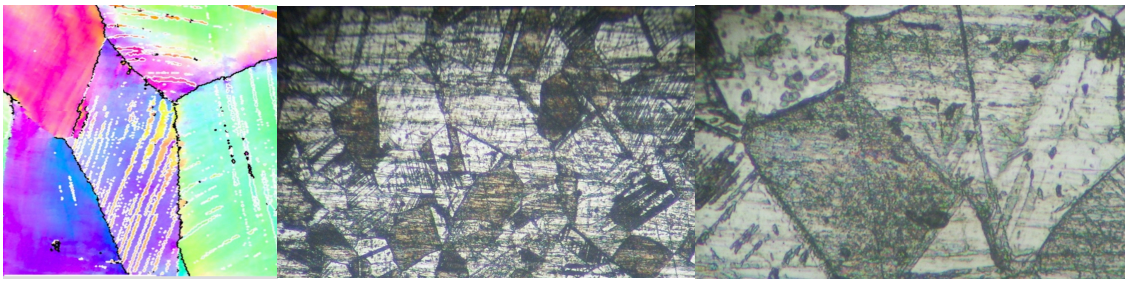
The two sets of Stainless Steel 316L specimens were prepared for microscopic viewing. The first step was to polish all the surfaces to get them as scratch free as possible. The parts were wet smoothed by a linish belt grinder using 180 grit abrasive sand paper (approx. 5 mins for each part). The samples were further polished successively with 220 and 1000 grit abrasive sand paper to acquire the necessary surface smoothness. Fig. 2 illustrates the preliminary polishing methods used.

Belt linish grinding **Surface polishing 1000 grit abrasive sand paper**

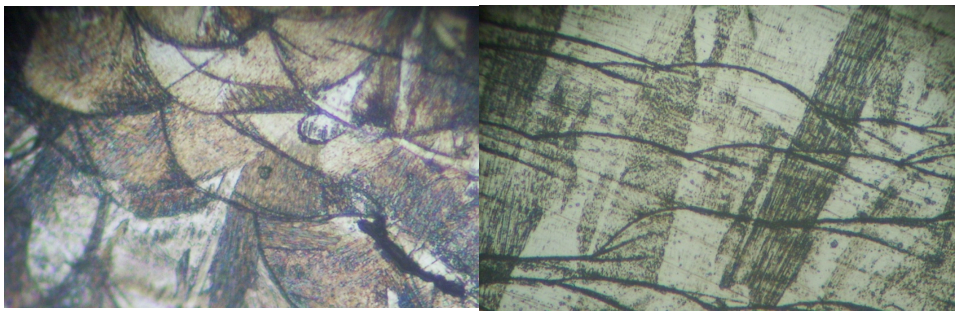
Fig. 2 Sample pictures of surface polishing

Maintaining a glossy look to the surfaces, a polishing paste (Microid Diamond Compound, LECO Corp. Michigan, USA) was applied to the surfaces and rubbed with a smooth cloth. Polishing was a preliminary stage to prepare the specimens for etching, hence an acidic solution was prepared containing pure white Alcohol 96%, Nitric Acid 2% (with a concentration of 69%) and Hydrochloric Acid 2%. Each designated surface on the specimens was submerged for approximately 20 mins.

The etched surfaces were subsequently inspected using a Carl Zeiss Axiovert 200 microscope for grain microstructure viewing. Fig. 3 shows 200x and 500x magnified images for the microstructure of the CNC machined core, machined cavity, SLM core, and SLM cavity respectively. When comparing the microstructure of Stainless Steel 316L of both the CNC machined core and cavity with the standard microstructure, there are no apparent differences (Odnobokova et al. 2014). Nevertheless, for the SLM inserts it is hard to distinguish the grain size and boundaries due to distortion caused by melting. The lack of uniform distribution of temperature during the build causes unpredictable formations and influences the uniformity of grain sizes.



Standard Stainless Steel 316L (Odnobokova et al. 2014) **CNC machined core** **CNC machined cavity**



SLM core **SLM cavity**

Fig. 3 Comparison between microstructure (200x and 500x magnification)

Hardness Test

A Vickers hardness test was conducted I to measure hardness for both sets of inserts. For the CNC machined specimen, the HV value is 270, while the SLM is 199. Therefore, increased lifetime, durability and wear resistance is expected of the CNC machined specimen as compared to the SLM.

Surface and Dimensional Measurements

In order to assess and quantify the roughness of the SLM specimens, a Talysurf instrument was used to measure the surface roughness. Fig. 4 illustrates a 2D drawing of the core and cavity inserts with the surfaces that have been selected and measured: surfaces A, B1, B2, and C. Table 2 gives the average roughness (Ra) values of the SLM specimens depicting rather high values for surface roughness in comparison to the surface roughness of the CNC machined specimen.

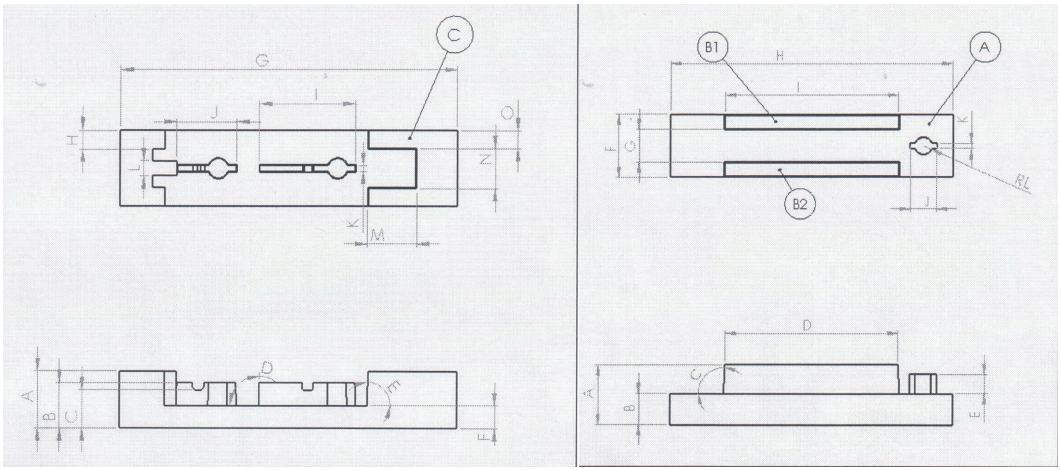


Fig. 4 2D drawing of core and cavity tool inserts

Table 2 Average roughness (Ra) measurements

Surface	Ra (um)
A	10
B1	14
B2	14
C	15

Further analysis determined the dimensional tolerances of the SLM and the CNC machined tool insert measurements in relation to the CAD geometry. The CNC machined tool insert shows no noticeable deviation in dimensional values, whereas the SLM tool inserts show slight dimensional errors. Specific dimensional measurements were accounted for as highlighted in Fig. 4. Furthermore, Tables 3 and 4 illustrate the specified measured values of both the core and cavity in relation to the geometric CAD measurements. A 0.005 mm shrinkage allowance is deliberately considered for polypropylene injection.

Table 3 Dimensional measurements for core tool inserts

Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)
A	15	14.9	-0.1	**I**	26	26	0
B	12	12.05	0.05	**J**	16	15.8	-0.2
C	10	10.05	0.05	**K**	2	2.03	0.03
D (Deg)	92°	91° 47’	-13’	**L**	4	4.01	-0.01
E (Deg)	88°	88° 13’	13’	**M**	12.7	12.71	0.01
F	6	6	0	**N**	9.5	9.4	-0.1
G	90	90.1	0.1	**O**	5	4.9	-0.10
H	5	5.15	0.15				

Table 4 Dimensional measurements for cavity tool insert

Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)
A	19.05	19	-0.05	**G**	10	10	0
B	10	10.05	0.05	**H**	90	90	0
C (Deg)	92°	92° 18’	18	**I**	56	55.96	-0.04
D	55.4	55.45	0.05	**J**	8.7	8.8	0.1
E	6	6.06	0.06	**K**	2	2.06	0.06
F	20	19.95	-0.05				

4 Injection Moulding

The SLM and CNC machined tool inserts were both assembled to the same tool plates. Therefore both sets of inserts would undergo the same impressions at the same working conditions, ensuring direct comparability of the results.

The tool was injected using a Nurnak MMRJ 130-225 Injection moulding machine with clamping force of 100 ton. Polypropylene was used with a material feed stock rate of 15 grams/stroke and injection pressure of 70-80 bar at a temperature of 170-190°C. The average cycle time was approximately 30 seconds. The net weight for the SLM-derived product was 4.20 g, whilst the CNC-derived product was 4.24 g. 500 impressions were batched into two packages, one for the SLM product and the other for the CNC machined product. 10 samples from each package were selected for 10 measurements. These measurements with their corresponding nominal values are given in Fig. 5. More importantly, it should be highlighted that the resulting dimensional measurements (as shown in Table 5) of the SLM product have minimal error in comparison with

the CNC product. Despite the fact that, the SLM tool insert measurements have shown deviations from the nominal values. Moreover, these results are caused by the shrinkage allowance of the polypropelene injected parts.

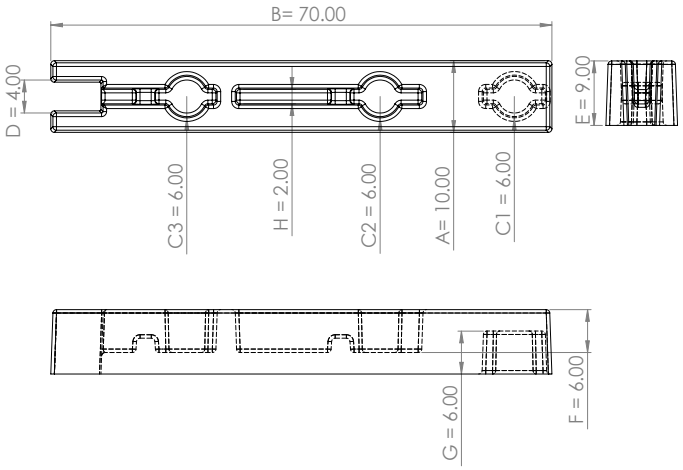


Fig. 5 Product measurements

Table 5 Dimensional measurements for CNC and SLM products

Dimensions	Nominal Values (mm)	Average CNC Product Measurement (mm)	Error (mm)	Average SLM Product Measurement (mm)	Error (mm)
A	10.00	9.75	0.04	9.75	0.00
B	70.00	69.03	0.05	69.64	0.02
C1 (Φ)	6.00	5.78	0.04	5.80	0.00
C2 (Φ)	6.00	5.67	0.05	5.20	0.00
C3 (Φ)	6.00	5.66	0.05	5.50	0.00
D	4.00	4.00	0.00	4.00	0.00
E	9.00	8.77	0.05	8.80	0.00
F	6.00	6.20	0.01	5.90	0.00
G	6.00	6.00	0.02	5.75	0.00
H	2.00	2.02	0.04	1.95	0.00

5 Conclusions

The results from the different experiments that were executed on the tool insert are summarized as follows: the SLM tool insert is productive and achieves significant benefits in terms of cost, product functionality and dimensional accuracy. During the spectral analysis test, chemical composition of both inserts was within acceptable range as compared to the standard composition of Stainless Steel 316L. Nevertheless, when observing the SLM inserts, grain size and boundaries were indefinable due to distortion caused by melting as compared to the CNC machined insert. As for the surface roughness, SLM lags behind CNC machining but with a slight difference. Finally, the resulting dimensional measurements of the SLM product showed no error in comparison with the CNC product proving product reliability.

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Appendix B.

El Kashouty, M. F., Rennie, A. E. W. and Ghazy, M. (2019) ‘Tool life performance of injection mould tooling fabricated by Selective Laser Melting for high- volume production’, Materials, 12(23). doi: 10.3390/ma122333910.

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Tool Life Performance of Injection Mould Tooling Fabricated by Selective Laser Melting for High-Volume Production

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Abstract: Rapid Tooling processes are developing and proving to be a reliable method to compete with subtractive techniques for tool making. This paper investigates large volume production of components produced from Selective Laser Melting (SLM) fabricated injection moulding tool inserts. To date, other researchers have focused primarily on investigating the use of additive manufacturing technology for injection moulding for low-volume component production rather than high volume production. In this study, SLM technology has been used to fabricate four Stainless Steel 316L tool inserts of a similar geometry for an after-market automotive spare part. The SLM tool inserts have been evaluated to analyse the maximum number of successful injections and quality of performance. Microstructure inspection and chemical composition analysis have been investigated. Performance tests were conducted for the four tool inserts before and after injection moulding in the context of hardness testing and dimensional accuracy. For the first reported time, 150,000 injected products were successfully produced from the four SLM tool inserts. Tool inserts performance was monitored under actual operating conditions considering high-level demands. In the scope of this research, SLM proved to be a dependable manufacturing technique for most part geometries and an effective alternative to subtractive manufacturing for high-volume injection moulding tools for the aftermarket automotive sector.

Keywords: Rapid Tooling; additive manufacturing; Selective Laser Melting; injection moulding; tool inserts; automotive industry

1. Introduction

Selective Laser Melting (SLM) is an additive manufacturing (AM) process that produces three-dimensional (3D) functional metallic parts [1,2] directly from CAD data by selectively melting metallic powder using a laser beam, forming near net-shaped layered components that typically require post processing for surface finish improvement [3,4]. AM processes facilitate fabrication of geometrically complex components and freeform designs, as opposed to the limitations associated with conventional subtractive machining [5,6]. Despite these positive aspects, AM techniques continue to exhibit disadvantages that must be addressed and surpassed [7,8].

Studies have discussed an approach to improving AM techniques to provide a better-quality surface finish on fabricated metallic parts [9,10]. Currently in this context, Ahn and Yakout et al. [11,12] stated that none of the commercially available AM technologies has the ability to produce net-shaped

components that require no further post-processing. Furthermore, Guo et al. [13] mentioned that parts fabricated by AM processes may require post-processing due to low dimensional accuracy and poor surface quality. Conversely, Gokuldoss et al. [14] reviewed that SLM technology tends to produce accurate parts or that minimal tolerance is required. Advances in AM are progressing to improve surface finish, dimensional accuracy, and durability; advances in machining research are also in progress [15].

Although affordable alternatives are sought after to avoid the use of tooling, in most part reproduction, rapid manufacturing is an alternative that has been unable to overcome the use of tooling as indicated by Wohlers [16]. Tooling continues to be essential to many industries for higher-volume production quantities because of the benefits of speed and cost. Tool making is a complex procedure and demands the use of high-end technology and skilled labour; therefore, industries are seeking out the use of Computer Numerical Control (CNC) machines in order to produce components with high quality despite the longer machining time and cost of manufacturing the tools [17]. However, recent research has proven the success of incorporating AM in the toolmaking process for low-volume production [18].

Researchers have shown that Rapid Tooling (RT) is a technique with great potential that aims to significantly reduce the product development cycle [19,20], eventually yielding cost and time benefits [21]. Wohlers [16] indicated that AM should not be overlooked as a technology that can produce tools, with significant potential to produce tooling inserts. There are two approaches to rapid tool manufacturing: direct and indirect tooling. Ding et al. and Au et al. [22,23] stated that direct tooling does not necessitate the production of a pattern, as tool inserts are produced directly. The use of each depends on the potential characteristics required by the manufacturers and the size of the production volume [24]. Contrary, indirect tooling necessitates the use of a master pattern that can be produced using an additive manufacturing method such as Selective Laser Sintering (SLS) or Stereolithography (SLA).

Long-term consistent tools should be capable of producing several thousands of parts before eventually wearing out. Levy et al. and Kruth et al. [25,26] highlighted the importance of tooling applications particularly for injection moulding, while other techniques such as sheet metal forming and forging dies were considered for low volume production. Previous successful studies were reviewed by Rahmati & Dickens [27] for low volume production of injection mould tooling. Kashouty et al. [28] presented a comparative study to assess additive and subtractive manufacturing technologies through fabricating two identical tool inserts that produced 500 injected components. Other studies focused on producing 500 components and subjecting the tool to severe stress and thermal conditions while performing the necessary tests to obtain the required data. Moreover, during the injection process, theoretical and analytical investigation of the tools were carried out. Additional studies by Xhang et al. [29] specified the durability of carbon fibre reinforced photopolymer tool inserts up to 2500 injections before a deterioration of the tool inserts was noticeably observed. This 'soft' tooling process was suitable for production volumes that range from 1000 to 10,000 cycles of injection moulding.

Other research analysed and reviewed the use of RT for the production of tools and dies, whether direct or indirect for low-volume or high-volume production, without conducting a more in-depth evaluation of the number of parts produced [30,31]. Ponche et al. [32] proposed a numerical chain based on a new design for AM methodology detailing both design requirements and manufacturing specificities, whilst Nagahanumaiah & Mukherjee [33] presented a systematic approach for manufacturability analysis of moulds produced by RT methods, the approach being founded on three phases: mould feature manufacturability; secondary elements compatibility; and cost effectiveness. The presented methodology not only assisted in RT process selection, but also facilitated the process of recognising minor adjustments to a tool design that eventually improves its manufacturability and cost. Ahn [11] presented research that investigated methods to overcome limitations of conventional tools in the context of energy consumption, environmental impact and material usage to develop eco-friendly tools. Machining time and cost is significantly reduced when compared to subtractive

manufacturing approaches based on CNC machining for tool manufacturing [29]. Brooke [34] referred to Hopkinson's argument that High Speed Sintering (HSS) will eventually displace CNC technologies for the production of components in high volumes. Achillas et al. [18] debated that AM technologies are not capable of replacing injection moulding for medium and high production volumes. However, RT could be incorporated for low volume production to achieve shorter lead-times and reduced production costs. Mahshid et al. [35] specified that advances in laser-based AM processes permitted fabrication of complex metal components that are impossible to achieve using subtractive processes alone.

Akula and Karunakaran [36] proposed that certain characteristics must be maintained for RT processes to ensure the success of manufacturing accurate tools. To ensure viability of AM technology, geometric and dimensional quality should be improved for rapid tools, whilst eliminating human intervention and reducing cost and time, to be as close as that attained in the case of conventionally manufactured tools [33]. Gu et al. [37] discussed the necessity of producing parts that meet the mechanical properties required by industry, hence, emphasising that the role of AM is towards functional components that serve industrial sectors. Flynn et al. [7] reviewed the most common approaches to finishing AM fabricated metal components through subtractive machining, thermal, chemical and electrochemical processing. Maamoun et al. [38] studied the effect of thermal post processing on the performance of SLM parts. Machining is generally used to improve dimensional accuracy in near-net shaping processes such as moulding. Additional context is reported within the literature for surface quality expectations of AM metallic parts. Spierings et al. [39] recommended finishing of AM components using CNC turning for selected types of steels to achieve the desired surface roughness. Löber et al. [10] used grinding, whilst Rossi et al. [40] were able to report the distinct variation in values of surface roughness between vertical and horizontal surfaces, that clearly signify the importance of build orientation. Zhang et al. [41] presented a study that focused on fabricating micro-structured injection mould tools for the production of thermoplastic microfluidic chips, however, signifying that surface finish and precision needs improvement.

Current research indicates that improving injection moulding cycle time is an important aspect when considering high-performance tools rather than the time taken to produce the tool [16]. Mahshid et al. [35,42] reviewed the possibility of achieving an alternative to manufacturing tools that is capable of producing a lightweight structure that potentially decreases material and manufacturing cost, and eventually leads to a decrease in production cycle time and increasing tool longevity. Interest over recent years is directed towards high-performance tools, however, only examples of low-volume production are given in recent literature. Therefore, more research must be oriented towards tooling for high-volume production and presenting the necessary means for investigating the outcomes. The research presented here focuses on the production of SLM tool inserts and assessing their durability and quality through high volume production of injection moulded components.

This paper considers the processes employed for fabricating four sets of injection moulding tool inserts, with a detailed description of the experimental work undertaken. After the experiments were conducted, the tool inserts were tested for durability and how they were used for the injection moulding of multiple thousands of products from each of the four tool inserts. The injection moulding process was performed in four stages. The four sets of tool inserts each achieved 10,000 injections whereupon the first tool insert was then removed. The remaining three sets of tool inserts reached 20,000 injections and then the second tool insert was detached. The same process was repeated for the remaining two sets of tool inserts and 30,000 injections were completed, after which the third tool insert was removed from the bolster. The last tool insert achieved 150,000 cumulative injections. Experiments were conducted prior to the injection process to inspect microstructure using a Scanning Electron Microscope (SEM), analyzing intermetallic carbide formation with a linked Energy Dispersive Spectroscopy (EDS) system, and hardness tests using Micro-vickers hardness tester to examine the influence and impact of the injection moulding process on the hardness of the material. Further experiments were required to be carried out after the injection moulding process was completed to ensure tool longevity in the context of hardness testing and measuring dimensional accuracy.

Mechanical performance of an injection moulding tool insert such as tool hardness, wear resistance, surface roughness and dimensional accuracy significantly affects the production process. Therefore, this study investigates hardness, dimensional accuracy, and wear resistance of the SLM fabricated tool inserts through the injection of 150,000 parts.

2. Materials and Methods

2.1. Overall Framework

The framework methodology employed in this study is structured to outline the major steps this research work follows: firstly, the four Stainless Steel 316 L tool inserts required for investigating this study were fabricated simultaneously using SLM technology. After the tool inserts were built and removed from the build chamber, microstructure analysis was conducted to explore particle formation of the laser melted specimens, layer structure, and chemical composition. Three types of tests were managed: optical microscopic inspection using a Carl Zeiss Axiovert 200 microscope, SEM inspection using an ultra-high-resolution Leo Supra 55, and EDS analysis. After the microstructure inspection and analysis was successfully investigated, more tests on the fabricated tool inserts were required. The purpose of these tests was to examine micro-hardness and dimensional accuracy of the fabricated tool inserts prior to use in the injection moulding process. Microhardness was achieved using a Leco Vickers micro-hardness tester with a square-based diamond pyramid indenter and 10 Kg load subjected to each half of the tool inserts with a dwell time of 15 s. Each tool insert were categorised into batches and a sample of products was inspected for dimensional accuracy and functionality. At stage two of injection moulding, the first tool insert was excluded, and the remaining three inserts were mounted on the same bolster to continue production until 20,000 injections were completed. The same tests that were performed at previous stages were conducted after the tool inserts were dismounted. Sampling and inspection of dimensional accuracy and functionality of the produced parts were implemented at this stage. The same procedure was followed for the remaining two tool inserts by removing the second tool insert and examining the third and fourth tool inserts and their respective products. After the fourth tool insert successfully achieves 40,000 injections, injection moulding was continued to attempt to reach the goal of producing 150,000 dimensionally accurate, and functionally approved products.

2.2. Tool Insert Fabrication

SLM was used for fabrication of four sets of tool insert specimens directly from 3D CAD data models at an automotive spare-parts manufacturing company. The build was conducted on a Realizer SLM 250 with a laser power of 200W and build orientation as shown in Figure 1. The maximum part dimensions were 90 mm × 20 mm × 15 mm. The final fabricated tool insert core and cavity are shown in Figure 2. Parts were scaled in the CAD model to compensate for allowances caused by shrinkage during cooling of the injected products. Stainless Steel 316L powder was the material in use for the builds, with particle size nominally in the range of 45–150 μm and a layer thickness of 50 μm.

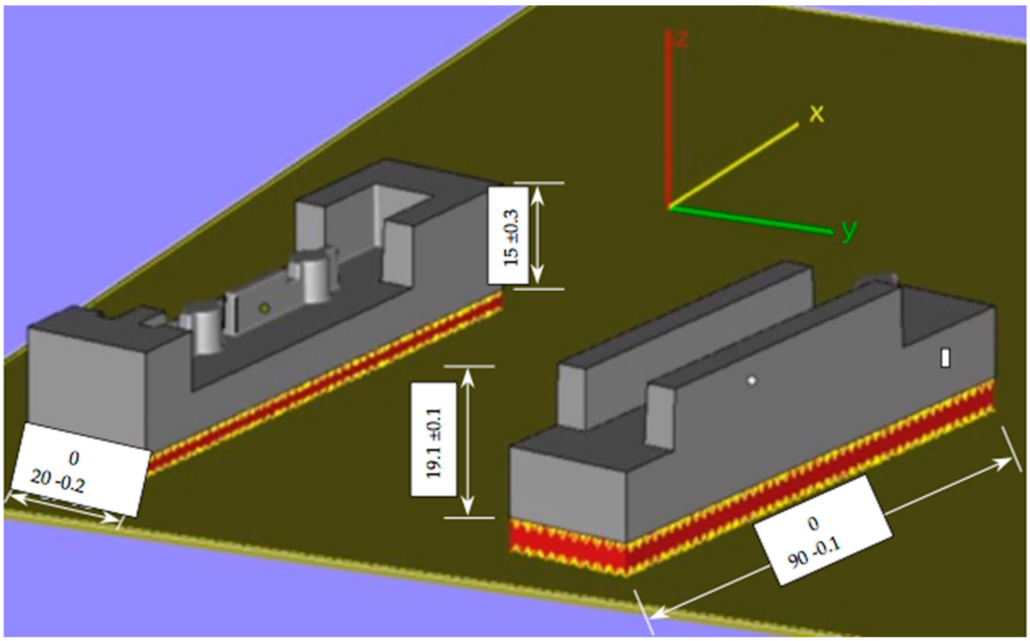

Figure 1. Part orientation, layer structure, and main dimensions (mm) during sintering process.

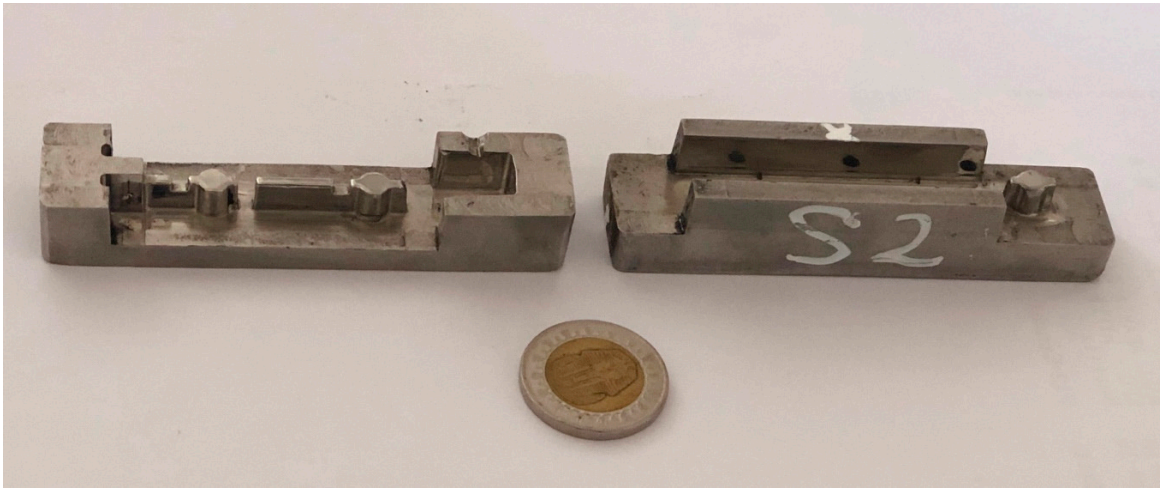

Figure 2. One set of SLM fabricated Core and Cavity tool inserts.

During the SLM fabrication process, the hatch distance defined as the spacing between two consecutive laser beams, identified that the hatch X and Y distance was set at 0.1 mm respectively. Initially, sand blasting was used to remove the excess powder after the fabrication process to ensure accurate surface mating of the Cores with the Cavities of each set of inserts. However, experimental procedures were carried out to investigate microstructure and chemical composition. Further investigations were performed prior to and after injection moulding in the context of microhardness analysis and geometrical accuracy.

3. Tool Experimentation, Results and Discussion

3.1. Microstructure

Four sets of tool inserts were prepared for inspection by optical microscopy. The parts were wet smoothed using a linishing belt grinder with 180 grit abrasive sandpaper for approximately 5 min for each part. The samples were further polished successively with 220 and 1000 grit abrasive sandpaper to acquire the necessary surface finish. To maintain a glossy look, a polishing paste (Microid

Diamond Compound, LECO Corp., St. Joseph, MI, USA) was applied to the surfaces and rubbed with a smooth cloth.

To reveal the microstructure, the polished samples were immersed in a chemical acidic solution for 20 min; the solution contained 96% pure white Alcohol, 2% Nitric Acid (with a concentration of 69%) and 2% Hydrochloric Acid. After removal from the solution, the specimens were cleaned in distilled water. Inspection of the specimens suggested the presence of carbides and porosity along the surface of the layers. Images were captured and magnified to 200x and 500x respectively. Image capturing was repeated three times for each of the five regions of interest chosen on the same specimen to confirm the evidence that higher contents of carbides are detected. The elemental chemical composition of the fabricated specimens was determined using a Spectral Analyser as shown in Table 1. Captured images of the magnified surface are shown in Figure 3.

Table 1. Stainless Steel 316L elemental weights (Wt%).

	Wt %								
Sample	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Fe**
SS 316 L Standard [43]	0.035	0.75	2	0.045	0.03	16-18	2-3	10-14	Balance
SLM	0.024	0.41	1.52	0.023	0.021	16.057	2.38	10.397	Balance

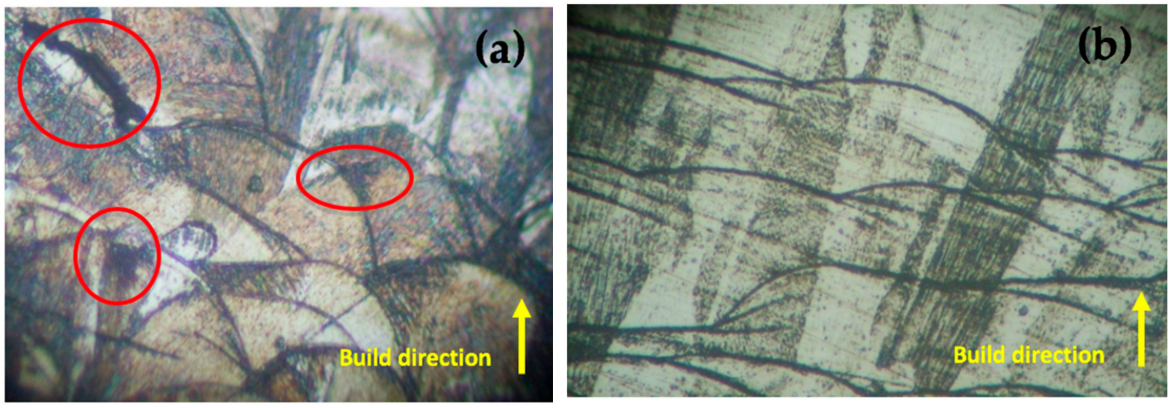

Figure 3. 200x (**a**) and 500x (**b**) magnification of inspected specimen on Carl Zeiss Axiovert 200 with evidence for presence of carbide inclusions.

SEM with a linked EDS system was employed to observe particle formation, layer structure, chemical composition, surface morphology, and microstructure of the laser melted specimens. As highlighted in Figure 3, the presence of intermetallic carbides is concentrated in some regions more than others along the layer surface of the sintered specimens. Three measurements of the layer thickness were recorded for a particular region of the layer as shown in Figure 4. The average recorded layer thickness is 47.17 µm at 228x magnification. The procedure was repeated three times for each region, with five separate regions considered.

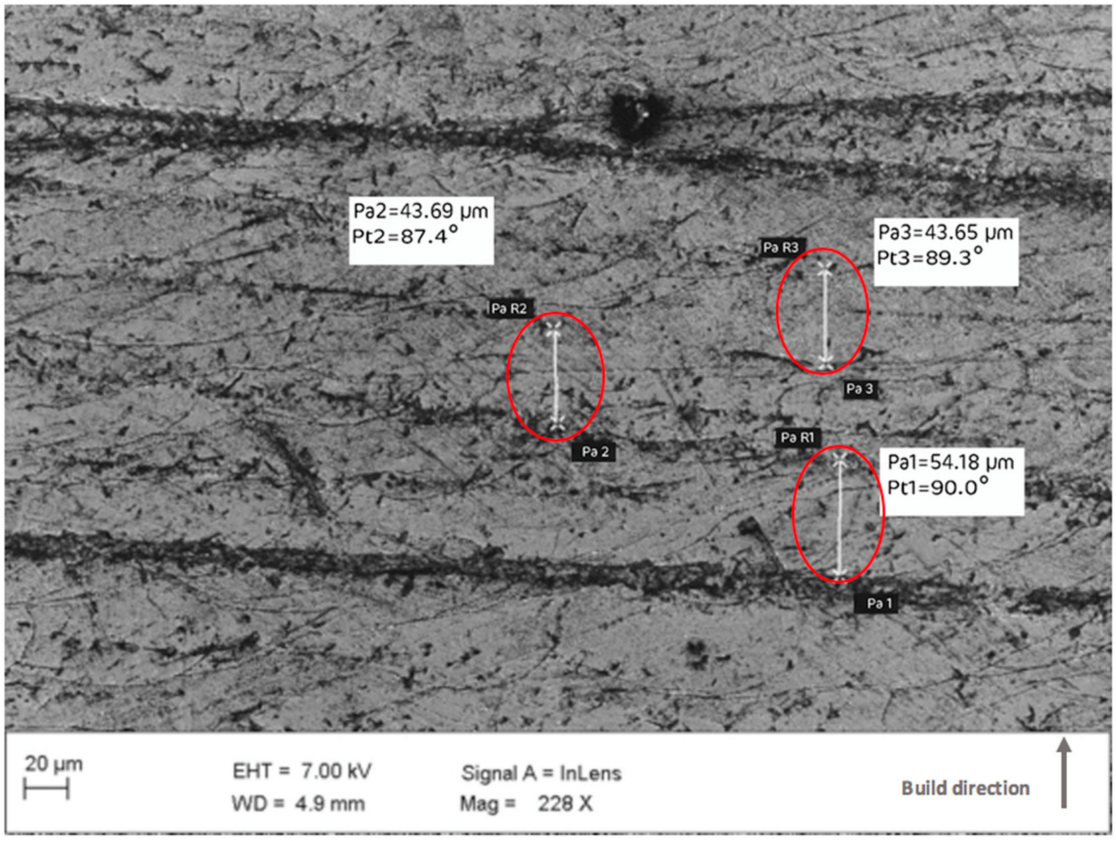

Figure 4. SEM micrographs of SLM tool insert surface with recorded layer thickness at three different points.

Images captured from the SEM provide significant evidence that formation of intermetallic carbides is present along the layer surface of the sintered specimens. Carbide formation is concentrated in some regions more than others, specifically along the boundary of each individual layer. During the laser melting process, the presence of high concentrated weights of chromium, nickel, and molybdenum in Stainless Steel 316L allows carbides to form resulting in comparably superior mechanical properties. Particularly, higher microhardness, enhanced tensile strength, fatigue life, and good corrosion resistance, as compared to commercial Stainless Steel 316 L [44]. The prospect of knowing the elemental type of intermetallic particle that is formed involves extensive analysis. An EDS system was employed to detect the type and size of intermetallic particles that may cause carbide formation. Quantitative analysis of the alloying elements of Stainless Steel 316L was conducted. Figure 5 shows a micrograph of the presence of intermetallic particles along the layer boundary. Images captured are magnified to 150x. The image capture process is repeated three times for the specified region, with five separate regions considered. At different magnifications using SEM, several significant features were discernable. At low magnification, layer melt pool alignment was observed, whilst at higher magnification, intersection between two-layer melt pools revealed a cellular structure and carbide formation.

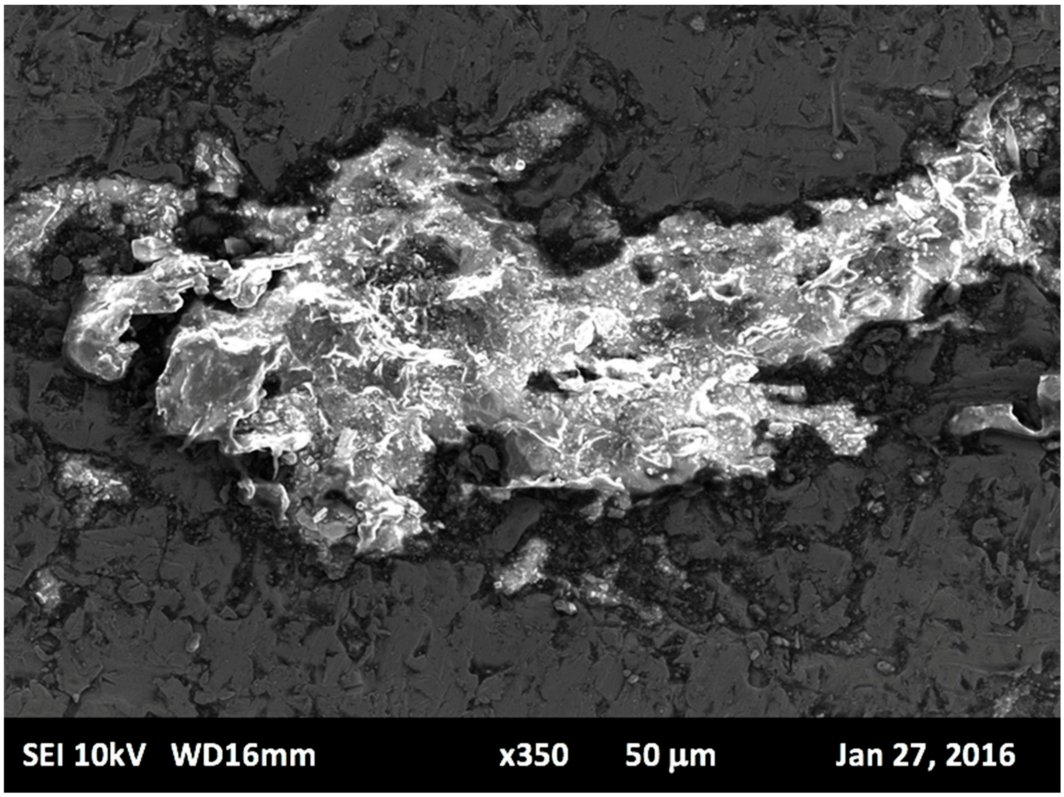

Figure 5. Carbide segregation due to layer boundary.

Figure 6 provides a summary of the results from the EDS analysis. The data indicates the type of intermetallic particle with the highest concentration level is Chromium accounting for 4000 intensity counts. Nickel accounts for 1000 counts, and Molybdenum has the lowest concentration level of 500 counts.

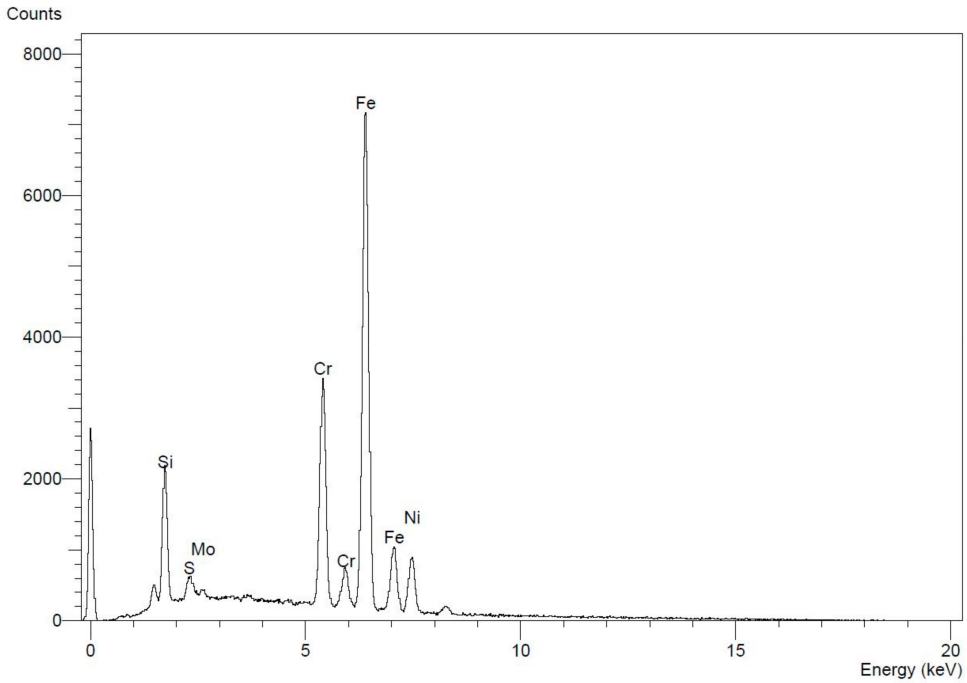

Figure 6. Elemental analysis using EDS for intermetallic particles segregated towards cell boundary, and demonstrating the enrichment of Cr, Ni, and Mo at the boundaries.

The results obtained from the optical microscopy test revealed that after inspection of the specimens, the presence of carbides and porosity along the surface of the layers is noticeable. The data obtained from the spectral analysis test matches with the standard acceptable range for Stainless Steel 316L [43]. Moreover, EDS analysis results confirmed the presence of highly concentrated areas of chromium, nickel, and molybdenum in Stainless Steel 316L allowing carbides to form resulting in reinforcements of some mechanical properties. Summarized in Figure 6, the data indicates the type of intermetallic particle with the highest concentration level. The highest concentration level accounted for was Chromium followed by Nickel, and the lowest concentration level was Molybdenum. Carbon was not counted nor classified in the EDS measurement, because it should only account for less than 2 wt.% of the chemical composition of the material, which is in good agreement of the alloy balance [45]. However, Silica is accounted for with a high concentration level due to the presence of an impurity within the formed carbide particle.

It is well known that during the SLM fabrication process, melt pools are created. Therefore, it was observed using SEM that the melt pools are aligned in an interlacing arrangement as a result of laser scanning patterns and rapid solidification, therefore a distortion to grain structure and boundaries causes considerable difference to microstructure scales for sintered stainless steel 316L [46].

3.2. Hardness Test

A micro-hardness test was employed to determine the Vickers hardness for the SLM fabricated specimens. The micro-hardness test was performed at two different stages of the research to determine the potential variation to hardness as a consequence of the thousands of impressions from continual injection moulding cycles. The first stage of micro-hardness tests was performed individually for the four sets of tool inserts after SLM fabrication and before the tool inserts were mounted for injection moulding. The second stage for testing micro-hardness of the four sets of tool inserts was conducted after the injection moulding process was completed.

For each specimen, two measurement points were recorded to monitor variation in hardness values before and after injection moulding. The values recorded are the resultant average of three readings from the same region. Figure 7 illustrates the changes observed in the hardness values according to the stage in which the test was performed. The Core and Cavity halves of tool insert set 1 have comparable values of 242 HV when tested prior to injection moulding. After 10,000 injections, tool insert set 1 was dismounted and further micro-hardness tests were undertaken. For the Core half, the hardness value had increased to 259 HV and the Cavity half increased to 264 HV. For the second set of tool inserts the same test procedure was conducted, the Core and Cavity had hardness readings of 243.3 HV and 237.6 HV respectively. After 20,000 injections, the second tool insert was dismounted, and hardness tests were performed. The Core hardness value increased to 263.3 HV, while the Cavity increased to 259.6 HV. The Core and Cavity hardness readings before commencing injections for the third tool insert were 237.6 HV and 240 HV respectively. At 30,000 injections, the third tool set is dismounted, the Core hardness reading increased to 263.6 HV and for the Cavity the hardness value increased to 258.3 HV. The fourth tool insert set recorded hardness values of 241 HV and 238 HV for the Core and Cavity respectively before injections. After 40,000 injections, the hardness value for the Core insert increased to 238.3 HV and 248.3 HV for the Cavity.

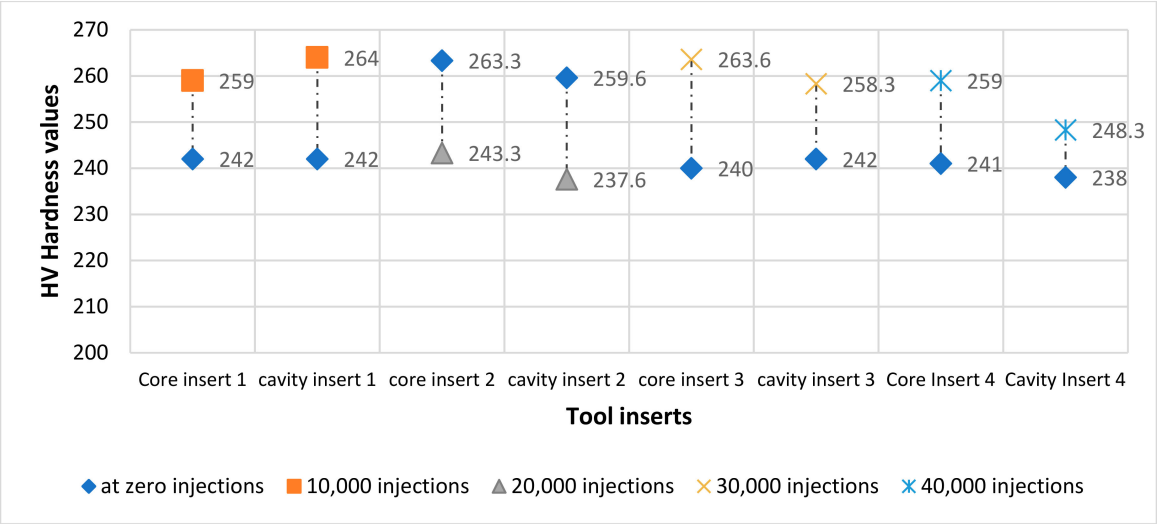

Figure 7. Changes in micro-hardness of the SLM specimens depicts variation prior to and after injection moulding using each tool insert.

The preset value on the machine for layer thickness is set at 50 µm, but it is known that variation in layer thickness can result due to heat dispersions along the built layer. Since increasing layer thickness increases the porosity, hardness eventually decreases with this increase in layer thickness [47]. Moreover, the presence of gas pores depending on their shape and size are also expected to cause defects on the surface in the form of surface porosity. Therefore, the specimens were examined for porosity inclusions.

It is noted that there is a minor increase to the hardness value from the initial material before injection moulding is commenced. This increase in hardness could be explained due to changes of the temperature to which the tool is exposed during processing which has a strong influence on the phase composition, the microstructure and the mechanical performance of 316L stainless steel [48].

3.3. Dimensional Measurements

Further analysis is necessary to determine deviation in measurements from the nominal values after the tool inserts are fabricated, to detect the existence of wear. Polypropylene was the material used for the injected products, so a 1.5 % shrinkage allowance for injection moulding is compensated for during the design stage. Specific dimensional measurements were accounted for in each Core and Cavity of the four SLM tool insert sets. A Zeiss Abbe Horizontal Metroscope and a Zeiss Universal Measuring Machine were used for measuring the dimensional accuracy of the specimens. The tolerances were set according to the automotive spare-parts manufacturing company's standards for tool manufacturing. The dimensions for each Core and Cavity are illustrated in Figures 8 and 9 for the four sets of tool inserts. Dimensional accuracy of all the tool inserts was examined for each of the 15 Core dimensions and the 12 Cavity dimensions specified. Each is the resultant average of three measurements for the same dimension. Four internal and external dimensions were investigated for each tool insert and the dimensions noted are a representation of the rest of the dimensions and their outcomes. The four dimensions selected for this study are dimensions I and N shown in Figure 8 (Core), and dimensions E and G shown in Figure 9 (Cavity). Table 2: lists the dimensions used for measurement assessment of the tool inserts.

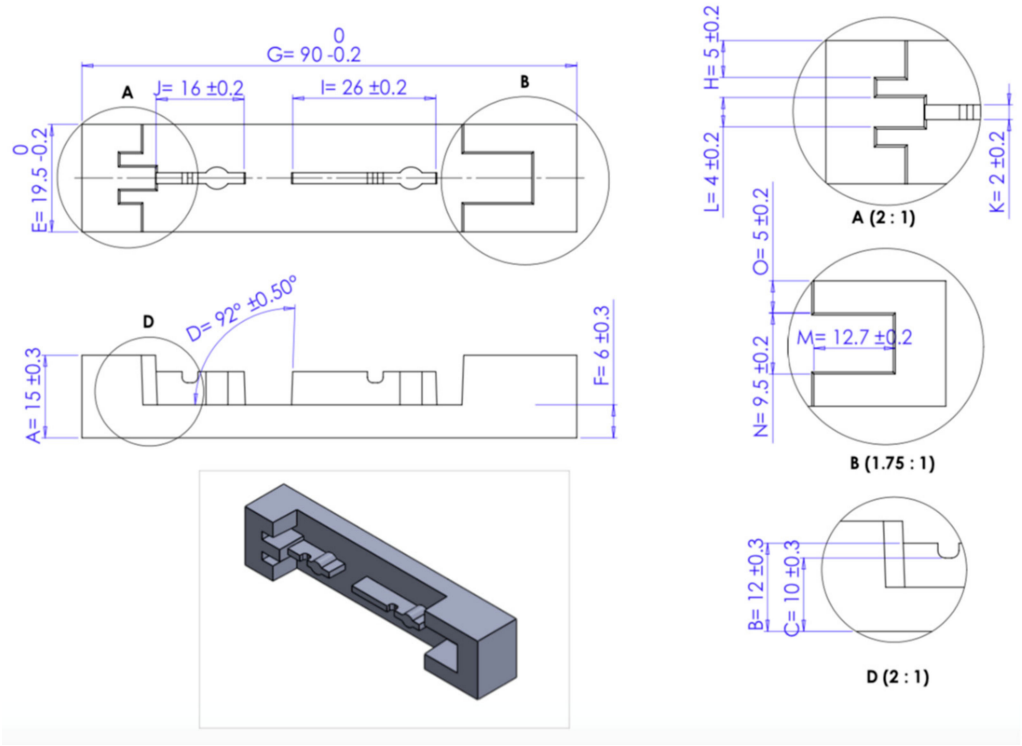

Figure 8. SLM Core measurements (with tolerances indicated).

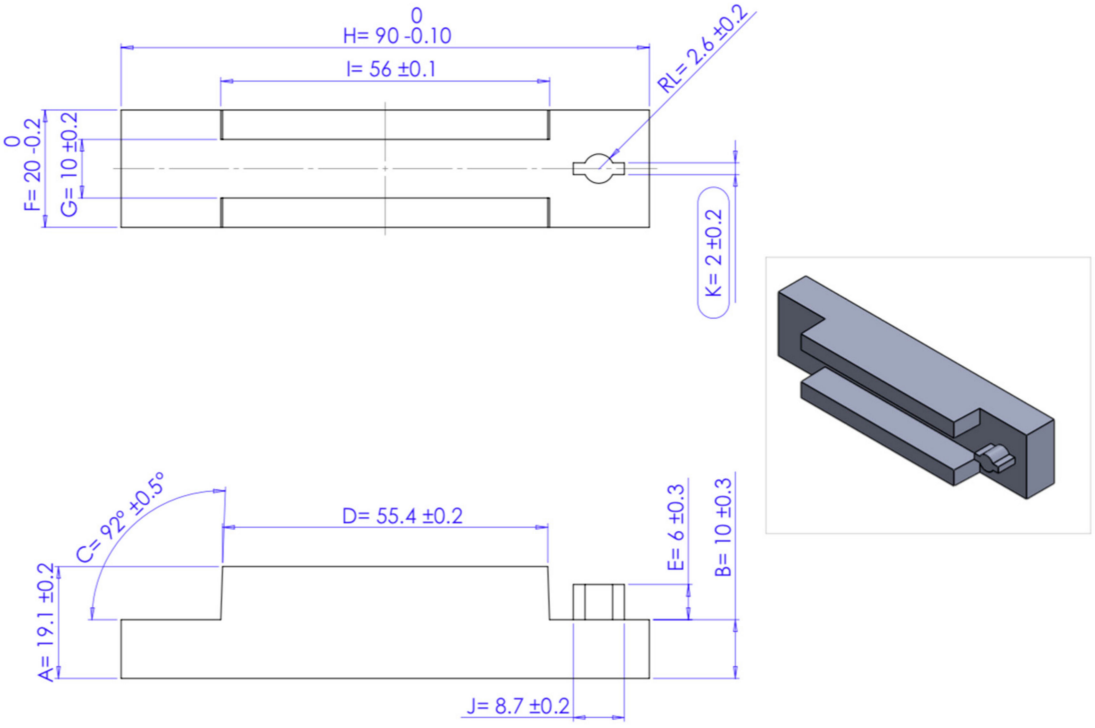

Figure 9. SLM Cavity measurements (with tolerances indicated).

Table 2. Dimensions indicators used for measurement assessment of tool inserts.

Dimension	Location	Type
I	Core	External
N	Core	Internal
E	Cavity	External
G	Cavity	Internal

Measurements were recorded for the four sets of tool inserts after the SLM process and before injection moulding was initiated. Measurements taken before injection for Core halves 1, 2, 3 and 4 are within the range of permissible design tolerance. After 10,000 injections are completed for Tool 1, the Core and Cavity inserts are dismounted, and further dimensional examination is required. After 20,000 injections on tool 2, the same procedure was repeated, and the Core and Cavity inserts were dismounted for further dimensional examination. For tool inserts 3 and 4, the same procedure was repeated by dismounting the third set of tool inserts after 30,000 injections and the fourth tool inserts after 40,000 injections for further dimensional examination.

Dimension I of the Core inserts is an external dimension and has a nominal value of 26 mm and a design tolerance of ± 0.2 mm. Dimension N of the Core inserts is an internal dimension with a nominal value of 6 mm, with a permissible design tolerance of ± 0.2 mm. For the tool Cavities, dimension E is external with a nominal value of 6 mm and ± 0.3 mm design tolerance. Dimension G is an internal dimension of the tool Cavities, the nominal value is set at 10 mm with a ± 0.2 mm design tolerance. Table 3 illustrates the recorded measurements of dimensions I, N, E, and G before and after the injection moulding process and the deviation from the upper and lower permissible tolerances of each dimension. Figure 10 demonstrates dimensional measurements of the tool inserts with upper and lower tolerances.

Table 3. Dimensional measurements before and after injection process and deviation from permissible tolerances (mm).

	Dimension I			Dimension N		
Tool Number	**Measurements before Injection (mm)**	**Measurements after Injection (mm)**	**Deviation from Permissible Tolerance (mm)**	**Measurements before Injection (mm)**	**Measurements after Injection (mm)**	**Deviation from Permissible Tolerance (mm)**
Tool 1 10,000 parts	25.8	25.72	−0.08	9.48	9.81	0.11
Tool 2 20,000 parts	25.8	25.47	−0.33	9.50	9.92	0.22
Tool 3 30,000 parts	25.9	25.64	−0.16	9.55	9.77	0.07
Tool 4 40,000 parts	25.8	25.70	−0.10	9.70	9.81	0.11
	Dimension E			**Dimension G**		
Tool Number	**Measurements before Injection (mm)**	**Measurements after Injection (mm)**	**Deviation from Permissible Tolerance (mm)**	**Measurements before Injection (mm)**	**Measurements after Injection (mm)**	**Deviation from Permissible Tolerance (mm)**
Tool 1 10,000 Parts	5.80	5.46	−0.24	10.0	10.05	0.05
Tool 2 20,000 parts	5.84	5.63	−0.07	10.0	10.4	0.4
Tool 3 30,000 Parts	5.67	5.47	−0.23	10.04	10.2	0.16
Tool 4 40,000 Parts	5.67	5.48	−0.22	10.04	10.34	0.3

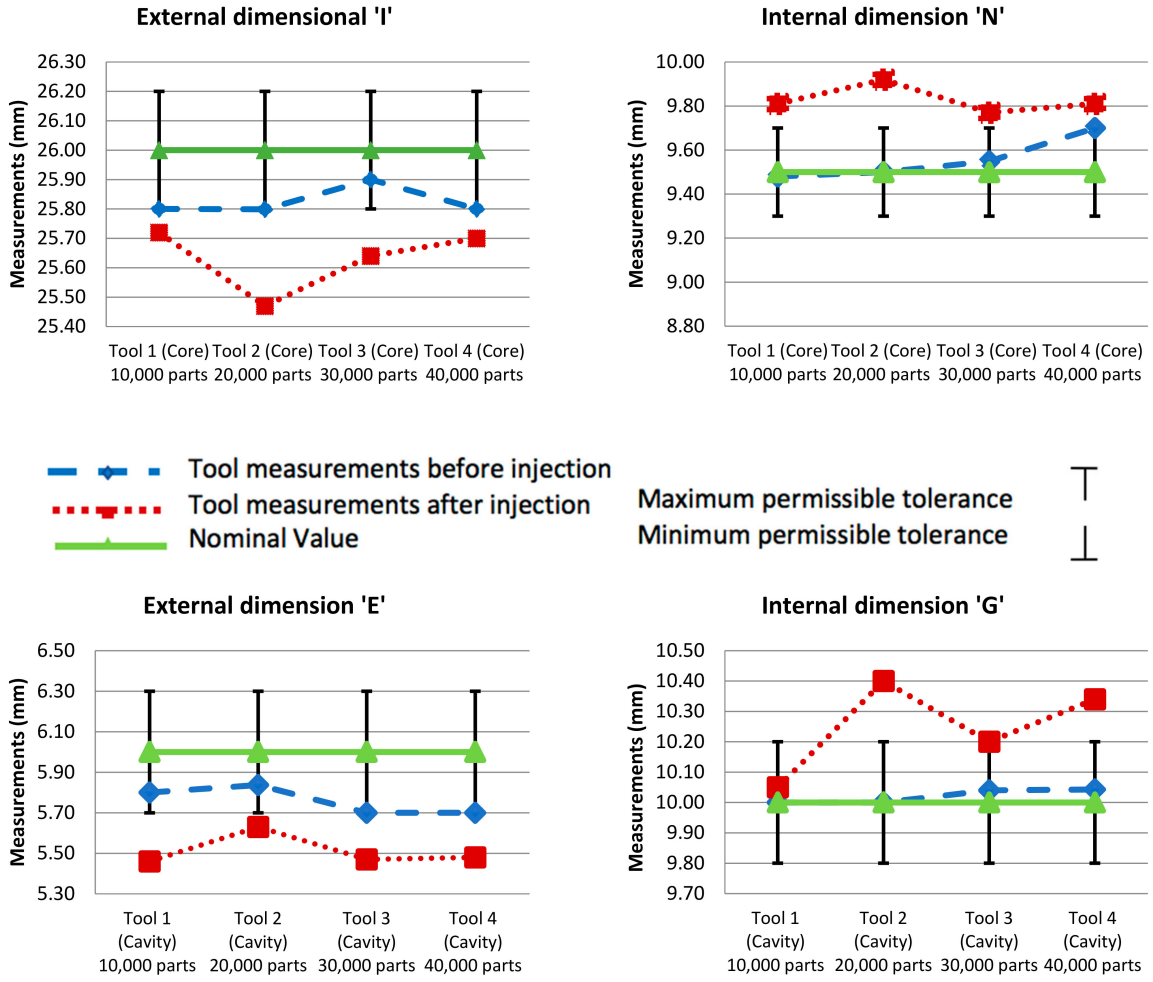

Figure 10. Dimensional measurements of Core and Cavity of the tool inserts with upper and lower tolerances.

It is noted that changes in dimensional accuracy are interpreted as progressive wear due to the many thousands of components produced through the injection moulding process. For external dimension I all four Cores were subjected to wear in addition to deviation from the lower maximum permissible tolerance. As for internal dimension N, all four cores deviated from the upper permissible tolerance. For the tool Cavities, recorded values of the measurements of external dimension E taken after the injection moulding indicates that the Cavities have experienced wear deviating from the lower permissible tolerance. As for internal dimension G, measurements documented for two of the four Cavities, cavity of tool 1 and 3 show that the values are within the acceptable tolerance range. However, cavities of tool 2 and 4 are beyond the upper permissible tolerance range. After analysing the recorded data for measurements taken before and after injection moulding, it was noted that wear does increase as the number of injections increase, but not necessarily in a consistent ratio to the number of injections. However, changes in dimensional accuracy are sufficient to confirm that the tools are susceptible to wear due to the progressive and continued loads exerted on the tools by the injection moulding process. Additionally, it is noted that for external dimensions deviation from the accepted tolerance tends to surpass the lower permissible range. Contrary to internal dimensions, deviation tends to surpass the upper permissible tolerance.

4. Product Evaluation of Injection Moulding

Evaluating the SLM-fabricated tool inserts was implemented through injection moulding. The parts produced were investigated to analyse dimensional accuracy, surface quality, and product functionality.

4.1. Injection Moulding

The injection moulding was conducted using a Nurnak MMRJ 130-225 moulding machine with clamping force of 100 ton. Polypropylene was chosen as the material for injection moulding with a stock feed rate of 25 g/stroke, injection pressure 75 bar and the temperature maintained constant at 220 °C. During the injection moulding process, the tool inserts temperature was constantly monitored using an infrared heat detector and maintained at 20 °C to avoid overheating. The melt temperature was controlled to ensure consistency and uniformity of the process parameters.

4.2. Dimensional Accuracy of Injection Parts

The four sets of tool inserts were installed within the same bolster using the same working conditions to ensure parametric consistency. The steel mould base plates were machined with rectangular pockets to fit the tool inserts within. Figure 11 shows the position of the inserts after they were mounted onto the bolster. The average cycle time was calculated to be approximately 34 s. 19 g was the total weight of the product tree with four components attached, with the net weight of each component produced being 4 g.

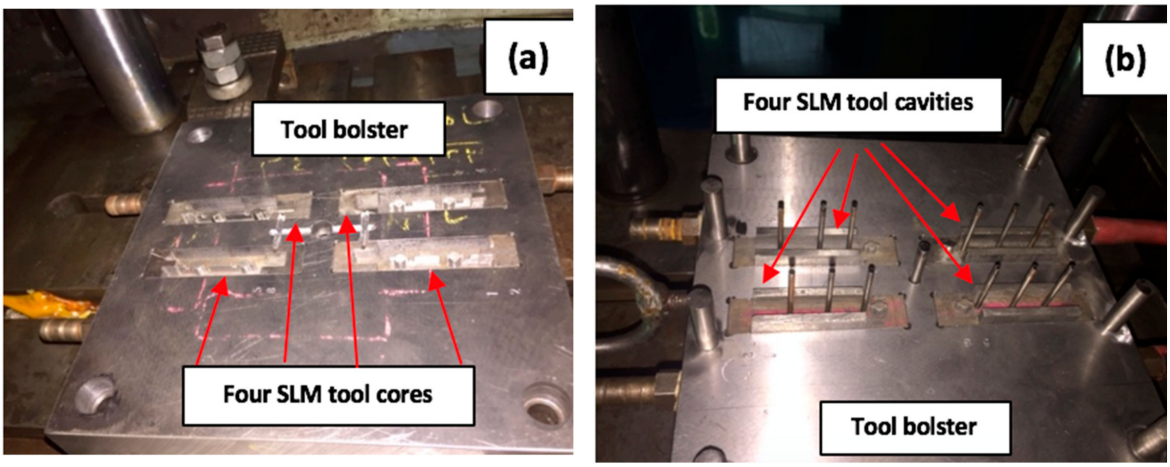

Figure 11. Four sets of tool inserts mounted on the bolster (**a**) Four SLM core inserts (**b**) Four SLM cavity inserts.

The injected products were grouped into smaller batches for each run. When injection is initiated, polypropylene is rapidly forced into the tool Cavities and as a result, a sudden pressure increase is exerted on the tool inserts. This pressure increase is the highest pressure reached during the injection process. Therefore, after thousands of successive injections, the applied force on the Core features may cause fractures, cracking or wear on the tool inserts that will eventually change the dimensional accuracy of the parts produced. A number of the components were selected by way of sampling, to analyse possible variations in dimensional measurements as the injection moulding process progressed.

It is certain that product measurements are required to prove accuracy of the tool inserts. However, measuring the entirety of the product output (i.e., tens of thousands of injected components) was not realistic, therefore a sample size was required to represent the targeted population. The sample sizes are determined based on a sampling Equation [49] as follows:

$$n = \left[\frac{Z_{\frac{\alpha}{2}}}{E}\right]^2$$

where, n = sample size, Z = standard normal score from the normal curve table [49] based on the degree of confidence interval, E = maximum permissible error depending on population, Confidence interval = 90% and $\alpha = 0.1$.

The sampling equation is used to determine the optimum sample size for each of the four runs. The maximum permissible error varies from each run depending on the increase in product population. Values were set with consideration regarding the number of samples to be selected with a tradeoff between the time taken to measure each sample and the cost of measuring them. For runs 1 to 4, the maximum permissible error was set at 0.2, 0.15, 0.1 and 0.1 respectively. Production runs are categorised into four runs depicting batching of 10,000, 20,000, 30,000, and 40,000 parts per run. For each run, a number of samples were randomly selected for functional inspection and to ascertain dimensional accuracy. Therefore, the number of samples to be selected as calculated by the sample equation for each run were as follows: 42, 80, 120, and 166 samples respectively. Each run is divided into smaller batches, for each batch, two samples are randomly selected for measurement and the average value is taken for those two values. Therefore, the average value calculated is recorded for each batch. The recorded values are 21, 40, 60, and 83 respectively for each run. Figure 12 is an illustration of the part dimensions to be measured and their nominal values. Two dimensions D and H of the parts produced, are selected for discussion in this paper, the selected dimensions and their outcomes being representations of the remaining unstated dimensions.

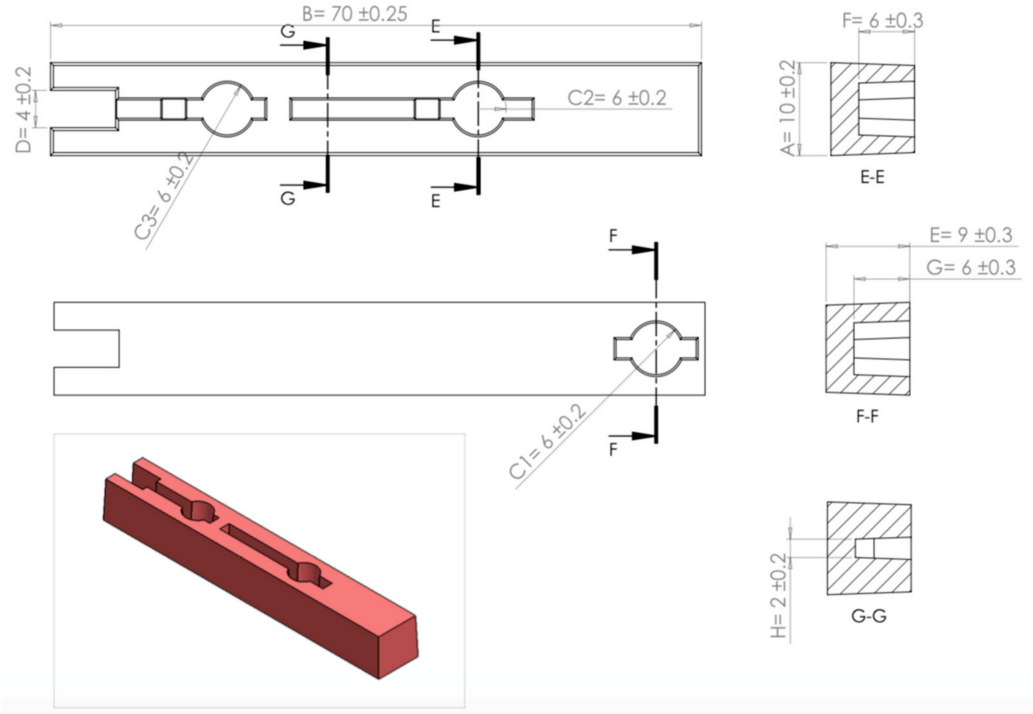

Figure 12. Injected part illustration with dimensional measurements and tolerances.

Figure 13 demonstrates dimensional deviation for dimension D (internal dimension) over time. A ±0.2 mm design tolerance is set to ensure acceptability of the part as an end product. Most of the recorded values of the four batches were defined to be within the acceptable tolerance range of the measurements. However, for runs 2, 3 and 4, a few outlier batch values were spotted dispersing outside the limit zone, and these values were considered negligible in comparison to the values of the rest of the batches.

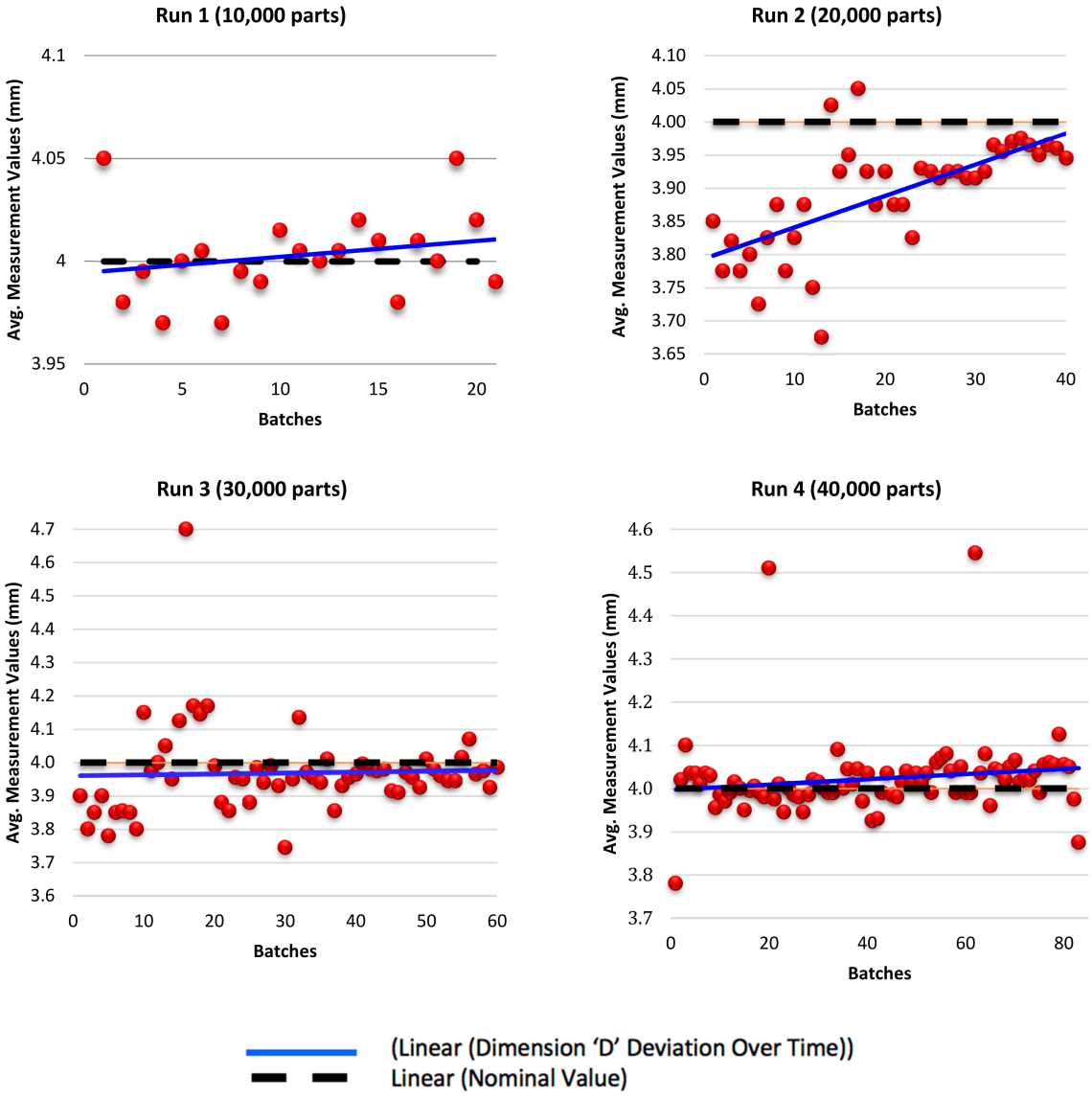

Figure 13. Sample measurements for dimension 'D' deviation over time for run 1, run 2, run 3, and run 4.

Measurement values for Dimension H (external dimension) are illustrated in Figure 14 for runs 1, 2, 3 and 4 respectively. A ±0.2 mm design tolerance is set to ensure acceptability of the part as an end product. The recorded measurements were within the acceptable tolerance range.

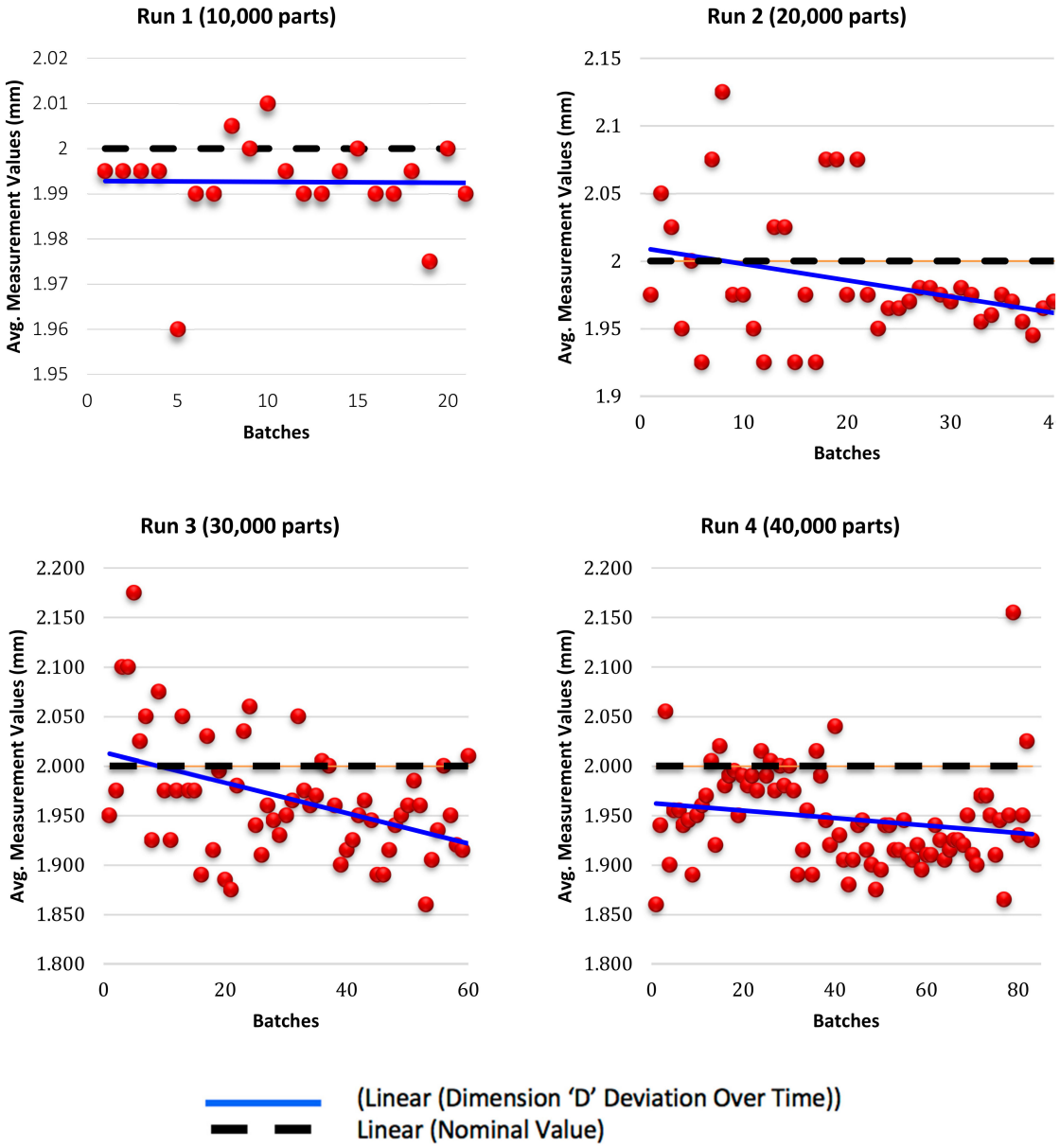

Figure 14. Sample measurements for dimension 'H' deviation over time for run 1, run 2, run3, and run 4.

For dimension D, most of the recorded values of the four batches were defined to be within the acceptable tolerance range of the measurements. It was noted that as injection moulding progresses, recorded values of the batches demonstrate a direct linear regression trending towards the nominal value. In conclusion, a positive linear regression of the measurement values of internal dimension D depicts the development of wear on the specified tools as a function of the number of progressive injections. It was noted that measured values at the beginning of injection moulding were widely scattered and gradually drifted towards the acceptable range within the limits of the nominal values.

For dimension H, the recorded measurements were within the acceptable tolerance range. Moreover, data formation along the trend line represents a negative linear regression that emphasises the direct relation between the progression of wear and the number of samples. Kanagarajah et al. [50] discussed that elemental segregation of intermetallic particles has significant impact on the corrosion characteristics as well as wear resistance along the built layers, yet strength is adversely affected causing the material to be brittle which may have an unfavourable effect on tool insert longevity.

4.3. Injection Moulding of 150,000 Parts

Previous research was reviewed by Nagahanumaiah [51] and it was clearly stated that there has been no published work on the quality and effect of injection moulding on Direct Metal Laser Sintering (DMLS) fabricated tools – their work was completed through the production of 5000 parts. The work of Dolinšek [52] indicated the recommendations made by EOS Manufacturing Solutions that metallic moulds are capable of withstanding 100,000 injections but with no practical proof to indicate tool life performance and wear resistance. Therefore, this study was directed to successfully accomplish the production of 150,000 injections from the SLM fabricated tool insert, ensuring that no damage will occur to the tool inserts after successive tens of thousands of injections.

40,000 injections was the initial limit reached for the fourth tool set and no signs of fracture, cracks, or wear were noticeable. Therefore, a new goal was set to further guarantee that the fourth tool insert could withstand more injections runs. The goal was to reach 150,000 injections in total with no apparent failure to either the tool set or the components produced. As 40,000 components were already produced from the fourth tool set, a further 110,000 additional injections were to be produced for the purpose of completing 150,000 components in total. Each run was set to produce 10,000 components, each batch being divided into smaller volumes of 1000 components and labelled consecutively from 1-1000, 1001-2000 and so forth. Figure 15 displays the produced part.

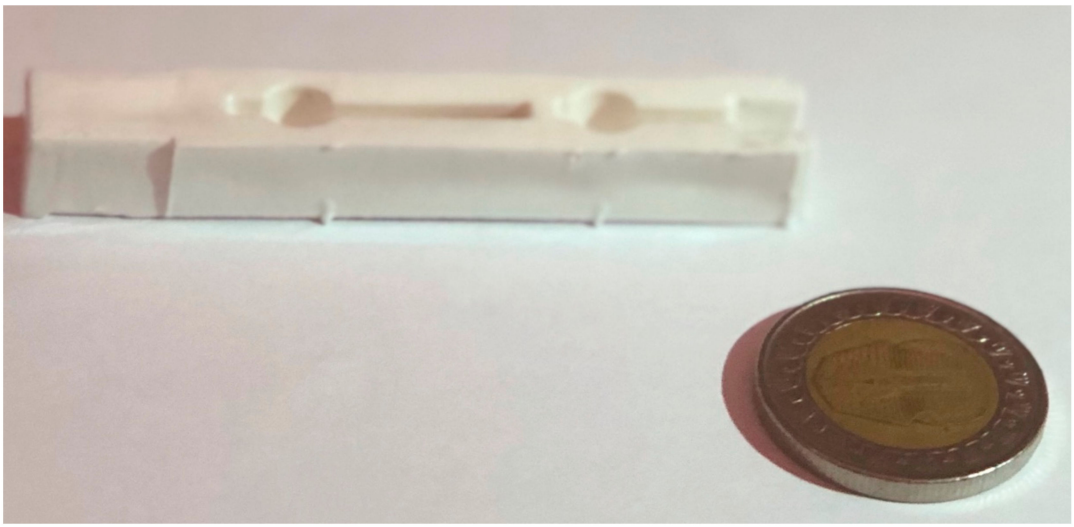

Figure 15. Sample batch production of 1000 components of injected parts.

The same sampling equation is used to determine the optimum sample size for the production runs. The maximum permissible error was set at 0.1. Therefore, the number of samples to be selected for each run was 170 samples. For each batch of 1000 components, 17 samples were randomly selected for visual inspection and fitting. Figure 16 displays one sample from each of the eleven runs after injection of 10,000 from each run. From each run, 170 samples were selected for inspection, the parts inspected and compared together to identify if there were any significant defects. After the inspection process, the parts were fitted to the headlamp housing to ensure product functionality. Functional success is perceived through successful assembly of the part produced from the injection moulding process to the headlamp, this is achieved based on an industrial quality control procedure to ensure the functionality of the end-use product through ease of assembly and accurate fixation of the part. Shown in Figure 16 is a sample illustration of the fitting process. As a result, the parts were deemed acceptable in terms of visual inspection and product functionality. Moreover, the samples appear to be in an acceptable shape showing no signs of flash or over-moulding, cracks or surface imperfections. Therefore, the tool insert proved to remain faultless, and it is expected could continue production of multiple hundreds of thousands before failure might occur.

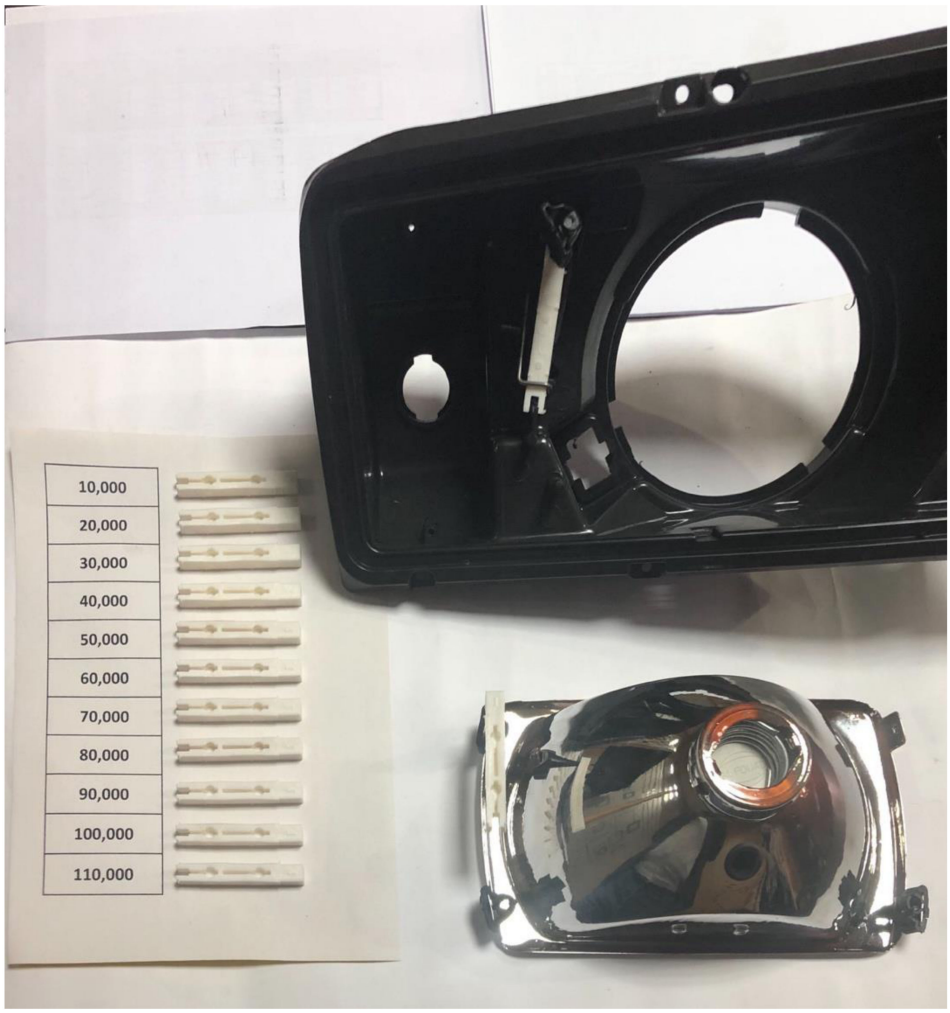

Figure 16. Sample demonstration of visual inspection and component fitting to headlight housing.

Previous work reviewed by Nagahanumaiah and Dolinšek [51,52] expressed uncertainties related to SLM capabilities in fabricating injection moulding tools that can be used for high-volume production of thousands of parts, referring to limitations of the SLM technology in producing functional products with high quality as opposed to conventional injection moulding. However, after the tool inserts proved to be successful in producing tens of thousands of functional products without failure, more production runs were initiated to guarantee longevity of the tool inserts. The fourth tool insert that produced 40,000 products continued production until 150,000 parts were produced. The number of samples selected for inspection for each of the eleven runs was 170 samples. Parts were visually inspected and functionally approved through fitting the parts in the headlight's housing to ensure product validity. The parts proved to be functional and visually acceptable showing no signs of defects. Therefore, the tool insert proved to be in a faultless form, and it is expected could continue production of multiple hundreds of thousands more parts before failure occurs.

5. Conclusions

Experimental work conducted on the four stainless steel 316L tool inserts fabricated using SLM lead to the following conclusions:

- Microstructure and EDS analysis confirmed the inclusion of a high content of carbides along the edge of each individual layer. The elements with the highest concentration were Chromium, Nickel, and Molybdenum respectively. Therefore, the existence of carbides caused by the laser

melting process resulted in reinforcing microhardness and projected a positive outcome for durability due to elemental segregation.

- For the first reported time, SLM fabricated tool inserts proved to be successful in performance with regard to injection moulding of 150,000 parts. The four tool insert sets were run for 10,000, 20,000, 30,000, and 40,000 injections respectively. Finally, after the fourth tool insert successfully completed 40,000 injections, further production runs were continued to achieve 150,000 injections. It was proven that the fourth set of tool inserts was able to withstand 150,000 injections without any significant signs of failure.
- Wear is acknowledged as a result of the progression of the injection moulding process. However, steadiness in the wear rate was noted amid large production runs. Alterations to dimensional accuracy verifies that the tool inserts are liable to wear due to successive loads by the injection moulding process.
- It is concluded from the work done in this research that additive manufacturing SLM technology proved to be a reliable technique for fabricating Stainless steel 316 L injection moulding tool inserts for the aftermarket automotive industry.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

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Appendix C.

Instruction Manual RBF-200 Rotating Beam Fatigue Testing Machine.

INSTRUCTION MANUAL

MODEL RBF-200

ROTATING BEAM
FATIGUE TESTING MACHINE

Fatigue Dynamics, Inc.
P.O. Box 2533
Dearborn, MI 48123

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TABLE OF CONTENTS

1.0 DESCRIPTION

1.1 General

The RBF-200 is a compact, bench mounted machine designed to apply reversed bending loads to unthreaded, straight shank specimen bars. Included is a cycle counter (99,999,900 maximum count), adjustable speed spindle (500 to 10,000 cpm), and a calibrated beam amd poise system which can apply an infinitely adjustable moment of up to 200 inch-pounds to the cantilevered end of the specimen bar. Collet sizes available include 1/4, 3/8, and 1/2 inch diameters. Unless specified otherwise, a 1/2 inch pair of collets is furnished with the machine. Other collet sizes are available on special order within the range of 1/4 to 1/2 inch diameter.

1.2 Detail

1.2.1 Motor and Spindle

The motor is a 1/2 HP, 115 volt, universal type which is powered by a variable transformer to control the speed from 500 to 10,000 RPM. The motor drives a spindle assembly through a flexible coupling.

> CAUTION: The motor must not be operated at a speed over 10,000 RPM!

The spindle assembly consists of the shaft, bearings, and oil filled housing. A sight gage is provided on the back of the machine for maintaining the proper oil level in the spindle.

1.2.2 Moment Beam

The bending moment loading beam is numbered from 0 to 200 inch-pounds at successive 10 inch-pound increments. The interval between each 10 inch-pound increment is marked with successive one inch-pound divisions. A locking screw is provided in the poise weight to secure it at the desired bending moment setting.

1.2.3 Cutoff Switch

A snap action reset switch is furnished to automatically shut off the machine at specimen failure. It is located under the end of the calibrated beam in such a manner that when the beam drops at specimen failure, the bottom of the adjustable screw actuates the switch. The nuts on the screw are adjusted to stop the beam from damaging the switch after actuation. The switch must be reset with the tab at the outside end of the machine before testing can be resumed.

1.2.4 Cycle counter

The six digit resettable counter (99,999,900 maximum count) is actuated by a switch which is directly driven by the spindle through a 100 : 1 ratio.

2.0 INSTALLATION

2.1 Dimensions

The machine has the following approximate overall dimensions:

Length - 33 in.
Depth - 11 in.
Height - 11 in.

2.2 Weight

The machine weighs approximately 125 pounds.

2.3 Mounting

The four corners of the machine should be shimmed as required to level it in both directions. It is suggested that the corners be secured with 3/8 inch diameter bolts to a mounting surface with adequate flatness to prevent distorting the frame.

If the machine causes an objectionable noise level during testing, vibration absorbtion media can be placed under the machine while maintaining a level position.

2.4 Wiring

Unless otherwise tagged, the machine must be plugged into a 115 VAC, 60 Hz grounded outlet with a 5 amp minimum capacity.

2.5 Lubrication

Fill the spindle assembly through the sight gage with a light spindle oil such as Standard Sohio Spin #60 or equivalent. Fill to approximately mid way on the sight glass until a very slight amount of oil leaks out the spindle end cap during initial run-up.

3.0 OPERATION

3.1 Specimen Set-up

The specimen should be set up in the machine in accordance with the following step-by-step sequence refering to Fig 1.

a. Loosen the lock screw fixing the poise weight to the calibrated beam and move the weight to the zero position at the extreme left end of the beam.

b. Loosen the nuts holding the safety bar at the end of the load arm and swing the bar free of the load arm.

c. Pull the safety guard straight upward free from the phenolic block base. The guard is retained only by a friction fit.

d. Swing the load arm up and to the right so that a specimen bar may be inserted into the drive spindle collet. Position the load arm to prevent contact with the free end of the specimen.

Before inserting the specimen into the drive spindle collet, wipe the specimen clean and carefully check for any burrs, flats, or ridges. Stone away any discontinuities that might interfere with the even distribution of the collets gripping action. Also wipe clean the specimen bores in both collets.

Specimen bars should be pushed into the collets until either the specimen bottoms or the front face of the collet lines up with the end of the tangent on the specimen.

e. Tighten the drive spindle collet onto the specimen. The collet must be tightened sufficiently to prevent any relative movement between the collet and specimen which could cause fretting corrosion.

f. Manually rotate the assembly and check for run-out. The run-out should not exceed .001 inch at the drive spindle collet and .003 inch at the free end of the specimen.

If excessive run-out is present, loosen the collet sufficiently to allow rotating the specimen and/or the collet slightly. Tighten the collet and recheck the run-out.

g. Insert the free end of the specimen into the load arm collet observing the same procedures and precautions noted above for the drive spindle.

In wrenching tight the load arm collet, particular care should be taken to insure that pure torsional wrenching is used and that no bending forces are imparted to the specimen.

h. Again rotate the assembly and check the final run-out on the right hand end of the load arm which should not exceed .006 inch. If excessive run-out is present, repeat the procedure described in step f. It may be necessary tap the specimen free from the collet. Tighten the collet and recheck the run-out.

i. Set the counter to "zero".

j. Turn the speed control knob counter-clockwise to the zero position. Back off the cutoff switch adjusting screw on the beam as required to prevent the switch from tripping by the movement of the load arm as it comes up to speed.

Push down the cutoff switch reset tab extending through the right hand end of the machine base.

With the fingers of the right hand, grasp the load arm bearing *housing* to damp out any resonances and slowly rotate the speed control knob clockwise to bring the machine up to the desired speed.

The speed may be readily determined from a counter/timer relationship. Two zeroes must be added to the indicated reading of the counter for the actual spindle count.

k. After the spindle speed has been roughly adjusted to its desired rate, slowly move the poise weight along the calibrated beam to the required bending moment setting.

While adjusting the position of the poise weight, watch for interference between the cutoff switch adjusting screw and the switch guard.

Fix the weight to the beam by tightening the lock screw and quickly reset the counter to zero without stopping the machine.

The machine speed should be rechecked to determine if loading the specimen caused it to slow down.

1. Finally, adjust the cutoff switch actuation by slowly turning the adjusting screw clockwise until the switch actuates and the power is shut off. Immediately, and in the following sequence, back off the adjusting screw 1/2 turn, and push down the cutoff switch reset tab. This should be done as quickly as possible to minimize the loss of spindle speed.

The intent in this procedure as well as moving the weight to the desired moment setting *after* the machine has been brought up to speed is to minimize any overload condition on the specimen if the machine passes through a critical (resonant) speed. In addition, it is important to select a non-resonant test speed and to hold the load bearing housing with the fingers during any speed changes to dampen vibration when passing through critical speeds.

4.0 SPECIMEN DESIGN

The applicable inch-pound moment setting for the poise weight is generally determined on the basis of some desired bending stress level in the specimen. This moment may be determined from the equation:

$$M = 3.1416\ SD^3/32 = .0982\ SD^3$$

where:

M = Setting for poise weight in inch-pounds

S = Desired bending stress level in specimen at minimum cross section in pounds per sqare inch

D = Diameter of specimen at minimum cross section in inches

Suggested configurations and design information intended to insure reliability and reproducible data between specimen bars are shown in Fig 2.

F = weight $\quad M = \frac{\pi S D^3}{32}$ $\quad M = .0982(60{,}000)(.25)^3$

$S = \frac{32F}{\pi D^3}$ $\quad m = \frac{\pi S D^3}{32}$

$\frac{(32)m}{\pi D^3} = S$

~~B = 4~~ = l

$M \cdot 2 = \frac{\pi S D^3}{32}$

$S = 2M$

5.0 MAINTENANCE

5.1 Motor

At periodic intervals, such as every 6 months, the motor brush wear should be checked. Spare brushes are avaiable from Fatigue Dynamics, Inc. Brush inspection and replacement are explained in the attached Dayton instruction sheet. The motor bearings are sealed and permanently lubricated.

5.2 Spindle Bearings

The oil level must be maintained in the middle of the sight gage on the spindle assembly. Add oil to the sight gage by removing the screw cap. As the gage is filled, it may be necessary to blow gently onto the housing to allow the oil to flow into the spindle housing. Repeat this process until oil flows back into the gage to assure that an air lock is not giving a false indication of the oil level. Use a light spindle oil of approximately 60/100 SSU seconds. Suggested brands are:

Standard Oil of Ohio - Sohio Spin #60
Mobil Oil Co. - Velocite 10

The load arm bearing is sealed and permanently lubricated and requires no attention. The operating temperature of the bearing at high speed may be too hot to touch. This temperature rise is caused by the bearing seal and will decrease with usage. No harm will occur unless the temperature rises far enough to cause it to smoke.

Under reasonably clean environmental operating conditions, these bearings will perform satisfactorily for several years. When they become noisy or exhibit roughness or looseness, they should be replaced. A log of individual bearing operating time and replacement is recommended to insure uninterrupted testing.

5.3 Calibrated Beam and Load Arm Pivots

The pivot pins in the calibrated beam and load arm bearing housing should be cleaned and lubricated with a light machine oil at regular intervals not exceeding one month.

5.4 Spindle Axis

The drive spindle, load arm, collets, and bearings are components of the high speed spindle axis assembly. Because of the extremely adverse effect of vibration on this assemoly, due care should be excercised at all times in the handling and use of these components to prevent their being bumped, dented, bent, or otherwise abused.

Wear and tear on the collets and/or the bearings is generally evidenced by increasing difficulties with specimen run-out. This situation is best handled by replacing the components at fault.

6.0 ACCESSORIES

6.1 Collets

Collets are avaiable in the following sizes expressed as specimen shank diameter: 1/4, 3/8, and 1/2 inch.

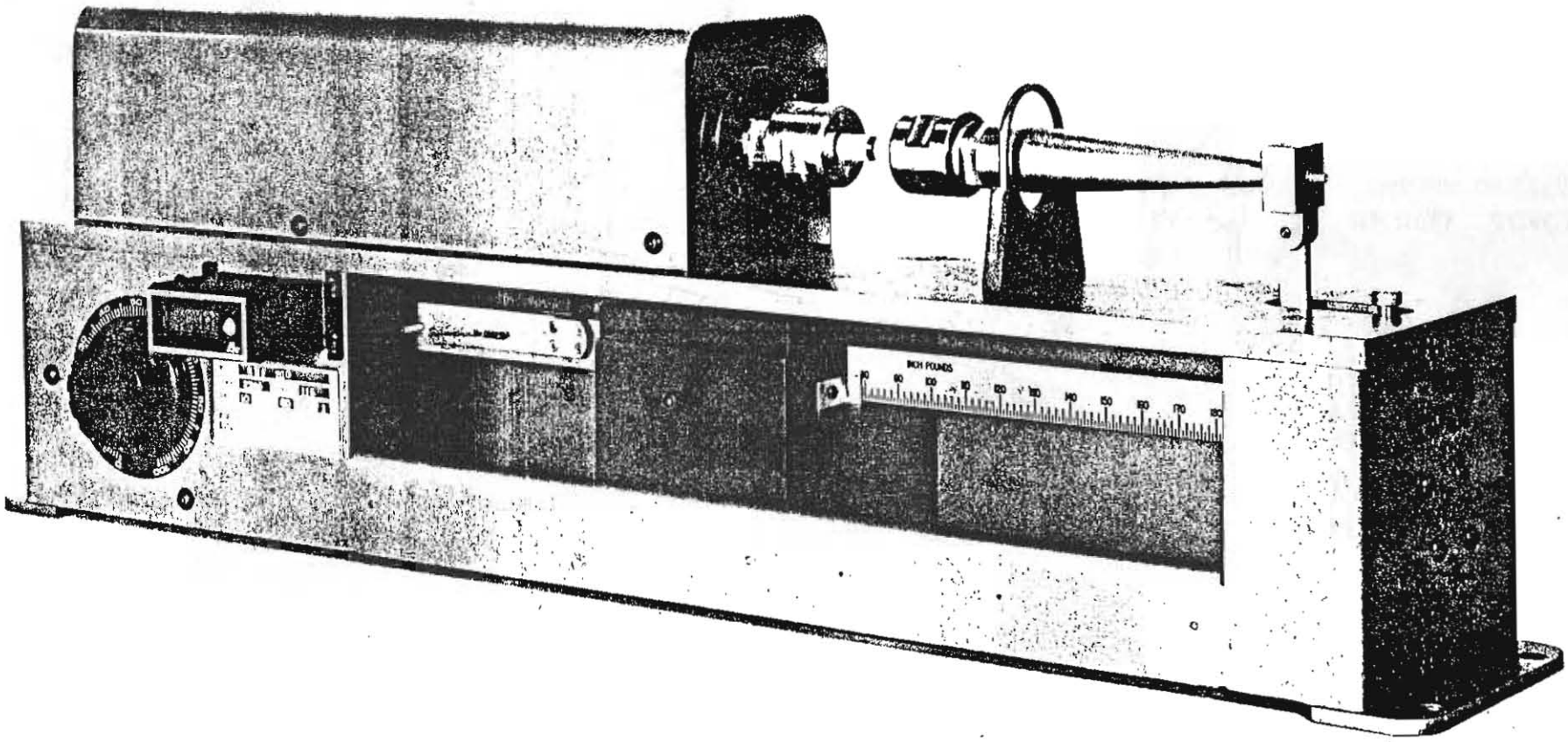
6.2 Corrosion Attachment and Pump

6.3 Wire and Tube Testing Attachment

7.0 APPLICABLE DRAWINGS

The following drawings apply to this machine:

Drawing No.	Title
300-044607	General Arrangement - 200 IN-LB Rotating Beam Testing Machine
C-40789 & PL-C-40789	Spindle Assembly
A-23773	Wiring Schematic


INCH POUNDS

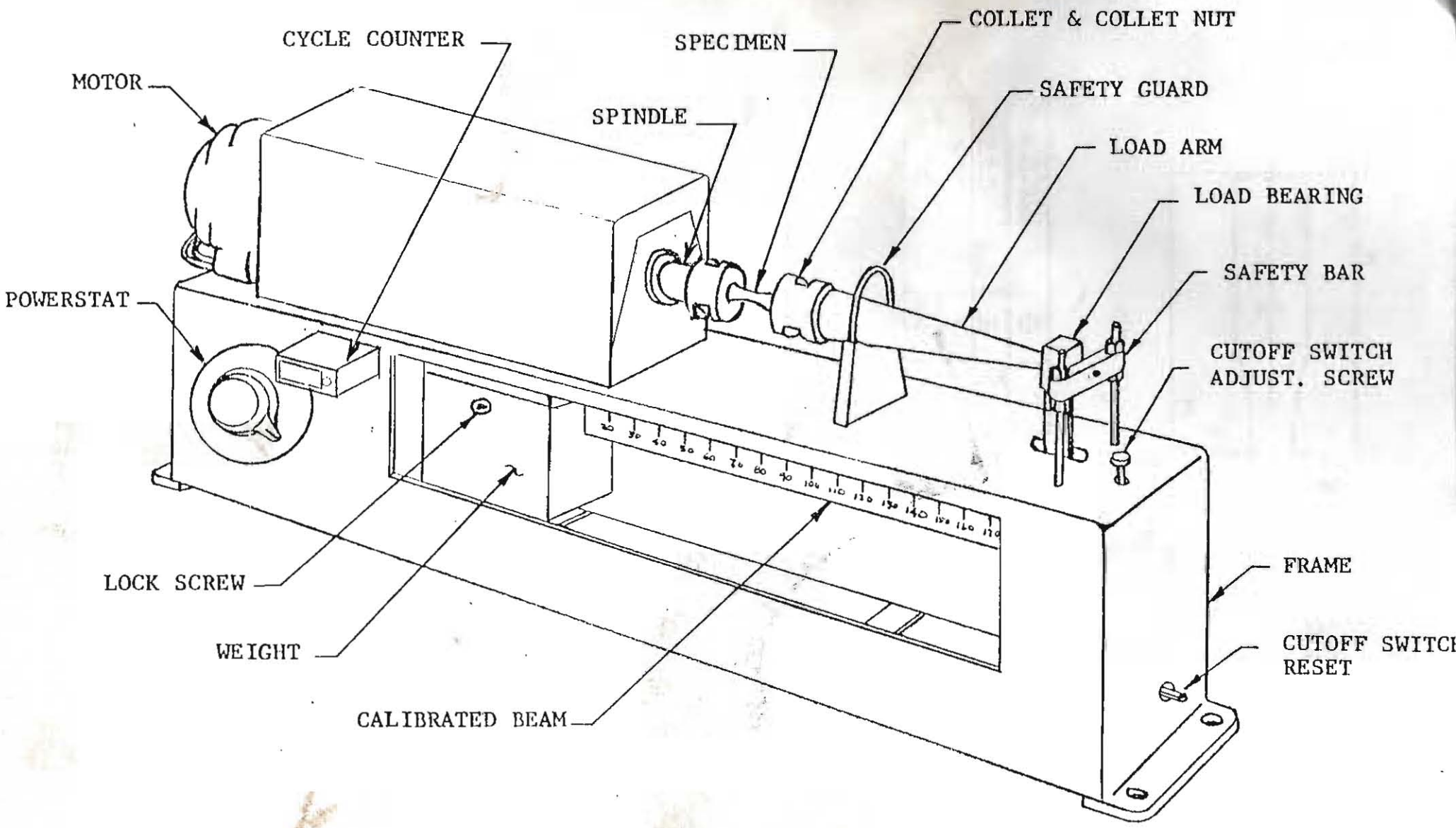
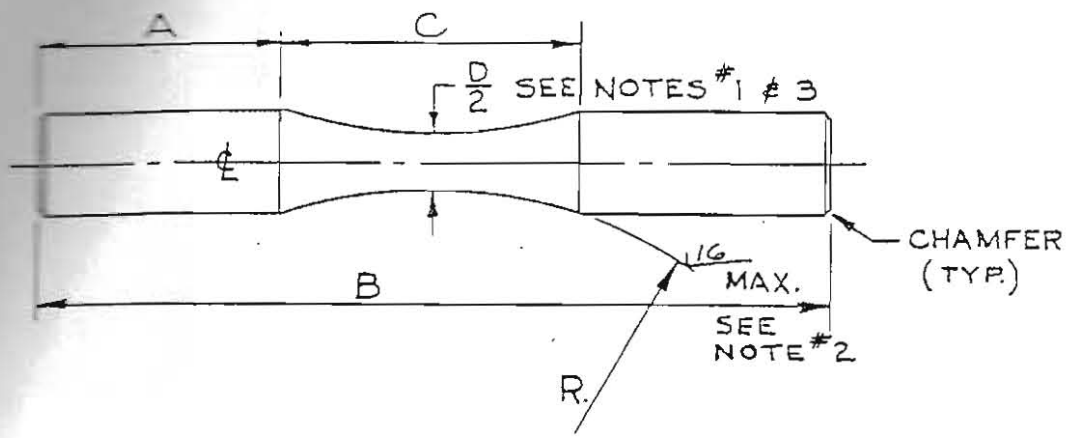
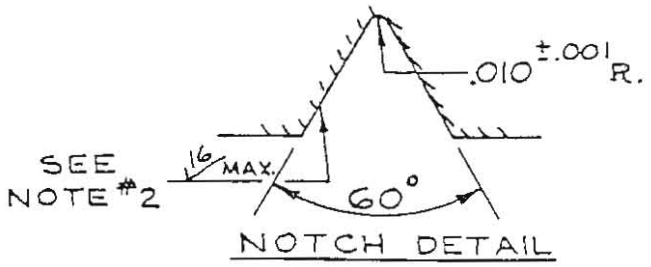
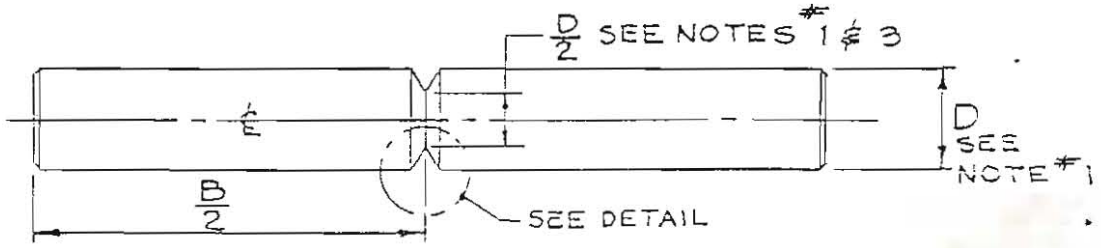

CYCLE COUNTER
SPECIMEN
COLLET & COLLET NUT
MOTOR
SAFETY GUARD
SPINDLE
LOAD ARM
LOAD BEARING
POWERSTAT
SAFETY BAR
CUTOFF SWITCH
ADJUST. SCREW
FRAME
LOCK SCREW
WEIGHT
CUTOFF SWITCH
RESET
CALIBRATED BEAM

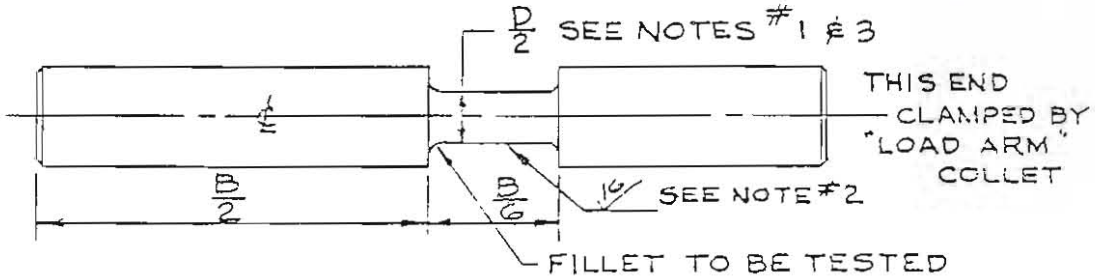
FIGURE 1



DIA. D $^{+.001}_{-.000}$	A	B	C
.250	5/8	2	3/4
.375	1	3	1
.500	1 1/4	4	1 1/2







NOTES:

1. Diameters "D" and "D/2" to be concentric within 0.001.
2. Test section finish to be free of nicks, dents, scratches, and circumferential tool marks. Polish longitudinally, progressing through 0,00 and 000 emery paper. Do not buff.
3. Adjust dimensions D/2 to identity through all specimens ±.0002

FIGURE 2: Suggested Test Specimen Configurations

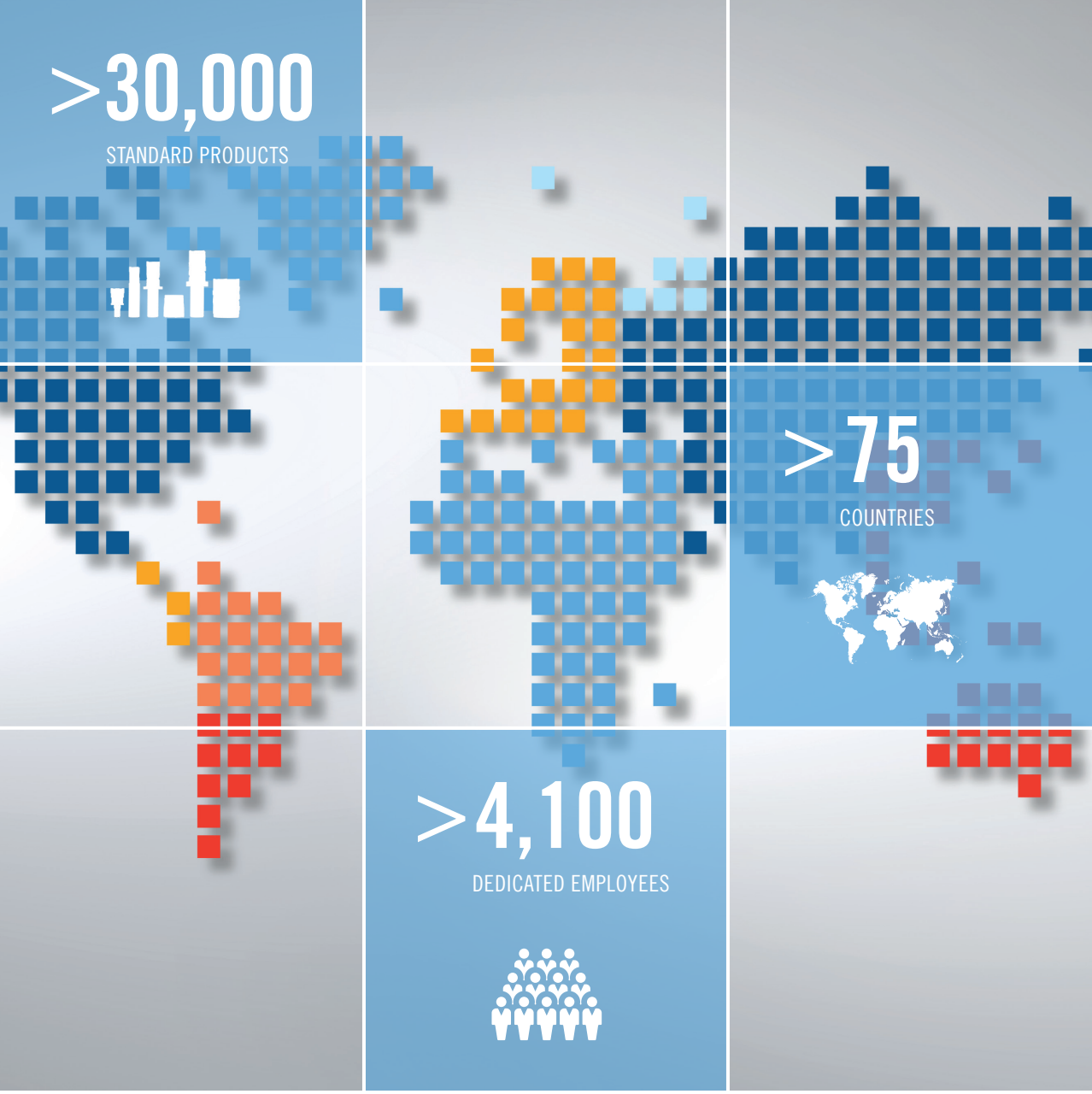
Appendix D.

SECO (2019a) catalog and technical guide 2019.2 Holemaking.

CATALOG & TECHNICAL GUIDE 2019.2

HOLEMAKING

SECO



Headquartered in Fagersta, Sweden and present in more than 75 countries, Seco Tools is a leading global provider of metal cutting solutions for milling, stationary tools, holemaking and tooling systems.

For more than 80 years, the company has provided the technologies, processes and support that manufacturers depend on for maximum productivity and profitability. For more information on how Seco's innovative products and expert services bring success to manufacturers across all industry segments, please visit www.secotools.com.

WELCOME TO SECO HOLEMAKING

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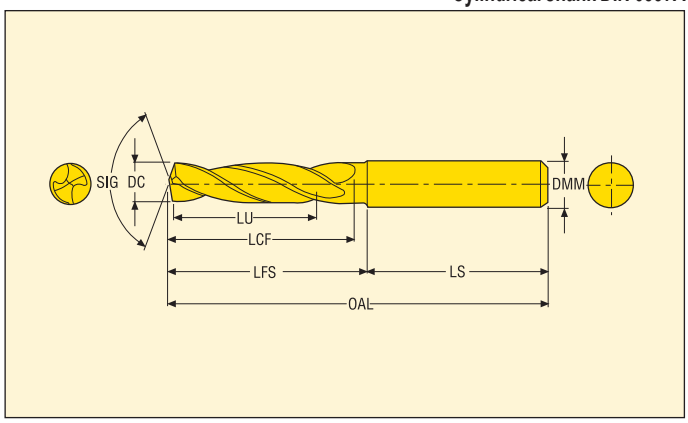
Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A

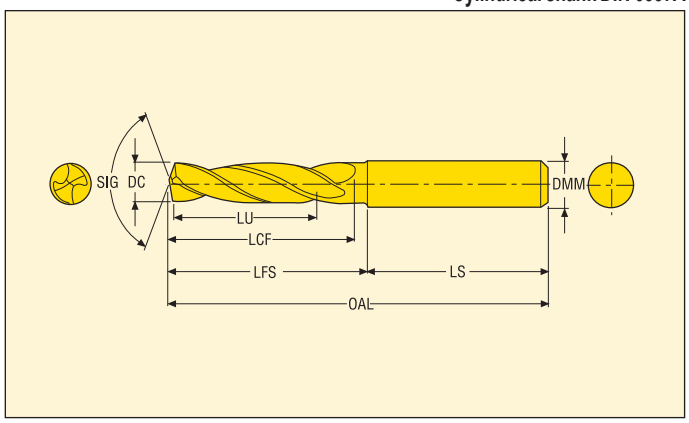


- External coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
3,0	–	14	02898974	SD1103-0300-014-06R1	62	26	36	20	6
3,1	–	14	02898975	SD1103-0310-014-06R1	62	26	36	20	6
3,2	–	14	02898977	SD1103-0320-014-06R1	62	26	36	20	6
3,25	–	14	02898978	SD1103-0325-014-06R1	62	26	36	20	6
3,3	–	14	02898979	SD1103-0330-014-06R1	62	26	36	20	6
3,4	–	14	02898980	SD1103-0340-014-06R1	62	26	36	20	6
3,5	–	14	02898981	SD1103-0350-014-06R1	62	26	36	20	6
3,6	–	14	02898983	SD1103-0360-014-06R1	62	26	36	20	6
3,65	–	14	02898984	SD1103-0365-014-06R1	62	26	36	20	6
3,7	–	14	02898985	SD1103-0370-014-06R1	62	26	36	20	6
3,8	–	17	02898986	SD1103-0380-017-06R1	66	30	36	24	6
3,9	–	17	02898987	SD1103-0390-017-06R1	66	30	36	24	6
4,0	–	17	02898989	SD1103-0400-017-06R1	66	30	36	24	6
4,1	–	17	02898990	SD1103-0410-017-06R1	66	30	36	24	6
4,2	–	17	02898991	SD1103-0420-017-06R1	66	30	36	24	6
4,3	–	17	02898992	SD1103-0430-017-06R1	66	30	36	24	6
4,4	–	17	02898994	SD1103-0440-017-06R1	66	30	36	24	6
4,5	–	17	02898995	SD1103-0450-017-06R1	66	30	36	24	6
4,6	–	17	02898996	SD1103-0460-017-06R1	66	30	36	24	6
4,65	–	17	02898997	SD1103-0465-017-06R1	66	30	36	24	6
4,7	–	17	02898998	SD1103-0470-017-06R1	66	30	36	24	6
4,8	–	20	02899000	SD1103-0480-020-06R1	66	30	36	28	6
4,9	–	20	02899001	SD1103-0490-020-06R1	66	30	36	28	6
5,0	–	20	02899002	SD1103-0500-020-06R1	66	30	36	28	6
5,1	–	20	02899003	SD1103-0510-020-06R1	66	30	36	28	6
5,159	13/64	20	02899004	SD1103-0516-020-06R1	66	30	36	28	6
5,2	–	20	02899005	SD1103-0520-020-06R1	66	30	36	28	6
5,3	–	20	02899006	SD1103-0530-020-06R1	66	30	36	28	6
5,4	–	20	02899007	SD1103-0540-020-06R1	66	30	36	28	6
5,5	–	20	02899008	SD1103-0550-020-06R1	66	30	36	28	6
5,55	–	20	02899009	SD1103-0555-020-06R1	66	30	36	28	6
5,6	–	20	02899011	SD1103-0560-020-06R1	66	30	36	28	6
5,7	–	20	02899012	SD1103-0570-020-06R1	66	30	36	28	6
5,8	–	20	02899013	SD1103-0580-020-06R1	66	30	36	28	6
5,9	–	20	02899014	SD1103-0590-020-06R1	66	30	36	28	6
5,953	15/64	20	02899015	SD1103-0595-020-06R1	66	30	36	28	6

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A

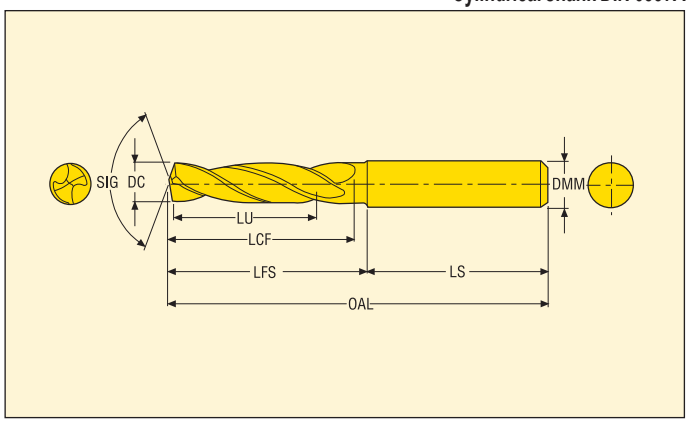


- External coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
6,0	–	20	02899016	SD1103-0600-020-06R1	66	30	36	28	6
6,1	–	24	02899017	SD1103-0610-024-08R1	79	43	36	34	8
6,2	–	24	02899018	SD1103-0620-024-08R1	79	43	36	34	8
6,3	–	24	02899019	SD1103-0630-024-08R1	79	43	36	34	8
6,35	1/4	24	02899020	SD1103-0635-024-08R1	79	43	36	34	8
6,4	–	24	02899021	SD1103-0640-024-08R1	79	43	36	34	8
6,5	–	24	02899022	SD1103-0650-024-08R1	79	43	36	34	8
6,6	–	24	02899024	SD1103-0660-024-08R1	79	43	36	34	8
6,747	17/64	24	02899025	SD1103-0675-024-08R1	79	43	36	34	8
6,8	–	24	02899026	SD1103-0680-024-08R1	79	43	36	34	8
6,9	–	24	02899027	SD1103-0690-024-08R1	79	43	36	34	8
7,0	–	24	02899028	SD1103-0700-024-08R1	79	43	36	34	8
7,1	–	29	02899029	SD1103-0710-029-08R1	79	43	36	41	8
7,144	9/32	29	02899030	SD1103-0714-029-08R1	79	43	36	41	8
7,2	–	29	02899031	SD1103-0720-029-08R1	79	43	36	41	8
7,3	–	29	02899032	SD1103-0730-029-08R1	79	43	36	41	8
7,4	–	29	02899033	SD1103-0740-029-08R1	79	43	36	41	8
7,5	–	29	02899034	SD1103-0750-029-08R1	79	43	36	41	8
7,55	–	29	02899036	SD1103-0755-029-08R1	79	43	36	41	8
7,6	–	29	02899037	SD1103-0760-029-08R1	79	43	36	41	8
7,7	–	29	02899038	SD1103-0770-029-08R1	79	43	36	41	8
7,8	–	29	02899040	SD1103-0780-029-08R1	79	43	36	41	8
7,9	–	29	02899041	SD1103-0790-029-08R1	79	43	36	41	8
7,938	5/16	29	02899042	SD1103-0794-029-08R1	79	43	36	41	8
8,0	–	29	02899043	SD1103-0800-029-08R1	79	43	36	41	8
8,1	–	35	02899044	SD1103-0810-035-10R1	89	49	40	47	10
8,2	–	35	02899045	SD1103-0820-035-10R1	89	49	40	47	10
8,3	–	35	02899046	SD1103-0830-035-10R1	89	49	40	47	10
8,4	–	35	02899048	SD1103-0840-035-10R1	89	49	40	47	10
8,5	–	35	02899049	SD1103-0850-035-10R1	89	49	40	47	10
8,6	–	35	02899050	SD1103-0860-035-10R1	89	49	40	47	10
8,7	–	35	02899051	SD1103-0870-035-10R1	89	49	40	47	10
8,8	–	35	02899053	SD1103-0880-035-10R1	89	49	40	47	10
8,9	–	35	02899054	SD1103-0890-035-10R1	89	49	40	47	10
9,0	–	35	02899055	SD1103-0900-035-10R1	89	49	40	47	10
9,1	–	35	02899056	SD1103-0910-035-10R1	89	49	40	47	10
9,128	23/64	35	02899058	SD1103-0913-035-10R1	89	49	40	47	10
9,2	–	35	02899059	SD1103-0920-035-10R1	89	49	40	47	10
9,3	–	35	02899060	SD1103-0930-035-10R1	89	49	40	47	10

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A



- External coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
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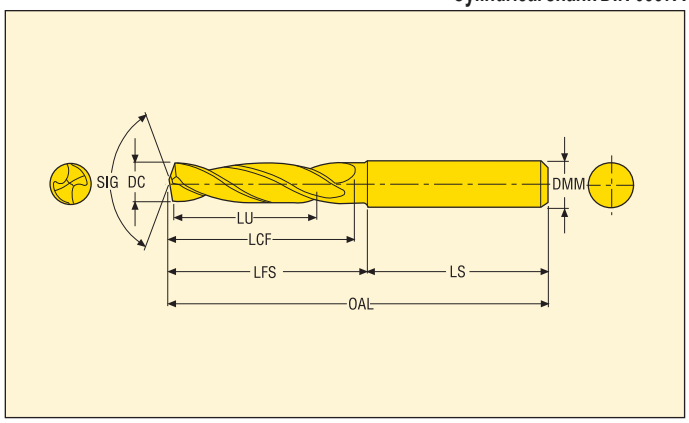
9,55	–	35	02899064	SD1103-0955-035-10R1	89	49	40	47	10
9,6	–	35	02899065	SD1103-0960-035-10R1	89	49	40	47	10
9,7	–	35	02899066	SD1103-0970-035-10R1	89	49	40	47	10
9,8	–	35	02899067	SD1103-0980-035-10R1	89	49	40	47	10
9,9	–	35	02899068	SD1103-0990-035-10R1	89	49	40	47	10
9,922	25/64	35	02899069	SD1103-0992-035-10R1	89	49	40	47	10
10,0	–	35	02899070	SD1103-1000-035-10R1	89	49	40	47	10
10,2	–	40	02899071	SD1103-1020-040-12R1	102	57	45	55	12
10,319	12/32	40	02899072	SD1103-1032-040-12R1	102	57	45	55	12
10,4	–	40	02899073	SD1103-1040-040-12R1	102	57	45	55	12
10,5	–	40	02899074	SD1103-1050-040-12R1	102	57	45	55	12
10,6	–	40	02899075	SD1103-1060-040-12R1	102	57	45	55	12
10,8	–	40	02899077	SD1103-1080-040-12R1	102	57	45	55	12
10,9	–	40	02899078	SD1103-1090-040-12R1	102	57	45	55	12
11,0	–	40	02899079	SD1103-1100-040-12R1	102	57	45	55	12
11,1	–	40	02899080	SD1103-1110-040-12R1	102	57	45	55	12
11,113	7/16	40	02899081	SD1103-1111-040-12R1	102	57	45	55	12
11,2	–	40	02899082	SD1103-1120-040-12R1	102	57	45	55	12
11,3	–	40	02899083	SD1103-1130-040-12R1	102	57	45	55	12
11,4	–	40	02899084	SD1103-1140-040-12R1	102	57	45	55	12
11,5	–	40	02899085	SD1103-1150-040-12R1	102	57	45	55	12
11,509	29/64	40	02899086	SD1103-1151-040-12R1	102	57	45	55	12
11,55	–	40	02899087	SD1103-1155-040-12R1	102	57	45	55	12
11,6	–	40	02899088	SD1103-1160-040-12R1	102	57	45	55	12
11,7	–	40	02899089	SD1103-1170-040-12R1	102	57	45	55	12
11,8	–	40	02899090	SD1103-1180-040-12R1	102	57	45	55	12
11,9	–	40	02899091	SD1103-1190-040-12R1	102	57	45	55	12
12,0	–	40	02899093	SD1103-1200-040-12R1	102	57	45	55	12
12,1	–	43	02899094	SD1103-1210-043-14R1	107	62	45	60	14
12,2	–	43	02899095	SD1103-1220-043-14R1	107	62	45	60	14
12,303	31/64	43	02899096	SD1103-1230-043-14R1	107	62	45	60	14
12,4	–	43	02899097	SD1103-1240-043-14R1	107	62	45	60	14
12,5	–	43	02899098	SD1103-1250-043-14R1	107	62	45	60	14
12,6	–	43	02899099	SD1103-1260-043-14R1	107	62	45	60	14
12,7	1/2	43	02899100	SD1103-1270-043-14R1	107	62	45	60	14
12,75	–	43	02899101	SD1103-1275-043-14R1	107	62	45	60	14
12,8	–	43	02899102	SD1103-1280-043-14R1	107	62	45	60	14

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A

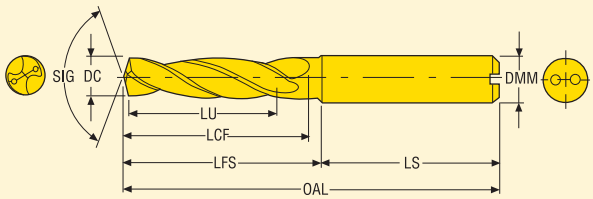


- External coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
12,9	–	43	02899103	SD1103-1290-043-14R1	107	62	45	60	14
13,0	–	43	02899104	SD1103-1300-043-14R1	107	62	45	60	14
13,1	–	43	02899105	SD1103-1310-043-14R1	107	62	45	60	14
13,2	–	43	02899106	SD1103-1320-043-14R1	107	62	45	60	14
13,3	–	43	02899107	SD1103-1330-043-14R1	107	62	45	60	14
13,4	–	43	02899108	SD1103-1340-043-14R1	107	62	45	60	14
13,494	17/32	43	02899109	SD1103-1349-043-14R1	107	62	45	60	14
13,5	–	43	02899110	SD1103-1350-043-14R1	107	62	45	60	14
13,6	–	43	02899111	SD1103-1360-043-14R1	107	62	45	60	14
13,7	–	43	02899112	SD1103-1370-043-14R1	107	62	45	60	14
13,8	–	43	02899113	SD1103-1380-043-14R1	107	62	45	60	14
13,9	–	43	02899114	SD1103-1390-043-14R1	107	62	45	60	14
14,0	–	43	02899115	SD1103-1400-043-14R1	107	62	45	60	14
14,2	–	45	02899116	SD1103-1420-045-16R1	115	67	48	65	16
14,5	–	45	02899119	SD1103-1450-045-16R1	115	67	48	65	16
14,7	–	45	02899120	SD1103-1470-045-16R1	115	67	48	65	16
14,75	–	45	02899121	SD1103-1475-045-16R1	115	67	48	65	16
14,8	–	45	02899122	SD1103-1480-045-16R1	115	67	48	65	16
15,0	–	45	02899123	SD1103-1500-045-16R1	115	67	48	65	16
15,1	–	45	02899124	SD1103-1510-045-16R1	115	67	48	65	16
15,3	–	45	02899125	SD1103-1530-045-16R1	115	67	48	65	16
15,5	–	45	02899126	SD1103-1550-045-16R1	115	67	48	65	16
15,7	–	45	02899127	SD1103-1570-045-16R1	115	67	48	65	16
15,8	–	45	02899128	SD1103-1580-045-16R1	115	67	48	65	16
16,0	–	45	02899130	SD1103-1600-045-16R1	115	67	48	65	16
16,5	–	51	02899131	SD1103-1650-051-18R1	123	75	48	73	18
17,0	–	51	02899132	SD1103-1700-051-18R1	123	75	48	73	18
17,5	–	51	02899133	SD1103-1750-051-18R1	123	75	48	73	18
18,0	–	51	02899134	SD1103-1800-051-18R1	123	75	48	73	18
18,5	–	55	02899135	SD1103-1850-055-20R1	131	81	50	79	20
19,0	–	55	02899136	SD1103-1900-055-20R1	131	81	50	79	20
19,05	3/4	55	02899137	SD1103-1905-055-20R1	131	81	50	79	20
19,5	–	55	02899138	SD1103-1950-055-20R1	131	81	50	79	20
20,0	–	55	02899139	SD1103-2000-055-20R1	131	81	50	79	20

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A



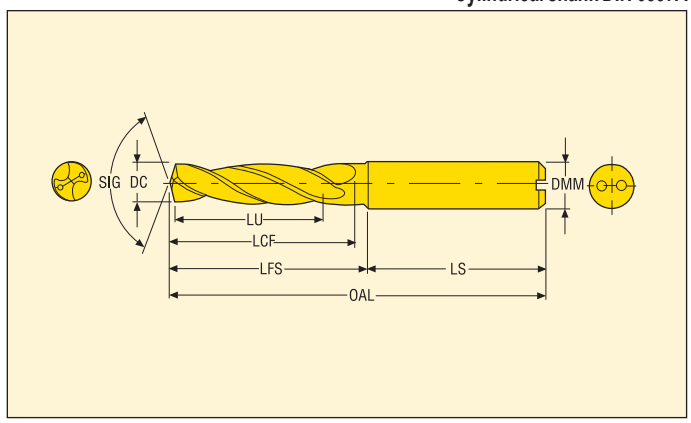
- Internal coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
3,0	–	14	02898244	SD1103A-0300-014-06R1	62	26	36	20	6
3,1	–	14	02898245	SD1103A-0310-014-06R1	62	26	36	20	6
3,175	1/8	14	02898246	SD1103A-0318-014-06R1	62	26	36	20	6
3,2	–	14	02898247	SD1103A-0320-014-06R1	62	26	36	20	6
3,25	–	14	02898248	SD1103A-0325-014-06R1	62	26	36	20	6
3,3	–	14	02898249	SD1103A-0330-014-06R1	62	26	36	20	6
3,4	–	14	02898250	SD1103A-0340-014-06R1	62	26	36	20	6
3,5	–	14	02898251	SD1103A-0350-014-06R1	62	26	36	20	6
3,572	9/64	14	02898252	SD1103A-0357-014-06R1	62	26	36	20	6
3,6	–	14	02898253	SD1103A-0360-014-06R1	62	26	36	20	6
3,65	–	14	02898254	SD1103A-0365-014-06R1	62	26	36	20	6
3,7	–	14	02898255	SD1103A-0370-014-06R1	62	26	36	20	6
3,8	–	17	02898256	SD1103A-0380-017-06R1	66	30	36	24	6
3,9	–	17	02898257	SD1103A-0390-017-06R1	66	30	36	24	6
3,969	5/32	17	02898258	SD1103A-0397-017-06R1	66	30	36	24	6
4,0	–	17	02898259	SD1103A-0400-017-06R1	66	30	36	24	6
4,1	–	17	02898260	SD1103A-0410-017-06R1	66	30	36	24	6
4,2	–	17	02898261	SD1103A-0420-017-06R1	66	30	36	24	6
4,3	–	17	02898262	SD1103A-0430-017-06R1	66	30	36	24	6
4,366	11/64	17	02898263	SD1103A-0437-017-06R1	66	30	36	24	6
4,5	–	17	02898264	SD1103A-0450-017-06R1	66	30	36	24	6
4,6	–	17	02898265	SD1103A-0460-017-06R1	66	30	36	24	6
4,65	–	17	02898266	SD1103A-0465-017-06R1	66	30	36	24	6
4,7	–	17	02898267	SD1103A-0470-017-06R1	66	30	36	24	6
4,8	–	20	02898269	SD1103A-0480-020-06R1	66	30	36	28	6
4,9	–	20	02898270	SD1103A-0490-020-06R1	66	30	36	28	6
5,0	–	20	02898271	SD1103A-0500-020-06R1	66	30	36	28	6
5,1	–	20	02898272	SD1103A-0510-020-06R1	66	30	36	28	6
5,2	–	20	02898275	SD1103A-0520-020-06R1	66	30	36	28	6
5,3	–	20	02898276	SD1103A-0530-020-06R1	66	30	36	28	6
5,4	–	20	02898277	SD1103A-0540-020-06R1	66	30	36	28	6
5,5	–	20	02898278	SD1103A-0550-020-06R1	66	30	36	28	6
5,55	–	20	02898279	SD1103A-0555-020-06R1	66	30	36	28	6
5,556	7/32	20	02898280	SD1103A-0556-020-06R1	66	30	36	28	6
5,6	–	20	02898281	SD1103A-0560-020-06R1	66	30	36	28	6
5,7	–	20	02898282	SD1103A-0570-020-06R1	66	30	36	28	6
5,8	–	20	02898283	SD1103A-0580-020-06R1	66	30	36	28	6
5,9	–	20	02898284	SD1103A-0590-020-06R1	66	30	36	28	6
5,953	–	20	02898285	SD1103A-0595-020-06R1	66	30	36	28	6
6,0	–	20	02898286	SD1103A-0600-020-06R1	66	30	36	28	6

Seco Universal – SD1103A

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A

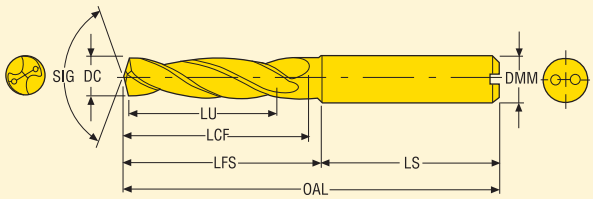


- Internal coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
6,1	–	24	02898287	SD1103A-0610-024-08R1	79	43	36	34	8
6,2	–	24	02898288	SD1103A-0620-024-08R1	79	43	36	34	8
6,3	–	24	02898289	SD1103A-0630-024-08R1	79	43	36	34	8
6,35	1/4	24	02898290	SD1103A-0635-024-08R1	79	43	36	34	8
6,4	–	24	02898291	SD1103A-0640-024-08R1	79	43	36	34	8
6,5	–	24	02898292	SD1103A-0650-024-08R1	79	43	36	34	8
6,6	–	24	02898293	SD1103A-0660-024-08R1	79	43	36	34	8
6,7	–	24	02898294	SD1103A-0670-024-08R1	79	43	36	34	8
6,747	17/64	24	02898295	SD1103A-0675-024-08R1	79	43	36	34	8
6,8	–	24	02898296	SD1103A-0680-024-08R1	79	43	36	34	8
6,9	–	24	02898297	SD1103A-0690-024-08R1	79	43	36	34	8
7,0	–	24	02898298	SD1103A-0700-024-08R1	79	43	36	34	8
7,1	–	29	02898299	SD1103A-0710-029-08R1	79	43	36	41	8
7,144	9/32	29	02898300	SD1103A-0714-029-08R1	79	43	36	41	8
7,2	–	29	02898301	SD1103A-0720-029-08R1	79	43	36	41	8
7,3	–	29	02898302	SD1103A-0730-029-08R1	79	43	36	41	8
7,4	–	29	02898303	SD1103A-0740-029-08R1	79	43	36	41	8
7,5	–	29	02898304	SD1103A-0750-029-08R1	79	43	36	41	8
7,55	–	29	02898306	SD1103A-0755-029-08R1	79	43	36	41	8
7,6	–	29	02898307	SD1103A-0760-029-08R1	79	43	36	41	8
7,7	–	29	02898308	SD1103A-0770-029-08R1	79	43	36	41	8
7,8	–	29	02898309	SD1103A-0780-029-08R1	79	43	36	41	8
7,9	–	29	02898310	SD1103A-0790-029-08R1	79	43	36	41	8
7,938	5/16	29	02898311	SD1103A-0794-029-08R1	79	43	36	41	8
8,0	–	29	02898312	SD1103A-0800-029-08R1	79	43	36	41	8
8,1	–	35	02898313	SD1103A-0810-035-10R1	89	49	40	47	10
8,2	–	35	02898314	SD1103A-0820-035-10R1	89	49	40	47	10
8,3	–	35	02898315	SD1103A-0830-035-10R1	89	49	40	47	10
8,334	21/64	35	02898316	SD1103A-0833-035-10R1	89	49	40	47	10
8,4	–	35	02898317	SD1103A-0840-035-10R1	89	49	40	47	10
8,5	–	35	02898318	SD1103A-0850-035-10R1	89	49	40	47	10
8,6	–	35	02898319	SD1103A-0860-035-10R1	89	49	40	47	10
8,7	–	35	02898320	SD1103A-0870-035-10R1	89	49	40	47	10
8,8	–	35	02898322	SD1103A-0880-035-10R1	89	49	40	47	10
8,9	–	35	02898323	SD1103A-0890-035-10R1	89	49	40	47	10
9,0	–	35	02898324	SD1103A-0900-035-10R1	89	49	40	47	10
9,1	–	35	02898325	SD1103A-0910-035-10R1	89	49	40	47	10
9,128	23/64	35	02898326	SD1103A-0913-035-10R1	89	49	40	47	10
9,2	–	35	02898327	SD1103A-0920-035-10R1	89	49	40	47	10
9,3	–	35	02898328	SD1103A-0930-035-10R1	89	49	40	47	10

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A



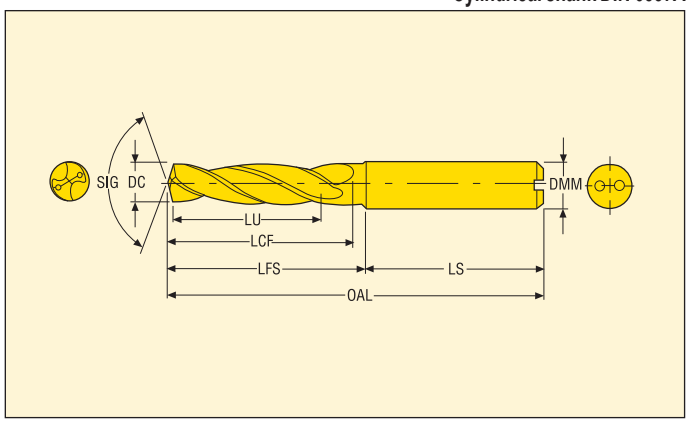
- Internal coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
9,4	–	35	02898329	SD1103A-0940-035-10R1	89	49	40	47	10
9,5	–	35	02898330	SD1103A-0950-035-10R1	89	49	40	47	10
9,55	–	35	02898332	SD1103A-0955-035-10R1	89	49	40	47	10
9,6	–	35	02898333	SD1103A-0960-035-10R1	89	49	40	47	10
9,7	–	35	02898334	SD1103A-0970-035-10R1	89	49	40	47	10
9,8	–	35	02898335	SD1103A-0980-035-10R1	89	49	40	47	10
9,9	–	35	02898336	SD1103A-0990-035-10R1	89	49	40	47	10
10,0	–	35	02898338	SD1103A-1000-035-10R1	89	49	40	47	10
10,2	–	40	02898339	SD1103A-1020-040-12R1	102	57	45	55	12
10,319	13/32	40	02898340	SD1103A-1032-040-12R1	102	57	45	55	12
10,4	–	40	02898341	SD1103A-1040-040-12R1	102	57	45	55	12
10,5	–	40	02898342	SD1103A-1050-040-12R1	102	57	45	55	12
10,6	–	40	02898343	SD1103A-1060-040-12R1	102	57	45	55	12
10,8	–	40	02898345	SD1103A-1080-040-12R1	102	57	45	55	12
10,9	–	40	02898346	SD1103A-1090-040-12R1	102	57	45	55	12
11,0	–	40	02898347	SD1103A-1100-040-12R1	102	57	45	55	12
11,1	–	40	02898348	SD1103A-1110-040-12R1	102	57	45	55	12
11,2	–	40	02898350	SD1103A-1120-040-12R1	102	57	45	55	12
11,3	–	40	02898351	SD1103A-1130-040-12R1	102	57	45	55	12
11,4	–	40	02898352	SD1103A-1140-040-12R1	102	57	45	55	12
11,5	–	40	02898353	SD1103A-1150-040-12R1	102	57	45	55	12
11,509	29/64	40	02898354	SD1103A-1151-040-12R1	102	57	45	55	12
11,55	–	40	02898355	SD1103A-1155-040-12R1	102	57	45	55	12
11,6	–	40	02898356	SD1103A-1160-040-12R1	102	57	45	55	12
11,7	–	40	02898357	SD1103A-1170-040-12R1	102	57	45	55	12
11,8	–	40	02898358	SD1103A-1180-040-12R1	102	57	45	55	12
11,9	–	40	02898359	SD1103A-1190-040-12R1	102	57	45	55	12
11,906	15/32	40	02898360	SD1103A-1191-040-12R1	102	57	45	55	12
12,0	–	40	02898361	SD1103A-1200-040-12R1	102	57	45	55	12
12,1	–	43	02898362	SD1103A-1210-043-14R1	107	62	45	60	14
12,2	–	43	02898363	SD1103A-1220-043-14R1	107	62	45	60	14
12,303	31/64	43	02898364	SD1103A-1230-043-14R1	107	62	45	60	14
12,4	–	43	02898365	SD1103A-1240-043-14R1	107	62	45	60	14
12,5	–	43	02898366	SD1103A-1250-043-14R1	107	62	45	60	14
12,6	–	43	02898367	SD1103A-1260-043-14R1	107	62	45	60	14
12,7	1/2	43	02898368	SD1103A-1270-043-14R1	107	62	45	60	14
12,75	–	43	02898369	SD1103A-1275-043-14R1	107	62	45	60	14
12,8	–	43	02898370	SD1103A-1280-043-14R1	107	62	45	60	14

Seco Universal – SD1103A

Drilling depth ~ 3 x D

Cylindrical shank DIN 6537A



- Internal coolant
- Point angle: 140°
- Coating: AlCrN
- Hole tolerance: IT8-9
- For cutting data see page(s) 101

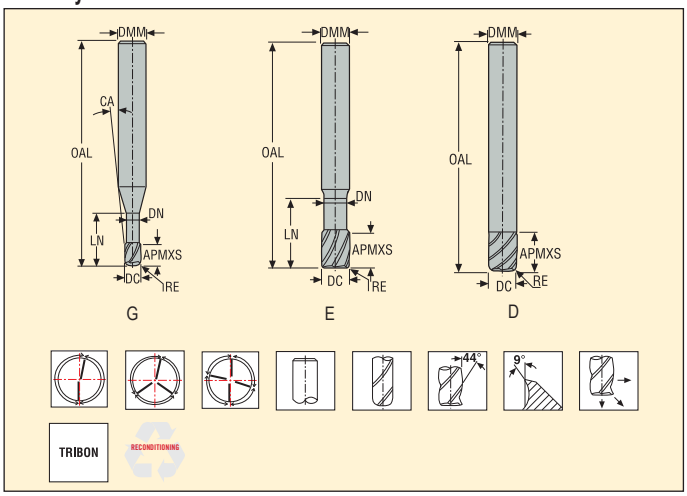
DC m7 (mm)	DC m7 (inch)	LU	Ordering and Product No.	Designation	Dimensions in mm				
					OAL	LFS	LS	LCF	DMM
12,9	–	43	02898371	SD1103A-1290-043-14R1	107	62	45	60	14
13,0	–	43	02898372	SD1103A-1300-043-14R1	107	62	45	60	14
13,1	–	43	02898373	SD1103A-1310-043-14R1	107	62	45	60	14
13,2	–	43	02898374	SD1103A-1320-043-14R1	107	62	45	60	14
13,3	–	43	02898375	SD1103A-1330-043-14R1	107	62	45	60	14
13,4	–	43	02898376	SD1103A-1340-043-14R1	107	62	45	60	14
13,494	17/32	43	02898377	SD1103A-1349-043-14R1	107	62	45	60	14
13,5	–	43	02898378	SD1103A-1350-043-14R1	107	62	45	60	14
13,6	–	43	02898379	SD1103A-1360-043-14R1	107	62	45	60	14
13,7	–	43	02898380	SD1103A-1370-043-14R1	107	62	45	60	14
13,8	–	43	02898381	SD1103A-1380-043-14R1	107	62	45	60	14
13,9	–	43	02898382	SD1103A-1390-043-14R1	107	62	45	60	14
14,0	–	43	02898383	SD1103A-1400-043-14R1	107	62	45	60	14
14,2	–	45	02898384	SD1103A-1420-045-16R1	115	67	48	65	16
14,5	–	45	02898386	SD1103A-1450-045-16R1	115	67	48	65	16
14,7	–	45	02898387	SD1103A-1470-045-16R1	115	67	48	65	16
14,75	–	45	02898388	SD1103A-1475-045-16R1	115	67	48	65	16
14,8	–	45	02898389	SD1103A-1480-045-16R1	115	67	48	65	16
15,0	–	45	02898390	SD1103A-1500-045-16R1	115	67	48	65	16
15,1	–	45	02898391	SD1103A-1510-045-16R1	115	67	48	65	16
15,3	–	45	02898392	SD1103A-1530-045-16R1	115	67	48	65	16
15,5	–	45	02898393	SD1103A-1550-045-16R1	115	67	48	65	16
15,7	–	45	02898394	SD1103A-1570-045-16R1	115	67	48	65	16
15,8	–	45	02898395	SD1103A-1580-045-16R1	115	67	48	65	16
16,0	–	45	02898397	SD1103A-1600-045-16R1	115	67	48	65	16
16,5	–	51	02898398	SD1103A-1650-051-18R1	123	75	48	73	18
17,0	–	51	02898399	SD1103A-1700-051-18R1	123	75	48	73	18
17,5	–	51	02898400	SD1103A-1750-051-18R1	123	75	48	73	18
18,0	–	51	02898401	SD1103A-1800-051-18R1	123	75	48	73	18
18,5	–	55	02898402	SD1103A-1850-055-20R1	131	81	50	79	20
19,0	–	55	02898403	SD1103A-1900-055-20R1	131	81	50	79	20
19,5	–	55	02898405	SD1103A-1950-055-20R1	131	81	50	79	20
20,0	–	55	02898406	SD1103A-2000-055-20R1	131	81	50	79	20

Appendix E.

SECO (2019b) catalog and technical guide 2019.2 Solid End Mills.

JHP750 – High performance – Titanium – Square – 2-4 Flutes – Cylindrical – Corner radius

Tolerances:
DMM=h5
DC=-0,02/-0,04 mm
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

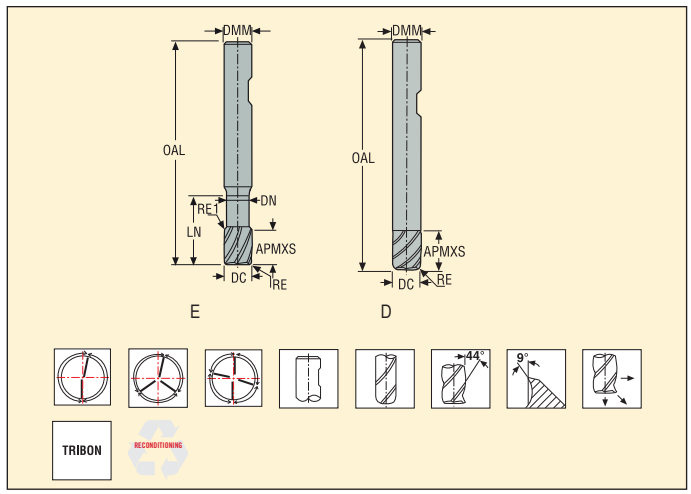


Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm						RE	CA	PCEDC	Cylindrical
				DC	DMM	APMXS	OAL	LN	DN				
02528232	750K080R040.0-TRIBON	1	D	8,0	8	16,0	55	–	–	0,4	–	4	■
02528234	750K100R040.0-TRIBON	1	D	10,0	10	20,0	65	–	–	0,4	–	4	■
02528236	750K100R150.0-TRIBON	1	D	10,0	10	20,0	65	–	–	1,5	–	4	■
02528238	750K120R040.0-TRIBON	1	D	12,0	12	24,0	75	–	–	0,4	–	4	■
02528242	750K120R150.0-TRIBON	1	D	12,0	12	24,0	75	–	–	1,5	–	4	■
02528244	750K160R040.0-TRIBON	1	D	16,0	16	32,0	90	–	–	0,4	–	4	■
02528250	750K160R150.0-TRIBON	1	D	16,0	16	32,0	90	–	–	1,5	–	4	■
02528253	750K200R080.0-TRIBON	1	D	20,0	20	40,0	100	–	–	0,8	–	4	■
02510010	750020R020.0-TRIBON	2	G	2,0	3	3,0	40	6	1,9	0,2	4,0	2	■
02510012	750030R020.0-TRIBON	2	E	3,0	3	4,5	40	9	2,8	0,2	–	2	■
02510013	750040R020.0-TRIBON	2	G	4,0	6	6,0	40	9	3,7	0,2	5,0	2	■
02510043	750050R030.0-TRIBON	2	G	5,0	6	7,5	40	9	4,6	0,3	3,0	2	■
02510044	750060R030.0-TRIBON	2	E	6,0	6	9,0	50	19	5,6	0,3	–	3	■
02510045	750080R040.0-TRIBON	2	E	8,0	8	16,0	60	24	7,4	0,4	–	4	■
02510046	750100R040.0-TRIBON	2	E	10,0	10	20,0	70	30	9,4	0,4	–	4	■
02510049	750100R080.0-TRIBON	2	E	10,0	10	20,0	70	30	9,4	0,8	–	4	■
02510053	750100R200.0-TRIBON	2	E	10,0	10	20,0	70	30	9,4	2,0	–	4	■
02510057	750120R040.0-TRIBON	2	E	12,0	12	24,0	80	35	11,4	0,4	–	4	■
02510060	750120R080.0-TRIBON	2	E	12,0	12	24,0	80	35	11,4	0,8	–	4	■
02510063	750120R200.0-TRIBON	2	E	12,0	12	24,0	80	35	11,4	2,0	–	4	■
02510065	750120R310.0-TRIBON	2	E	12,0	12	24,0	80	35	11,4	3,1	–	4	■
02510067	750140R080.0-TRIBON	2	E	14,0	14	28,0	90	45	13,4	0,8	–	4	■
02510071	750160R040.0-TRIBON	2	E	16,0	16	32,0	100	52	15,4	0,4	–	4	■
02510073	750160R080.0-TRIBON	2	E	16,0	16	32,0	100	52	15,4	0,8	–	4	■
02510077	750160R200.0-TRIBON	2	E	16,0	16	32,0	100	52	15,4	2,0	–	4	■
02510079	750160R310.0-TRIBON	2	E	16,0	16	32,0	100	52	15,4	3,1	–	4	■
02510081	750160R400.0-TRIBON	2	E	16,0	16	32,0	100	52	15,4	4,0	–	4	■
02510085	750200R080.0-TRIBON	2	E	20,0	20	40,0	125	75	19,4	0,8	–	4	■
02510087	750200R200.0-TRIBON	2	E	20,0	20	40,0	125	75	19,4	2,0	–	4	■

■ Stock standard. Subject to change refer to current price- and stock-list

JHP750 – High performance – Titanium – Square – 2-4 Flutes – Weldon – Corner radius

Tolerances:
DMM=h5
DC=-0,02/-0,04 mm
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6



Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm						RE	CA	PCEDC	Weldon
				DC	DMM	APMXS	OAL	LN	DN				
02528231	750K080R040-TRIBON	1	D	8,0	8	16	55	–	–	0,4	–	4	■
02528233	750K100R040-TRIBON	1	D	10,0	10	20	65	–	–	0,4	–	4	■
02528235	750K100R150-TRIBON	1	D	10,0	10	20	65	–	–	1,5	–	4	■
02528237	750K120R040-TRIBON	1	D	12,0	12	24	75	–	–	0,4	–	4	■
02528240	750K120R150-TRIBON	1	D	12,0	12	24	75	–	–	1,5	–	4	■
02528243	750K160R040-TRIBON	1	D	16,0	16	32	90	–	–	0,4	–	4	■
02528249	750K160R150-TRIBON	1	D	16,0	16	32	90	–	–	1,5	–	4	■
02528251	750K200R080-TRIBON	1	D	20,0	20	40	100	–	–	0,8	–	4	■
02611633	750K250R050-TRIBON	1	D	25,0	25	50	125	–	–	0,5	–	4	■
02611634	750K250R100-TRIBON	1	D	25,0	25	50	125	–	–	1,0	–	4	■
02528258	750080R040-TRIBON	2	E	8,0	8	16	60	24	7,4	0,4	–	4	■
02510047	750100R040-TRIBON	2	E	10,0	10	20	70	30	9,4	0,4	–	4	■
02510048	750100R080-TRIBON	2	E	10,0	10	20	70	30	9,4	0,8	–	4	■
02510052	750100R200-TRIBON	2	E	10,0	10	20	70	30	9,4	2,0	–	4	■
02510056	750120R040-TRIBON	2	E	12,0	12	24	80	35	11,4	0,4	–	4	■
02510058	750120R080-TRIBON	2	E	12,0	12	24	80	35	11,4	0,8	–	4	■
02510062	750120R200-TRIBON	2	E	12,0	12	24	80	35	11,4	2,0	–	4	■
02510064	750120R310-TRIBON	2	E	12,0	12	24	80	35	11,4	3,1	–	4	■
02510066	750140R080-TRIBON	2	E	14,0	14	28	90	45	13,4	0,8	–	4	■
02510070	750160R040-TRIBON	2	E	16,0	16	32	100	52	15,4	0,4	–	4	■
02510072	750160R080-TRIBON	2	E	16,0	16	32	100	52	15,4	0,8	–	4	■
02510076	750160R200-TRIBON	2	E	16,0	16	32	100	52	15,4	2,0	–	4	■
02510078	750160R310-TRIBON	2	E	16,0	16	32	100	52	15,4	3,1	–	4	■
02510080	750160R400-TRIBON	2	E	16,0	16	32	100	52	15,4	4,0	–	4	■
02510084	750200R080-TRIBON	2	E	20,0	20	40	125	75	19,4	0,8	–	4	■
02510086	750200R200-TRIBON	2	E	20,0	20	40	125	75	19,4	2,0	–	4	■

Remark: if cornerradius is >15% of DC then a_p=-30%, f_z=-20%

■ **Stock standard. Subject to change refer to current price- and stock-list**

Cutting data – JHP750 Slot milling

SMG		a_p/DC	f_z 2	3	4	5	6	8	10	12	14	16	18	20	25	v_c
S1	E/M/A	0,45	0,0075	0,011	0,015	0,019	0,022	0,030	0,038	0,044	0,050	0,055	0,060	0,065	0,075	31 (21 — 41)
S2	E/M/A	0,45	0,0075	0,011	0,015	0,019	0,022	0,030	0,038	0,044	0,050	0,055	0,060	0,065	0,075	25 (17 — 33)
S3	E/M/A	0,35	0,0046	0,0070	0,0095	0,012	0,014	0,019	0,024	0,028	0,032	0,034	0,036	0,040	0,044	21 (16 — 31)
S11	E/M/A	0,60	0,0085	0,013	0,017	0,022	0,026	0,034	0,042	0,050	0,055	0,065	0,070	0,075	0,080	95 (80 — 120)
S12	E/M/A	0,60	0,0085	0,013	0,017	0,022	0,026	0,034	0,042	0,050	0,055	0,065	0,070	0,075	0,080	70 (60 — 95)
S13	E/M/A	0,50	0,0075	0,011	0,015	0,019	0,022	0,030	0,038	0,044	0,050	0,055	0,060	0,065	0,070	55 (49 — 75)

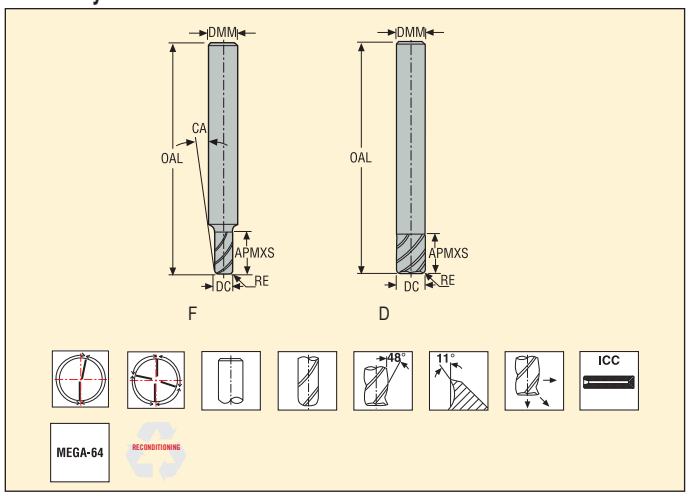
Cutting data – JHP750 Side milling

SMG		a_e/DC	a_p/DC	f_z 2	3	4	5	6	8	10	12	14	16	15	20	25	v_c
S1	E/M/A	0,060	1,2	0,016	0,024	0,032	0,040	0,048	0,065	0,080	0,095	0,11	0,12	0,13	0,14	0,15	50 (33 — 65)
S2	E/M/A	0,060	1,2	0,016	0,024	0,032	0,040	0,048	0,065	0,080	0,095	0,11	0,12	0,13	0,14	0,15	40 (27 — 55)
S3	E/M/A	0,040	1,2	0,012	0,018	0,024	0,030	0,036	0,048	0,060	0,070	0,080	0,090	0,095	0,10	0,11	35 (26 — 50)
S11	E/M/A	0,080	1,2	0,016	0,024	0,032	0,040	0,048	0,065	0,080	0,095	0,11	0,12	0,13	0,14	0,15	145 (125 — 185)
S12	E/M/A	0,080	1,2	0,016	0,024	0,032	0,040	0,048	0,065	0,080	0,095	0,11	0,12	0,13	0,14	0,15	110 (95 — 145)
S13	E/M/A	0,080	1,2	0,014	0,020	0,028	0,034	0,042	0,055	0,070	0,085	0,095	0,10	0,11	0,12	0,13	90 (75 — 115)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

JHP760 – High performance – Superalloy – Square – 2-4 Flutes – Cylindrical – Corner radius – ICC



Tolerances:
DMM=h5
DC=-0,02/-0,04 mm
RE= ±0,03 mm
Regrind possible if DC is ≥Ø6

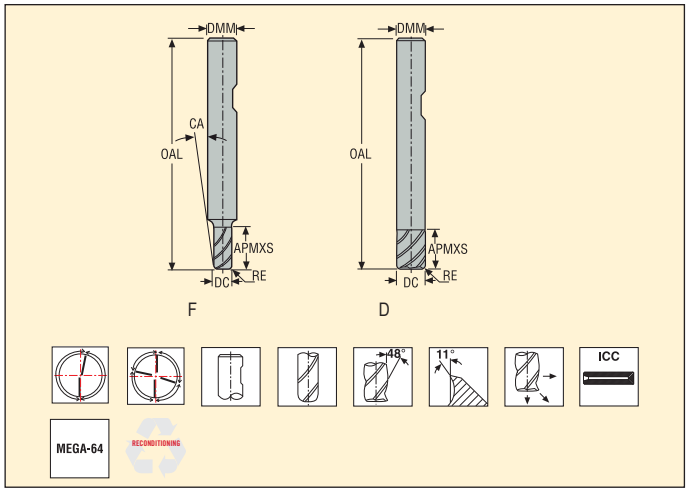
Ordering and Product No.	Designation	Length index	Tool shape	ICC	Dimensions in mm				RE	CA	PCEDC	Cylindrical
					DC	DMM	APMXS	OAL				
02623413	760040R040Z2.0A-MEGA-64	2	F	■	4,0	6	8	50	0,4	4,0	2	■
02734051	760040R020Z2.0A-MEGA-64	2	F	■	4,0	6	8	50	0,2	4,0	2	■
02734052	760050R020Z2.0A-MEGA-64	2	F	■	5,0	6	10	50	0,2	2,0	2	■
02623435	760050R040Z2.0A-MEGA-64	2	F	■	5,0	6	10	50	0,4	2,0	2	■
02734053	760060R020Z4.0A-MEGA-64	2	D	■	6,0	6	12	50	0,2	–	4	■
02623433	760060R040Z4.0A-MEGA-64	2	D	■	6,0	6	12	50	0,4	–	4	■
02623436	760080R040Z4.0A-MEGA-64	2	D	■	8,0	8	16	55	0,4	–	4	■
02623437	760080R100Z4.0A-MEGA-64	2	D	■	8,0	8	16	55	1,0	–	4	■
02623460	760100R040Z4.0A-MEGA-64	2	D	■	10,0	10	20	65	0,4	–	4	■
02623463	760100R100Z4.0A-MEGA-64	2	D	■	10,0	10	20	65	1,0	–	4	■
02623466	760100R150Z4.0A-MEGA-64	2	D	■	10,0	10	20	65	1,5	–	4	■
02623819	760120R040Z4.0A-MEGA-64	2	D	■	12,0	12	24	75	0,4	–	4	■
02623825	760120R100Z4.0A-MEGA-64	2	D	■	12,0	12	24	75	1,0	–	4	■
02623828	760120R150Z4.0A-MEGA-64	2	D	■	12,0	12	24	75	1,5	–	4	■
02623833	760120R310Z4.0A-MEGA-64	2	D	■	12,0	12	24	75	3,1	–	4	■
02734055	760200R040Z4.0A-MEGA-64	2	D	■	20,0	20	45	100	0,4	–	4	■
02623852	760200R080Z4.0A-MEGA-64	2	D	■	20,0	20	45	100	0,8	–	4	■
02623438	760L080R040Z4.0A-MEGA-64	3	D	■	8,0	8	28	65	0,4	–	4	■
02623461	760L100R040Z4.0A-MEGA-64	3	D	■	10,0	10	36	75	0,4	–	4	■
02623464	760L100R100Z4.0A-MEGA-64	3	D	■	10,0	10	36	75	1,0	–	4	■
02623467	760L100R150Z4.0A-MEGA-64	3	D	■	10,0	10	36	75	1,5	–	4	■
02623472	760L100R200Z4.0A-MEGA-64	3	D	■	10,0	10	36	75	2,0	–	4	■
02623807	760L100R310Z4.0A-MEGA-64	3	D	■	10,0	10	36	75	3,1	–	4	■
02623821	760L120R040Z4.0A-MEGA-64	3	D	■	12,0	12	42	90	0,4	–	4	■
02623826	760L120R100Z4.0A-MEGA-64	3	D	■	12,0	12	42	90	1,0	–	4	■
02623829	760L120R150Z4.0A-MEGA-64	3	D	■	12,0	12	42	90	1,5	–	4	■
02623831	760L120R200Z4.0A-MEGA-64	3	D	■	12,0	12	42	90	2,0	–	4	■
02623840	760L160R040Z4.0A-MEGA-64	3	D	■	16,0	16	50	100	0,4	–	4	■
02623842	760L160R100Z4.0A-MEGA-64	3	D	■	16,0	16	50	100	1,0	–	4	■
02623844	760L160R150Z4.0A-MEGA-64	3	D	■	16,0	16	50	100	1,5	–	4	■
02623846	760L160R200Z4.0A-MEGA-64	3	D	■	16,0	16	50	100	2,0	–	4	■

ICC = Internal Coolant Channel

■ **Stock standard. Subject to change refer to current price- and stock-list**

JHP760 – High performance – Superalloy – Square – 2-4 Flutes – Weldon – Corner radius – ICC

Tolerances:
DMM=h5
DC=-0,02/-0,4 mm
RE= ±0,03 mm
Regrind possible if DC is ≥Ø6



Ordering and Product No.	Designation	Length index	Tool shape	ICC	Dimensions in mm				RE	CA	PCEDC	Weldon
					DC	DMM	APMXS	OAL				
02734065	760040R020Z2.0A-MEGA-64W	2	F	■	4,0	6	8	50	0,2	–	2	□
02669339	760040R040Z2.0A-MEGA-64W	2	F	■	4,0	6	8	50	0,4	–	2	□
02734068	760050R020Z2.0A-MEGA-64W	2	F	■	5,0	6	10	50	0,2	–	2	□
02669340	760050R040Z2.0A-MEGA-64W	2	F	■	5,0	6	10	50	0,4	–	2	□
02734069	760060R020Z4.0A-MEGA-64W	2	D	■	6,0	6	12	50	0,2	–	4	□
02669341	760060R040Z4.0A-MEGA-64W	2	D	■	6,0	6	12	50	0,4	–	4	□
02669343	760080R040Z4.0A-MEGA-64W	2	D	■	8,0	8	16	55	0,4	–	4	□
02669344	760080R100Z4.0A-MEGA-64W	2	D	■	8,0	8	16	55	1,0	–	4	□
02623442	760100R040Z4A-MEGA-64	2	D	■	10,0	10	20	65	0,4	–	4	■
02623462	760100R100Z4A-MEGA-64	2	D	■	10,0	10	20	65	1,0	–	4	■
02623465	760100R150Z4A-MEGA-64	2	D	■	10,0	10	20	65	1,5	–	4	■
02623468	760100R200Z4A-MEGA-64	2	D	■	10,0	10	20	65	2,0	–	4	■
02623817	760120R040Z4A-MEGA-64	2	D	■	12,0	12	24	75	0,4	–	4	■
02623824	760120R100Z4A-MEGA-64	2	D	■	12,0	12	24	75	1,0	–	4	■
02623827	760120R150Z4A-MEGA-64	2	D	■	12,0	12	24	75	1,5	–	4	■
02623830	760120R200Z4A-MEGA-64	2	D	■	12,0	12	24	75	2,0	–	4	■
02623835	760120R400Z4A-MEGA-64	2	D	■	12,0	12	24	75	4,0	–	4	■
02623839	760160R040Z4A-MEGA-64	2	D	■	16,0	16	40	90	0,4	–	4	■
02623841	760160R100Z4A-MEGA-64	2	D	■	16,0	16	40	90	1,0	–	4	■
02623843	760160R150Z4A-MEGA-64	2	D	■	16,0	16	40	90	1,5	–	4	■
02623845	760160R200Z4A-MEGA-64	2	D	■	16,0	16	40	90	2,0	–	4	■
02734054	760200R040Z4A-MEGA-64	2	D	■	20,0	20	45	100	0,4	–	4	■
02623851	760200R080Z4A-MEGA-64	2	D	■	20,0	20	45	100	0,8	–	4	■
02734057	760250R050Z4A-MEGA-64	2	D	■	25,0	25	45	110	0,5	–	4	■
02720459	760L080R040Z4.0A-MEGA-64W	3	D	■	8,0	8	28	65	0,4	–	4	□
02669345	760L100R040Z4.0A-MEGA-64W	3	D	■	10,0	10	36	75	0,4	–	4	□
02669346	760L100R100Z4.0A-MEGA-64W	3	D	■	10,0	10	36	75	1,0	–	4	□
02669347	760L100R150Z4.0A-MEGA-64W	3	D	■	10,0	10	36	75	1,5	–	4	□
02669348	760L100R200Z4.0A-MEGA-64W	3	D	■	10,0	10	36	75	2,0	–	4	□
02669350	760L120R040Z4.0A-MEGA-64W	3	D	■	12,0	12	42	90	0,4	–	4	□
02669351	760L120R100Z4.0A-MEGA-64W	3	D	■	12,0	12	42	90	1,0	–	4	□
02669352	760L120R150Z4.0A-MEGA-64W	3	D	■	12,0	12	42	90	1,5	–	4	□
02669353	760L120R200Z4.0A-MEGA-64W	3	D	■	12,0	12	42	90	2,0	–	4	□
02669356	760L160R040Z4.0A-MEGA-64W	3	D	■	16,0	16	50	100	0,4	–	4	□
02669357	760L160R100Z4.0A-MEGA-64W	3	D	■	16,0	16	50	100	1,0	–	4	□
02669358	760L160R150Z4.0A-MEGA-64W	3	D	■	16,0	16	50	100	1,5	–	4	□
02669359	760L160R200Z4.0A-MEGA-64W	3	D	■	16,0	16	50	100	2,0	–	4	□

ICC = Internal Coolant Channel

■ **Stock standard. Subject to change refer to current price- and stock-list** □ Weldon available, delivery time is 3 days.

Cutting data – JHP760 Slot milling

SMG		a_p/DC	f_z 4	5	6	8	10	12	16	20	25	v_c
M1	E	1,0	0,016	0,020	0,024	0,032	0,040	0,050	0,065	0,080	0,10	110 (90 — 130)
M2	E	1,0	0,016	0,020	0,024	0,032	0,040	0,050	0,065	0,080	0,10	90 (75 — 105)
M3	E	0,80	0,013	0,016	0,019	0,026	0,032	0,038	0,050	0,065	0,080	60 (48 — 70)
M4	E	0,60	0,013	0,016	0,019	0,026	0,032	0,038	0,050	0,065	0,080	45 (37 — 55)
M5	E	0,60	0,013	0,016	0,019	0,026	0,032	0,038	0,050	0,065	0,080	37 (31 — 44)

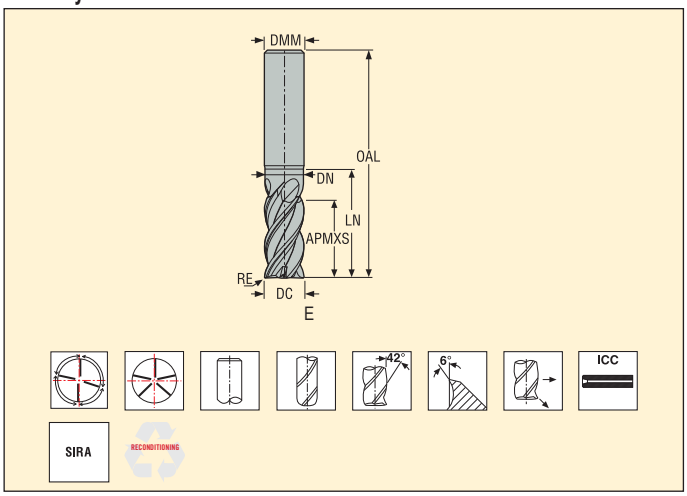
Cutting data – JHP760 Side milling

SMG		a_e/DC	a_p/DC	f_z 4	5	6	8	10	12	16	20	25	v_c
M1	E	0,30	1,5	0,032	0,040	0,048	0,065	0,080	0,095	0,12	0,13	0,15	120 (100 — 145)
M2	E	0,30	1,5	0,028	0,036	0,044	0,060	0,070	0,085	0,11	0,12	0,14	100 (85 — 120)
M3	E	0,30	1,4	0,026	0,032	0,038	0,050	0,065	0,075	0,095	0,11	0,12	65 (50 — 75)
M4	E	0,30	1,1	0,022	0,028	0,034	0,046	0,055	0,065	0,085	0,095	0,11	49 (41 — 60)
M5	E	0,30	1,1	0,022	0,028	0,034	0,046	0,055	0,065	0,085	0,095	0,11	41 (34 — 48)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

JHP770 – High performance – Titanium – Square – 4-5 Flutes – Cylindrical – Corner radius – ICC



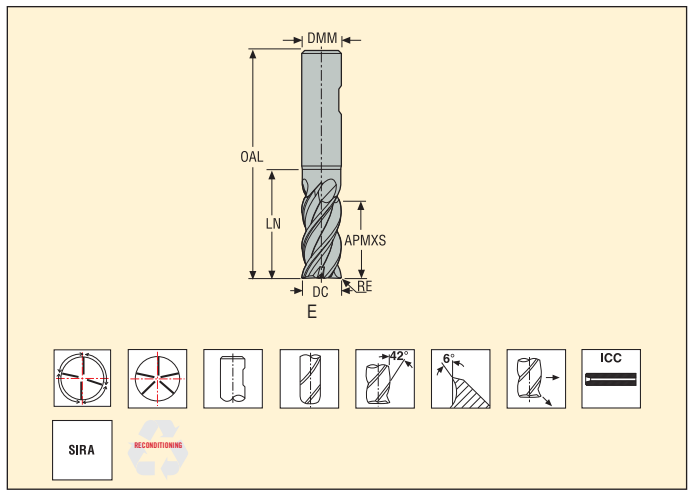
Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

Ordering and Product No.	Designation	Length index	Tool shape	ICC	Dimensions in mm						RE	PCEDC	Cylindrical
					DC	DMM	APMXS	OAL	LN	DN			
02760645	JHP770060E2R030.0Z4A-SIRA	2	E	■	6,0	6	12	60	18	5,6	0,3	4	■
02823416	JHP770080E2R050.0Z4A-SIRA	2	E	■	8,0	8	16	65	24	7,4	0,5	4	■
02823417	JHP770100E2R050.0Z4A-SIRA	2	E	■	10,0	10	20	75	30	9,4	0,5	4	■
02823418	JHP770100E2R100.0Z4A-SIRA	2	E	■	10,0	10	20	75	30	9,4	1,0	4	■
02823419	JHP770120E2R050.0Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	0,5	4	■
02823420	JHP770120E2R100.0Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	1,0	4	■
02760659	JHP770120E2R250.0Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	2,5	4	■
02823421	JHP770140E2R050.0Z4A-SIRA	2	E	■	14,0	14	28	95	42	13,4	0,5	4	■
02823422	JHP770160E2R050.0Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	0,5	4	■
02823423	JHP770160E2R100.0Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	1,0	4	■
02760663	JHP770160E2R250.0Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	2,5	4	■
02760664	JHP770160E2R310.0Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	3,1	4	■
02760665	JHP770160E2R400.0Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	4,0	4	■
02823424	JHP770200E2R050.0Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	0,5	4	■
02823425	JHP770200E2R100.0Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	1,0	4	■
02760668	JHP770200E2R250.0Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	2,5	4	■
02760669	JHP770200E2R310.0Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	3,1	4	■
02760670	JHP770200E2R400.0Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	4,0	4	■
02823427	JHP770250E2R100.0Z4A-SIRA	2	E	■	25,0	25	50	130	65	24,4	1,0	4	■
02760673	JHP770250E2R310.0Z4A-SIRA	2	E	■	25,0	25	50	130	65	24,4	3,1	4	■
02760674	JHP770250E2R400.0Z4A-SIRA	2	E	■	25,0	25	50	130	65	24,4	4,0	4	■
02810129	JHP770160E2R050.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	0,5	5	■
02810130	JHP770160E2R100.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	1,0	5	■
02810131	JHP770160E2R250.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	2,5	5	■
02810132	JHP770160E2R310.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	3,1	5	■
02810133	JHP770160E2R400.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	4,0	5	■
03093701	JHP770160E2R600.0Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	6,0	5	■
02810134	JHP770200E2R050.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	0,5	5	■
02810135	JHP770200E2R100.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	1,0	5	■
02810136	JHP770200E2R250.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	2,5	5	■
02810137	JHP770200E2R310.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	3,1	5	■
02810138	JHP770200E2R400.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	4,0	5	■
03093702	JHP770200E2R600.0Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	6,0	5	■
02810139	JHP770250E2R050.0Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	0,5	5	■
02810141	JHP770250E2R310.0Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	3,1	5	■
02810142	JHP770250E2R400.0Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	4,0	5	■
03093703	JHP770250E2R600.0Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	6,0	5	■

Remark: if cornerradius is >15% of DC → a_p=-30%, f_z=-20%
ICC = Internal Coolant Channel
■ **Stock standard. Subject to change refer to current price- and stock-list**

JHP770 – High performance – Titanium – Square – 4-5 Flutes – Weldon – Corner radius – – ICC

Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6



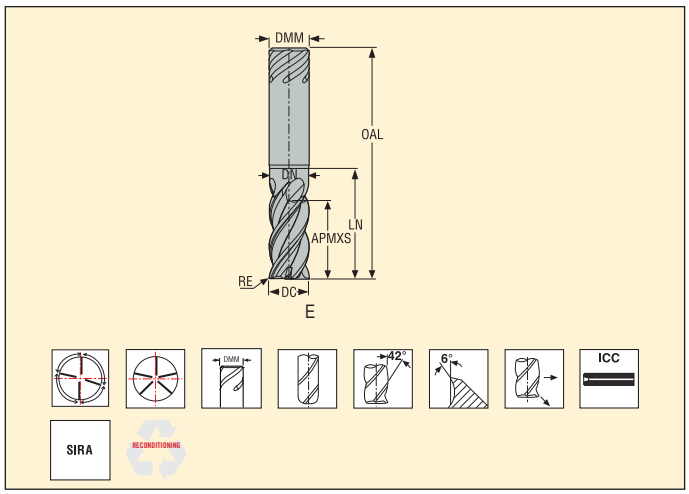
Ordering and Product No.	Designation	Length index	Tool shape	ICC	Dimensions in mm						RE	PCEDC	Weldon
					DC	DMM	APMXS	OAL	LN	DN			
02760796	JHP770060E2R030.3Z4A-SIRA	2	E	■	6,0	6	12	60	18	5,6	0,3	4	■
02823428	JHP770080E2R050.3Z4A-SIRA	2	E	■	8,0	8	16	65	24	7,4	0,5	4	■
02823429	JHP770100E2R050.3Z4A-SIRA	2	E	■	10,0	10	20	75	30	9,4	0,5	4	■
02823430	JHP770100E2R100.3Z4A-SIRA	2	E	■	10,0	10	20	75	30	9,4	1,0	4	■
02823431	JHP770120E2R050.3Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	0,5	4	■
02823432	JHP770120E2R100.3Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	1,0	4	■
02760805	JHP770120E2R250.3Z4A-SIRA	2	E	■	12,0	12	24	90	36	11,4	2,5	4	□
02823433	JHP770140E2R050.3Z4A-SIRA	2	E	■	14,0	14	28	95	42	13,4	0,5	4	■
02823434	JHP770160E2R050.3Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	0,5	4	■
02823435	JHP770160E2R100.3Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	1,0	4	■
02760810	JHP770160E2R250.3Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	2,5	4	■
02760811	JHP770160E2R310.3Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	3,1	4	□
02760817	JHP770160E2R400.3Z4A-SIRA	2	E	■	16,0	16	32	100	45	15,4	4,0	4	□
02823436	JHP770200E2R050.3Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	0,5	4	■
02823437	JHP770200E2R100.3Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	1,0	4	■
02760823	JHP770200E2R250.3Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	2,5	4	□
02760824	JHP770200E2R310.3Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	3,1	4	□
02760825	JHP770200E2R400.3Z4A-SIRA	2	E	■	20,0	20	40	115	55	19,4	4,0	4	□
02760828	JHP770250E2R310.3Z4A-SIRA	2	E	■	25,0	25	50	130	65	24,4	3,1	4	□
02760829	JHP770250E2R400.3Z4A-SIRA	2	E	■	25,0	25	50	130	65	24,4	4,0	4	□
02810143	JHP770160E2R050.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	0,5	5	■
02810144	JHP770160E2R100.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	1,0	5	■
02810145	JHP770160E2R250.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	2,5	5	□
02810146	JHP770160E2R310.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	3,1	5	■
02810147	JHP770160E2R400.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	4,0	5	□
03093711	JHP770160E2R600.3Z5A-SIRA	2	E	■	16,0	16	32	100	45	15,4	6,0	5	□
02810148	JHP770200E2R050.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	0,5	5	■
02810149	JHP770200E2R100.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	1,0	5	■
02810150	JHP770200E2R250.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	2,5	5	□
02810151	JHP770200E2R310.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	3,1	5	■
02810152	JHP770200E2R400.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	4,0	5	■
03093713	JHP770200E2R600.3Z5A-SIRA	2	E	■	20,0	20	40	115	55	19,4	6,0	5	□
02810153	JHP770250E2R050.3Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	0,5	5	■
02810154	JHP770250E2R100.3Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	1,0	5	■
02810155	JHP770250E2R310.3Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	3,1	5	□
02810156	JHP770250E2R400.3Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	4,0	5	□
03093715	JHP770250E2R600.3Z5A-SIRA	2	E	■	25,0	25	50	130	65	24,4	6,0	5	□

Remark: if cornerradius is >15% of DC → a_p=-30%, f_z=-20%
ICC = Internal Coolant Channel

■ **Stock standard. Subject to change refer to current price- and stock-list** □ Weldon available, delivery time is 3 days.


SECO
SAFE-LOCK

JHP770 – High performance – Titanium – Square – 4-5 Flutes – Safelock – Corner radius – ICC



Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

Ordering and Product No.	Designation	Length index	Tool shape	ICC	Dimensions in mm						RE	PCEDC	Safelock
					DC	DMM	APMXS	OAL	LN	DN			
02927944	JHP770120E2R050.9Z4A-SIRA	2	E	■	12,0	12	24	90	36	11	0,5	4	□
02927946	JHP770120E2R100.9Z4A-SIRA	2	E	■	12,0	12	24	90	36	11	1,0	4	□
02927947	JHP770120E2R250.9Z4A-SIRA	2	E	■	12,0	12	24	90	36	11	2,5	4	□
02927950	JHP770140E2R050.9Z4A-SIRA	2	E	■	14,0	14	28	95	42	13	0,5	4	□
02927952	JHP770160E2R100.9Z4A-SIRA	2	E	■	16,0	16	32	100	45	15	1,0	4	□
02927954	JHP770160E2R250.9Z4A-SIRA	2	E	■	16,0	16	32	100	45	15	2,5	4	□
02927956	JHP770160E2R310.9Z4A-SIRA	2	E	■	16,0	16	32	100	45	15	3,1	4	□
02927958	JHP770160E2R400.9Z4A-SIRA	2	E	■	16,0	16	32	100	45	15	4,0	4	□
02927960	JHP770200E2R050.9Z4A-SIRA	2	E	■	20,0	20	40	115	55	19	0,5	4	□
02927962	JHP770200E2R100.9Z4A-SIRA	2	E	■	20,0	20	40	115	55	19	1,0	4	□
02927964	JHP770200E2R250.9Z4A-SIRA	2	E	■	20,0	20	40	115	55	19	2,5	4	□
02927966	JHP770200E2R310.9Z4A-SIRA	2	E	■	20,0	20	40	115	55	19	3,1	4	□
02927968	JHP770200E2R400.9Z4A-SIRA	2	E	■	20,0	20	40	115	55	19	4,0	4	□
02927970	JHP770250E2R050.9Z4A-SIRA	2	E	■	25,0	25	50	130	65	24	0,5	4	□
02927972	JHP770250E2R100.9Z4A-SIRA	2	E	■	25,0	25	50	130	65	24	1,0	4	□
02927975	JHP770250E2R310.9Z4A-SIRA	2	E	■	25,0	25	50	130	65	24	3,1	4	□
02927976	JHP770250E2R400.9Z4A-SIRA	2	E	■	25,0	25	50	130	65	24	4,0	4	□
02927978	JHP770160E2R050.9Z4A-SIRA	2	E	■	16,0	16	32	100	45	15	0,5	4	□
02927949	JHP770160E2R050.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	0,5	5	□
02927953	JHP770160E2R100.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	1,0	5	□
02927955	JHP770160E2R250.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	2,5	5	□
02927957	JHP770160E2R310.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	3,1	5	□
02927959	JHP770160E2R400.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	4,0	5	□
03093712	JHP770160E2R600.9Z5A-SIRA	2	E	■	16,0	16	32	100	45	15	6,0	5	□
02927961	JHP770200E2R050.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	0,5	5	□
02927963	JHP770200E2R100.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	1,0	5	□
02927965	JHP770200E2R250.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	2,5	5	□
02927967	JHP770200E2R310.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	3,1	5	□
02927969	JHP770200E2R400.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	4,0	5	□
03093714	JHP770200E2R600.9Z5A-SIRA	2	E	■	20,0	20	40	115	55	19	6,0	5	□
02927971	JHP770250E2R050.9Z5A-SIRA	2	E	■	25,0	25	50	130	65	24	0,5	5	□
02927973	JHP770250E2R100.9Z5A-SIRA	2	E	■	25,0	25	50	130	65	24	1,0	5	□
02927974	JHP770250E2R310.9Z5A-SIRA	2	E	■	25,0	25	50	130	65	24	3,1	5	□
02927977	JHP770250E2R400.9Z5A-SIRA	2	E	■	25,0	25	50	130	65	24	4,0	5	□
03093716	JHP770250E2R600.9Z5A-SIRA	2	E	■	25,0	25	50	130	65	24	6,0	5	□

Remark: if cornerradius is >15% of DC → a_p=-30%, f_z=-20%
ICC = Internal Coolant Channel
□ Safelock available. Subject to change refer to current price-and stock-list.

Cutting data – JHP770 Slot milling

SMG		a_p/DC	f_z 6	8	10	12	14	16	20	25	v_c
S11	E	1,6	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,11	90 (90 — 120)
S12	E	1,6	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,11	70 (70 — 90)
S13	E	1,4	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,11	55 (55 — 70)

Cutting data – JHP770 Slot milling Internal coolant *

SMG		a_p/DC	f_z 6	8	10	12	14	16	20	25	v_c
S11	E	1,6	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,13	105 (95 — 120)
S12	E	1,6	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,13	80 (70 — 90)
S13	E	1,4	0,030	0,040	0,050	0,060	0,070	0,080	0,10	0,13	65 (55 — 70)

Cutting data – JHP770 Side milling

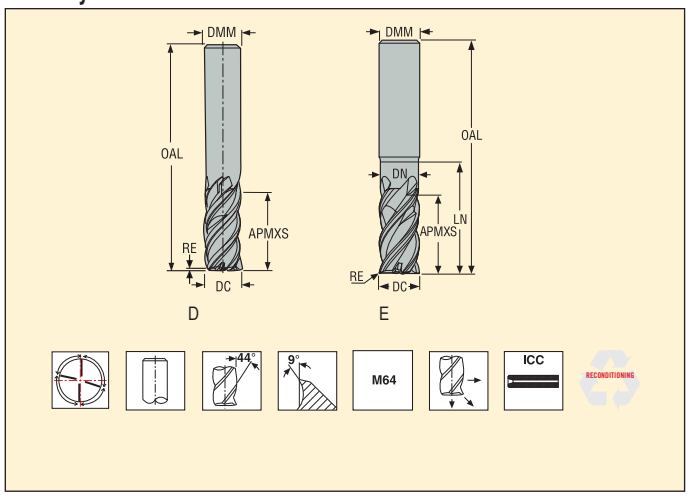
SMG		a_e/DC	a_p/DC	f_z 6	8	10	12	14	16	20	25	v_c
S11	E	0,40	1,8	0,050	0,065	0,080	0,095	0,11	0,12	0,14	0,14	100 (105 — 135)
S12	E	0,40	1,8	0,050	0,065	0,080	0,095	0,11	0,12	0,14	0,14	80 (80 — 100)
S13	E	0,40	1,8	0,042	0,055	0,070	0,085	0,095	0,11	0,12	0,12	65 (65 — 80)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

JHP780 – High performance – Superalloy – Square – 4-Flutes – Cylindrical – Corner radius – ICC

Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

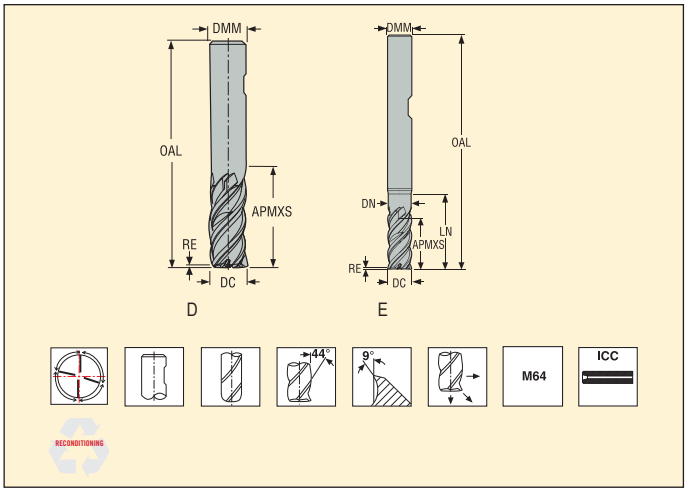


Ordering and Product No.	Designation	ICC	Length index	Tool shape	Dimensions in mm				LN	DN	RE	PCEDC	Cylindrical
					DC	DMM	APMXS	OAL					
03134984	JHP780060D1R030.0Z4A-M64	■	1	D	6,0	6	7,5	47	–	–	0,3	4	■
03134985	JHP780060D1R080.0Z4A-M64	■	1	D	6,0	6	7,5	47	–	–	0,8	4	■
03134986	JHP780080D1R040.0Z4A-M64	■	1	D	8,0	8	10,0	50	–	–	0,4	4	■
03134987	JHP780080D1R080.0Z4A-M64	■	1	D	8,0	8	10,0	50	–	–	0,8	4	■
03134988	JHP780100D1R040.0Z4A-M64	■	1	D	10,0	10	12,5	57	–	–	0,4	4	■
03134989	JHP780100D1R080.0Z4A-M64	■	1	D	10,0	10	12,5	57	–	–	0,8	4	■
03134990	JHP780120D1R040.0Z4A-M64	■	1	D	12,0	12	15,0	65	–	–	0,4	4	■
03134991	JHP780120D1R080.0Z4A-M64	■	1	D	12,0	12	15,0	65	–	–	0,8	4	■
03134992	JHP780060E2R030.0Z4A-M64	■	2	E	6,0	6	12,0	60	18,0	5,6	0,3	4	■
02760834	JHP780060E2R030.0Z4-M64		2	E	6,0	6	12,0	60	18,0	5,6	0,3	4	■
03134993	JHP780080E2R040.0Z4A-M64	■	2	E	8,0	8	16,0	65	24,0	7,4	0,4	4	■
02760842	JHP780080E2R040.0Z4-M64		2	E	8,0	8	16,0	65	24,0	7,4	0,4	4	■
03134994	JHP780100E2R040.0Z4A-M64	■	2	E	10,0	10	20,0	75	30,0	9,4	0,4	4	■
02760846	JHP780100E2R040.0Z4-M64		2	E	10,0	10	20,0	75	30,0	9,4	0,4	4	■
03134995	JHP780100E2R080.0Z4A-M64	■	2	E	10,0	10	20,0	75	30,0	9,4	0,8	4	■
02760847	JHP780100E2R080.0Z4-M64		2	E	10,0	10	20,0	75	30,0	9,4	0,8	4	■
03134996	JHP780120E2R040.0Z4A-M64	■	2	E	12,0	12	24,0	90	36,0	11,4	0,4	4	■
02760848	JHP780120E2R040.0Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	0,4	4	■
03134997	JHP780120E2R080.0Z4A-M64	■	2	E	12,0	12	24,0	90	36,0	11,4	0,8	4	■
02760849	JHP780120E2R080.0Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	0,8	4	■
02760850	JHP780120E2R150.0Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	1,5	4	■
02760851	JHP780120E2R250.0Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	2,5	4	■
02760852	JHP780140E2R040.0Z4-M64		2	E	14,0	14	28,0	95	42,0	13,4	0,4	4	■
03135000	JHP780160E2R040.0Z4A-M64	■	2	E	16,0	16	32,0	100	45,0	15,4	0,4	4	■
02760853	JHP780160E2R040.0Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	0,4	4	■
03135001	JHP780160E2R080.0Z4A-M64	■	2	E	16,0	16	32,0	100	45,0	15,4	0,8	4	■
02760861	JHP780160E2R080.0Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	0,8	4	■
02760862	JHP780160E2R310.0Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	3,1	4	■
02760863	JHP780160E2R400.0Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	4,0	4	■
03093704	JHP780160E2R600.0Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	6,0	4	■
02760865	JHP780200E2R040.0Z4-M64		2	E	20,0	20	40,0	115	55,0	19,4	0,4	4	■
02760866	JHP780200E2R080.0Z4-M64		2	E	20,0	20	40,0	115	55,0	19,4	0,8	4	■
02760867	JHP780200E2R310.0Z4-M64		2	E	20,0	20	40,0	115	55,0	19,4	3,1	4	■
02760868	JHP780200E2R400.0Z4-M64		2	E	20,0	20	40,0	115	55,0	19,4	4,0	4	■
03093706	JHP780200E2R600.0Z4-M64		2	E	20,0	20	40,0	115	55,0	19,4	6,0	4	■
02760870	JHP780250E2R080.0Z4-M64		2	E	25,0	25	50,0	130	65,0	24,4	0,8	4	■
02760874	JHP780250E2R400.0Z4-M64		2	E	25,0	25	50,0	130	65,0	24,4	4,0	4	■
03093707	JHP780250E2R600.0Z4-M64		2	E	25,0	25	50,0	130	65,0	24,4	6,0	4	■

ICC = Internal Coolant Channel

■ **Stock standard. Subject to change refer to current price- and stock-list**

JHP780 – High performance – Superalloy – Square – 4-Flutes – Weldon – Corner radius – ICC

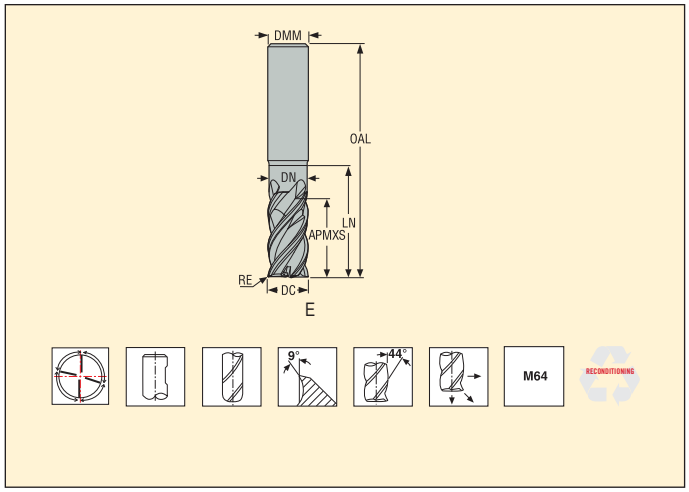


Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

Ordering and Product No.	Designation	ICC	Length index	Tool shape	Dimensions in mm				LN	DN	RE	PCEDC	Weldon
					DC	DMM	APMXS	OAL					
03135445	JHP780060D1R030.3Z4A-M64	■	1	D	6,0	6	7,5	47	–	–	0,3	4	■
03135446	JHP780060D1R080.3Z4A-M64	■	1	D	6,0	6	7,5	47	–	–	0,8	4	■
03135447	JHP780080D1R040.3Z4A-M64	■	1	D	8,0	8	10,0	50	–	–	0,4	4	■
03135449	JHP780080D1R080.3Z4A-M64	■	1	D	8,0	8	10,0	50	–	–	0,8	4	■
03135450	JHP780100D1R040.3Z4A-M64	■	1	D	10,0	10	12,5	57	–	–	0,4	4	■
03135451	JHP780100D1R080.3Z4A-M64	■	1	D	10,0	10	12,5	57	–	–	0,8	4	■
03135452	JHP780120D1R040.3Z4A-M64	■	1	D	12,0	12	15,0	65	–	–	0,4	4	■
03135453	JHP780120D1R080.3Z4A-M64	■	1	D	12,0	12	15,0	65	–	–	0,8	4	■
03135454	JHP780060E2R030.3Z4A-M64	■	2	E	6,0	6	12,0	60	18,0	5,6	0,3	4	■
02760878	JHP780060E2R030.3Z4-M64		2	E	6,0	6	12,0	60	18,0	5,6	0,3	4	■
03135455	JHP780080E2R040.3Z4A-M64	■	2	E	8,0	8	16,0	65	24,0	7,4	0,4	4	■
02760879	JHP780080E2R040.3Z4-M64		2	E	8,0	8	16,0	65	24,0	7,4	0,4	4	■
03135456	JHP780100E2R040.3Z4A-M64	■	2	E	10,0	10	20,0	75	30,0	9,4	0,4	4	■
02760880	JHP780100E2R040.3Z4-M64		2	E	10,0	10	20,0	75	30,0	9,4	0,4	4	■
03135457	JHP780100E2R080.3Z4A-M64	■	2	E	10,0	10	20,0	75	30,0	9,4	0,8	4	■
02760881	JHP780100E2R080.3Z4-M64		2	E	10,0	10	20,0	75	30,0	9,4	0,8	4	■
03134998	JHP780120E2R040.3Z4A-M64	■	2	E	12,0	12	24,0	90	36,0	11,4	0,4	4	■
02760883	JHP780120E2R040.3Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	0,4	4	■
03134999	JHP780120E2R080.3Z4A-M64	■	2	E	12,0	12	24,0	90	36,0	11,4	0,8	4	■
02760885	JHP780120E2R080.3Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	0,8	4	■
02760887	JHP780120E2R150.3Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	1,5	4	■
02766989	JHP780120E2R250.3Z4-M64		2	E	12,0	12	24,0	90	36,0	11,4	2,5	4	■
02760888	JHP780140E2R040.3Z4-M64		2	E	14,0	14	28,0	95	42,0	13,4	0,4	4	■
03135002	JHP780160E2R040.3Z4A-M64	■	2	E	16,0	16	32,0	100	45,0	15,4	0,4	4	■
02760889	JHP780160E2R040.3Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	0,4	4	■
03135003	JHP780160E2R080.3Z4A-M64	■	2	E	16,0	16	32,0	100	45,0	15,4	0,8	4	■
02760890	JHP780160E2R080.3Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	0,8	4	■
02760893	JHP780160E2R400.3Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	4,0	4	■
03093717	JHP780160E2R600.3Z4-M64		2	E	16,0	16	32,0	100	45,0	15,4	6,0	4	□

ICC = Internal Coolant Channel
■ **Stock standard. Subject to change refer to current price- and stock-list**

JHP780 – High performance – Superalloy – Square – 4-Flutes – Weldon – Corner radius

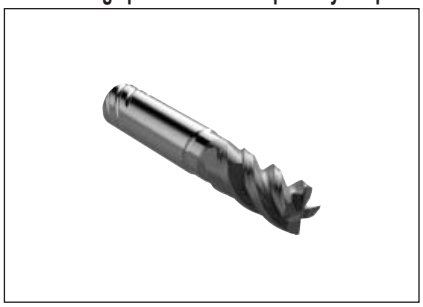


Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6

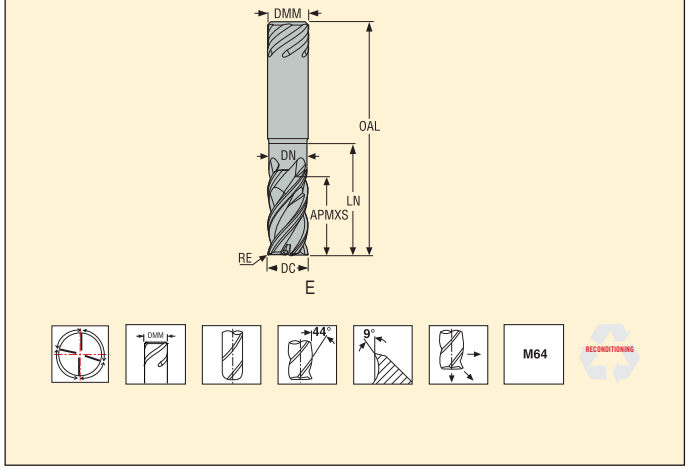
Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm				LN	DN	RE	PCEDC	Weldon
				DC	DMM	APMXS	OAL					
02760894	JHP780200E2R040.3Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	0,4	4	■
02760896	JHP780200E2R080.3Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	0,8	4	■
02760900	JHP780250E2R040.3Z4-M64	2	E	25,0	25	50,0	130	65,0	24,4	0,4	4	■
02760901	JHP780250E2R080.3Z4-M64	2	E	25,0	25	50,0	130	65,0	24,4	0,8	4	■
02760903	JHP780250E2R400.3Z4-M64	2	E	25,0	25	50,0	130	65,0	24,4	4,0	4	■
03093709	JHP780250E2R600.3Z4-M64	2	E	25,0	25	50,0	130	65,0	24,4	6,0	4	□
02760897	JHP780200E2R310.3Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	3,1	4	■
02760898	JHP780200E2R400.3Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	4,0	4	■
03093719	JHP780200E2R600.3Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	6,0	4	□

■ **Stock standard. Subject to change refer to current price- and stock-list** □ Weldon available, delivery time is 3 days.

JHP780 – High performance – Superalloy – Square – 4 Flutes – Safelock



Tolerances:
DMM=h5
DC=e7
RE= ±0,02 mm
Regrind possible if DC is ≥Ø6



Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm				LN	DN	RE	PCEDC	Safelock
				DC	DMM	APMXS	OAL					
03093718	JHP780160E2R600.9Z4-M64	2	E	16,0	16	32,0	100	45,0	15,4	6,0	4	☐
03093720	JHP780200E2R600.9Z4-M64	2	E	20,0	20	40,0	115	55,0	19,4	6,0	4	☐
03093710	JHP780250E2R600.9Z4-M64	2	E	25,0	25	50,0	130	65,0	24,4	6,0	4	☐

■ Stock standard. Subject to change refer to current price- and stock-list

Cutting data – JHP780 Slot milling

SMG		a_p/DC	f_z 6	8	10	12	14	16	20	25	 v_c
S1	E	0,80	0,020	0,028	0,034	0,042	0,048	0,055	0,070	0,085	44 (37 — 50)
S2	E	0,80	0,020	0,028	0,034	0,042	0,048	0,055	0,070	0,085	35 (30 — 40)
S3	E	0,60	0,012	0,016	0,020	0,024	0,028	0,032	0,040	0,050	25 (20 — 30)

Cutting data – JHP780 Side milling

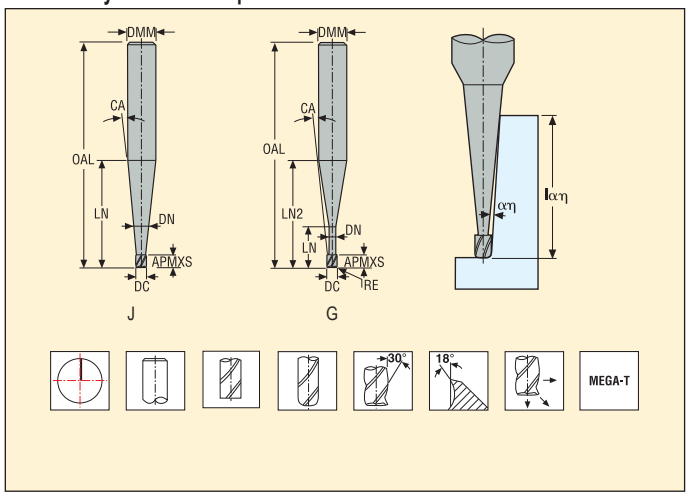
SMG		a_e/DC	a_p/DC	f_z 6	8	10	12	14	16	20	25	 v_c
S1	E	0,30	1,0	0,036	0,048	0,060	0,070	0,080	0,090	0,10	0,12	50 (45 — 60)
S2	E	0,30	1,0	0,036	0,048	0,060	0,070	0,080	0,090	0,10	0,12	42 (36 — 48)
S3	E	0,30	0,80	0,036	0,048	0,060	0,070	0,080	0,090	0,10	0,11	28 (22 — 33)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

JM403/JM404/JM406 – Miniature – Aluminium – Square – 1 Flute – Cylindrical – Sharp or corner radius

Tolerances:
Run-out=<0,005 mm
DMM=h5
DC<0,6=-0,005/-0,013, DC≥0,6=-0,005/-0,015 mm
RE= ±0,01 mm



Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm								CA	PCEDC	Max. cut depth rel. to αη (lαη, ref)*					
				DC	DMM	APMXS	OAL	LN	LN2	DN	RE			WDX0	WDX05	WDX1	WDX15	WDX2	WDX3
02568429	403002-MEGA-T	1	J	0,2	3	0,2	40	–	6,0	–	–	13,5	1	0,2	0,3	0,3	0,3	0,4	0,4
02568430	403003-MEGA-T	1	J	0,3	3	0,3	40	–	5,9	–	–	13,0	1	0,3	0,4	0,4	0,4	0,5	0,5
02568431	403004-MEGA-T	1	J	0,4	3	0,4	40	–	5,8	–	–	13,0	1	0,4	0,5	0,5	0,6	0,6	0,6
02568432	403005-MEGA-T	1	J	0,5	3	0,5	40	–	5,8	–	–	12,5	1	0,5	0,6	0,6	0,7	0,7	0,8
02568434	403ML005R005-MEGA-T	2	G	0,5	3	0,5	40	1,5	6,7	0,45	0,05	11,0	1	1,5	1,6	1,7	1,7	1,8	1,9
02568441	403ML006R005-MEGA-T	2	G	0,6	3	0,6	40	2,0	7,0	0,55	0,05	10,0	1	2,0	2,1	2,2	2,3	2,3	2,5
02568450	403ML008R005-MEGA-T	2	G	0,8	3	0,8	40	2,5	7,1	0,75	0,05	9,0	1	2,5	2,6	2,7	2,8	2,9	3,2
02568456	403ML010R010-MEGA-T	2	G	1,0	3	1,0	40	4,0	8,3	0,95	0,1	7,5	1	4,0	4,2	4,3	4,5	4,6	5,0
02568472	406ML012R010-MEGA-T	2	G	1,2	6	1,2	50	4,5	14,0	1,15	0,1	10,0	1	4,5	4,7	4,9	5,0	5,2	5,6
02568478	406ML015R010-MEGA-T	2	G	1,5	6	1,5	50	5,0	14,0	1,4	0,1	9,5	1	5,1	5,3	5,5	5,7	5,9	6,4
02577246	404ML020R010-MEGA-T	2	G	2,0	4	2,0	40	6,0	10,4	1,9	0,1	6,0	1	6,1	6,3	6,6	6,8	7,0	7,6
02568437	403XL005R005-MEGA-T	5	G	0,5	3	0,5	40	4,0	9,21	0,45	0,05	8,0	1	4,0	4,2	4,3	4,5	4,6	5,0
02568445	403XL006R005-MEGA-T	5	G	0,6	3	0,6	40	5,0	10,0	0,55	0,05	7,0	1	5,0	5,2	5,4	5,6	5,8	6,3
02568453	403XL008R005-MEGA-T	5	G	0,8	3	0,8	40	7,0	11,6	0,75	0,05	5,5	1	7,0	7,3	7,5	7,8	8,1	8,8
02568459	403XL010R010-MEGA-T	5	G	1,0	3	1,0	40	8,5	12,8	0,95	0,1	5,0	1	8,5	8,8	9,1	9,5	9,8	10,6
02568475	406XL012R010-MEGA-T	5	G	1,2	6	1,2	50	10,0	19,5	1,15	0,1	7,5	1	10,0	10,4	10,7	11,1	11,5	12,5
02568482	406XL015R010-MEGA-T	5	G	1,5	6	1,5	60	12,0	21,0	1,4	0,1	6,5	1	12,1	12,5	13,0	13,4	13,9	15,1
02568490	406XL020R010-MEGA-T	5	G	2,0	6	2,0	60	16,0	24,1	1,9	0,1	5,0	1	16,1	16,7	17,3	17,9	8,5	20,0

* The effective under -neck length for the various draft angles. Remark ∞ = infinity, no collision in projection length area.

Cutting data – JM403/JM404/406 Slot milling

SMG		a_e/DC	a_p/DC	f_z							
				0,5	0,6	0,8	1,0	1,2	1,5	2,0	v_c
N1	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	365 (305 — 425)
N2	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	235 (195 — 275)
N3	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	155 (130 — 180)

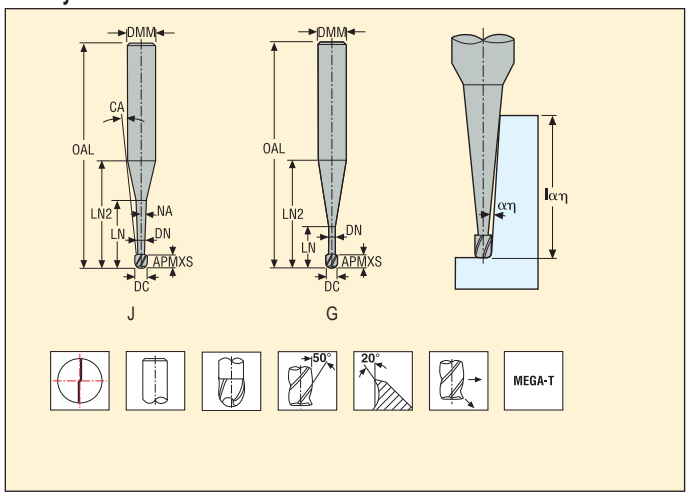
Cutting data – JM403/JM404/406 Side milling

SMG		a_e/DC	a_p/DC	f_z							
				0,5	0,6	0,8	1,0	1,2	1,5	2,0	v_c
N1	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	365 (305 — 425)
N2	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	235 (195 — 275)
N3	E	0,50	0,70	0,015	0,018	0,024	0,030	0,036	0,042	0,050	155 (130 — 180)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

JM413/JM416 – Miniature – Aluminium – Ball nose – 2 Flute – Cylindrical



Tolerances:
Run-out=<0,005 mm
DMM=h5
DC <0,6=-0,005/-0,013 mm, DC≥0,6=-0,005/-0,015 mm
RE= ±0,005 mm

Ordering and Product No.	Designation	Length index	Tool shape	Dimensions in mm							CA	PCEDC	Max. cut depth rel. to αη (lαη, ref)*					
				DC	DMM	APMXS	OAL	LN	LN2	DN			WDX0	WDX05	WDX1	WDX15	WDX2	WDX3
02568709	413ML005TN-MEGA-T	2	J	0,5	3	0,375	40	–	6,6	0,45	11,5	2	1,5	1,5	1,6	1,6	1,7	1,8
02568711	413L005-MEGA-T	3	G	0,5	3	0,375	40	2,5	7,7	0,45	10,0	2	2,5	2,6	2,7	2,8	2,9	3,1
02568719	413L006-MEGA-T	3	G	0,6	3	0,45	40	3,0	8,0	0,55	9,0	2	3,0	3,1	3,2	3,3	3,5	3,7
02568727	413L008-MEGA-T	3	G	0,8	3	0,6	40	4,0	8,6	0,75	8,0	2	4,0	4,2	4,3	4,4	4,6	4,9
02568736	413L010-MEGA-T	3	G	1,0	3	0,75	40	5,0	9,3	0,95	7,0	2	5,0	5,2	5,4	5,5	5,7	6,2
02568765	416L012-MEGA-T	3	G	1,2	6	0,9	50	6,0	15,5	1,15	9,5	2	6,0	6,2	6,4	6,6	6,9	7,4
02568772	416L015-MEGA-T	3	G	1,5	6	1,125	50	7,5	16,5	1,4	8,5	2	7,6	7,9	8,1	8,4	8,7	9,3
02568779	416L020-MEGA-T	3	G	2,0	6	1,5	50	10,0	18,1	1,9	7,0	2	10,1	10,4	10,8	11,1	11,5	12,4
02568714	413XL005-MEGA-T	5	G	0,5	3	0,375	40	4,0	9,2	0,45	8,0	2	4,0	4,2	4,3	4,5	4,6	5,0
02568722	413XL006-MEGA-T	5	G	0,6	3	0,45	40	5,0	10,0	0,55	7,5	2	5,0	5,2	5,4	5,6	5,8	6,2
02568731	413XL008-MEGA-T	5	G	0,8	3	0,6	40	7,0	11,6	0,75	6,0	2	7,0	7,3	7,5	7,8	8,0	8,7
02568740	413XL010-MEGA-T	5	G	1,0	3	0,75	40	8,5	12,8	0,95	5,0	2	8,5	8,8	9,1	9,4	9,8	10,5
02568768	416XL012-MEGA-T	5	G	1,2	6	0,9	50	10,0	19,5	1,15	7,5	2	10,0	10,4	10,7	11,1	11,5	12,4
02568775	416XL015-MEGA-T	5	G	1,5	6	1,125	60	12,0	21,0	1,4	6,5	2	12,1	12,2	12,9	13,4	13,9	14,9
02568782	416XL020-MEGA-T	5	G	2,0	6	1,5	60	16,0	24,1	1,9	5,0	2	16,1	16,6	17,2	17,8	18,4	19,8

* The effective under -neck length for the various draft angles. Remark ∞ = infinity, no collision in projection length area.

Cutting data – JM413/416 Copy milling roughing

SMG		a_e/DC	a_p/DC	f_z 0,5	0,6	0,8	1	1,2	1,5	2	 v_c
N1	E	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	385 (365 — 510)
N2	E	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	245 (235 — 330)
N3	E	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	165 (155 — 220)
N11	E	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	320 (290 — 435)
TS1	A	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	385 (365 — 510)
TP1	A	0,30	0,30	0,030	0,036	0,048	0,060	0,070	0,085	0,10	385 (365 — 510)

For cutting data recalculations, see page 420-428.

SMG = Seco material group
Coolant = A=air D=dry E=emulsion M=mist spray
v_c= m/min
f_z = mm
a_p (mm)/DC (mm)= factor
a_e (mm)/DC (mm)= factor
All cutting data are target values

Appendix F.

Matlab programming code.

(i) FBMAS Initialization

```
aa = str2num(char(get(handles.edit1,'String')));
cc = str2num(char(get(handles.edit2,'String')));
dd = str2num(char(get(handles.edit5,'String')));

if isempty(aa)==1 || aa<1
    msgbox('Input part length!')
elseif isempty(cc)==1 || cc<1
    msgbox('Input part width!')
elseif isempty(dd)==1 || dd<1
    msgbox('Input part height')
end

hole=get(handles.checkbox1,'Value');
hole=double(hole);

slot=get(handles.checkbox2,'Value');
slot=double(slot);

pocket=get(handles.checkbox5,'Value');
pocket=double(pocket);

boss=get(handles.checkbox6,'Value');
boss=double(boss);

pattern=get(handles.checkbox10,'Value');
pattern=double(pattern);

if hole==0
    if slot==0
        if pocket==0
            if boss==0
                if pattern==0
                    msgbox ('Select at least one feature design!')
                end
            end
        end
    end

else
    if aa>500
        if hole==0
            if slot==0
                if pocket==0
                    if boss==0
                        if pattern==0
                            msgbox ('Select at least one feature
design!')
                        else

                            qqq=questdlg('Is it possible to separate the
part into modules?', ...
                                'Question', ...
```

```
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    msgbox('It is recommended to
separate the part into modules before any further evaluation is
conducted.')
                                case 'No'
                                    msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                            end
                        end

                    else
                        qqq=questdlg('Is it possible to separate the
part into modules?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                msgbox('It is recommended to separate
the part into modules before any further evaluation is conducted.')
                            case 'No'
                                msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                        end
                    end

                else
                    qqq=questdlg('Is it possible to separate the part
into modules?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            msgbox('It is recommended to separate the
part into modules before any further evaluation is conducted.')
                        case 'No'
                            msgbox('Recommended manufacturing technique
is Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
                    end
                end

            else
                qqq=questdlg('Is it possible to separate the part into
modules?', ...
                    'Question', ...
                    'Yes','No','NO');
                switch qqq
                    case 'Yes'
                        msgbox('It is recommended to separate the part
into modules before any further evaluation is conducted.')
                    case 'No'
                        msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
                end
            end
        else
            qqq=questdlg('Is it possible to separate the part into
modules?', ...
                'Question', ...
```

```
                'Yes','No','NO');
            switch qqq
                case 'Yes'
                    msgbox('It is recommended to separate the part into
modules before any further evaluation is conducted.')
                case 'No'
                    msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
            end
        end

    elseif cc>280
        if hole==0
            if slot==0
                if pocket==0
                    if boss==0
                        if pattern==0
                            msgbox ('Select at least one feature
design!')
                        else
                            qqq=questdlg('Is it possible to separate the
part into modules?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    msgbox('It is recommended to
separate the part into modules before any further evaluation is
conducted.')
                                case 'No'
                                    msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                            end
                        end
                    else
                        qqq=questdlg('Is it possible to separate the
part into modules?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                msgbox('It is recommended to separate
the part into modules before any further evaluation is conducted.')
                            case 'No'
                                msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                        end
                    end

                else
                    qqq=questdlg('Is it possible to separate the part
into modules?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            msgbox('It is recommended to separate the
part into modules before any further evaluation is conducted.')
                        case 'No'
                            msgbox('Recommended manufacturing technique
is Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
```

```
                    end
                end

            else
                qqq=questdlg('Is it possible to separate the part into
modules?', ...
                    'Question', ...
                    'Yes','No','NO');
                switch qqq
                    case 'Yes'
                        msgbox('It is recommended to separate the part
into modules before any further evaluation is conducted.')
                    case 'No'
                        msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
                end
            end

        else
            qqq=questdlg('Is it possible to separate the part into
modules?', ...
                'Question', ...
                'Yes','No','NO');
            switch qqq
                case 'Yes'
                    msgbox('It is recommended to separate the part into
modules before any further evaluation is conducted.')
                case 'No'
                    msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
            end
        end

    elseif dd>850
        if hole==0
            if slot==0
                if pocket==0
                    if boss==0
                        if pattern==0
                            msgbox ('Select at least one feature
design!')
                        else
                            qqq=questdlg('Is it possible to separate the
part into modules?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    msgbox('It is recommended to
separate the part into modules before any further evaluation is
conducted.')
                                case 'No'
                                    msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                            end
                        end

                    else
                        qqq=questdlg('Is it possible to separate the
part into modules?', ...
                            'Question', ...
```

```
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                msgbox('It is recommended to separate
the part into modules before any further evaluation is conducted.')
                            case 'No'
                                msgbox('Recommended manufacturing
technique is Subtractive Manufacturing. Otherwise, the part is too large
to be fabricated as one part using SLM technology.')
                        end
                    end

                else
                    qqq=questdlg('Is it possible to separate the part
into modules?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            msgbox('It is recommended to separate the
part into modules before any further evaluation is conducted.')
                        case 'No'
                            msgbox('Recommended manufacturing technique
is Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
                    end
                end

            else
                qqq=questdlg('Is it possible to separate the part into
modules?', ...
                    'Question', ...
                    'Yes','No','NO');
                switch qqq
                    case 'Yes'
                        msgbox('It is recommended to separate the part
into modules before any further evaluation is conducted.')
                    case 'No'
                        msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
                end
            end

        else
            qqq=questdlg('Is it possible to separate the part into
modules?', ...
                'Question', ...
                'Yes','No','NO');
            switch qqq
                case 'Yes'
                    msgbox('It is recommended to separate the part into
modules before any further evaluation is conducted.')
                case 'No'
                    msgbox('Recommended manufacturing technique is
Subtractive Manufacturing. Otherwise, the part is too large to be
fabricated as one part using SLM technology.')
            end
        end
    end
end
```

```
get(handles.checkbox2,'Value') == 0) %     &&
get(handles.checkbox5,'Value') == 0 && get(handles.checkbox6,'Value') ==
0 && get(handles.checkbox10,'Value') == 0)
if aa<=500 && cc<=280 && dd<=850
get(handles.checkbox2,'Value') == 0      &&
get(handles.checkbox5,'Value') == 0 && get(handles.checkbox6,'Value') ==
0 && get(handles.checkbox10,'Value') == 0)
    hole=get(handles.checkbox1,'Value');
    slot=get(handles.checkbox2,'Value');
    slot=double(slot);
    aa=sum(slot);
    global x
    x=aa;
    pocket=get(handles.checkbox5,'Value');
    pocket=double(pocket);
    bb=sum(pocket);
    global y
    y=bb;
    boss=get(handles.checkbox6,'Value');
    boss=double(boss);
    cc=sum(boss);
    global z
    z=cc;
    pattern=get(handles.checkbox10,'Value');
    pattern=double(pattern);
    ee=sum(pattern);
    global yy
    yy=ee;
end

    if sum(hole)==1
        hole_num
    elseif sum(slot)==1
        slot_num
    elseif sum(pocket)==1
        pocket_num
    elseif sum(boss)==1
        boss_num
    elseif sum(pattern)==1
        pattern_num
    end
end

if (get(handles.checkbox7,'Value') ~= 0)
    set(handles.checkbox8,'Enable','OFF')
else
    set(handles.checkbox8,'Enable','ON')
end

if (get(handles.checkbox8,'Value') ~= 0)
    set(handles.checkbox7,'Enable','OFF')
else
    set(handles.checkbox7,'Enable','ON')
end
```

(ii) Entry of number of hole groups

```
function pushbutton1_Callback(hObject, eventdata, handles)
global number
number = str2num(char(get(handles.edit1,'String')));
h1=isempty(number);

if number<=0
```

```
    msgbox('Please input the number of designs!')
    elseif h1==1
    msgbox('Please input the number of designs!')
elseif number>5
    msgbox('Input a valid number of designs!')
end

if h1~=1
    if number>=1 && number<=5
       window2
    end
end
```

(iii) Hole feature

```
function radiobutton1_Callback(hObject, eventdata, handles)
set(handles.radiobutton17,'Value',0)

function radiobutton2_Callback(hObject, eventdata, handles)
set(handles.radiobutton16,'Value',0)

function radiobutton14_Callback(hObject, eventdata, handles)
set(handles.edit2,'Enable','ON')
set(handles.radiobutton15,'Value',0)

function radiobutton15_Callback(hObject, eventdata, handles)
set(handles.edit2,'Enable','OFF')
set(handles.radiobutton14,'Value',0)

function radiobutton16_Callback(hObject, eventdata, handles)
set(handles.radiobutton2,'Value',0)

function radiobutton17_Callback(hObject, eventdata, handles)
set(handles.radiobutton1,'Value',0)

function radiobutton18_Callback(hObject, eventdata, handles)
set(handles.radiobutton19,'Value',0)

function radiobutton19_Callback(hObject, eventdata, handles)
set(handles.radiobutton18,'Value',0)

function radiobutton20_Callback(hObject, eventdata, handles)
set(handles.edit5,'Enable','OFF')
set(handles.edit4,'Enable','OFF')
set(handles.edit8,'Enable','OFF')
set(handles.radiobutton21,'Value',0)

function radiobutton21_Callback(hObject, eventdata, handles)
set(handles.edit5,'Enable','ON')
set(handles.edit4,'Enable','ON')
set(handles.edit8,'Enable','ON')
set(handles.radiobutton20,'Value',0)

function radiobutton30_Callback(hObject, eventdata, handles)
set(handles.radiobutton31,'Value',0)
set(handles.popupmenu9,'Enable','ON')

function radiobutton31_Callback(hObject, eventdata, handles)
set(handles.radiobutton30,'Value',0)
set(handles.popupmenu9,'Enable','OFF')
```

```
function radiobutton25_Callback(hObject, eventdata, handles)

function pushbutton3_Callback(hObject, eventdata, handles)
a = str2num(char(get(handles.edit5,'String')));
c = str2num(char(get(handles.edit4,'String')));
d = str2num(char(get(handles.edit6,'String')));
e = str2num(char(get(handles.edit8,'String')));

if (get(handles.radiobutton1,'Value') == 0 &&
get(handles.radiobutton17,'Value') == 0)
    msgbox('Select an answer!')
elseif (get(handles.radiobutton21,'Value') == 0 &&
get(handles.radiobutton20,'Value') == 0)
    msgbox('Select an answer!')
elseif (get(handles.radiobutton30,'Value') == 0 &&
get(handles.radiobutton31,'Value') == 0)
    msgbox('Select an answer!')
elseif isempty(d)==1 || d<=0
    msgbox('Input a valid hole diameter!')

    %%negative draft
elseif (get(handles.radiobutton1,'Value') ~= 0)

    if get(handles.radiobutton21,'Value')~=0
        if isempty(c)==1 || c<10
            msgbox('Input a valid undercut hole diameter!')
        elseif isempty(a)==1 || a<1
            msgbox('Input a valid undercut hole depth!')
        elseif isempty(e)==1 || e<1
            msgbox('Input a valid undercut hole length!')

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM, it is challenging to create a negative draft using
subtractive manufacturing techniques.')
        end

    else
        set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM, it is challenging to create a negative draft using
subtractive manufacturing techniques.')
    end

    %undercut
elseif get(handles.radiobutton21,'Value')~=0
    if isempty(c)==1 || c<10
        msgbox('Input a valid undercut hole diameter!')
    elseif isempty(a)==1 || a<1
        msgbox('Input a valid undercut hole depth!')
    elseif isempty(e)==1 || e<1
        msgbox('Input a valid undercut hole length!')
   elseif c==10
        f=(c-6)/2;
        if a<=f
            if e<=7
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')
popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
```

```
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')

                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10

                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
```

```
                                    end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                        end
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                            end
                        end

                    else
                        if d<0.2
                            msgbox('Input a valid hole diameter!')
                        elseif d>=0.2 && d<2
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
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                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                            end
                    end

                elseif d>=2 && d<10
                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                            end
                    end

                elseif d>=10 && d<=20
                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            qqq=questdlg('Is it a lateral hole?',
...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
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                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

 elseif c==11
        f=(c-6)/2;
        if a<=f
            if e<=7
                if (get(handles.radiobutton30,'Value') ~= 0)
                contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
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                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
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                                                case 'Yes'
                                                    set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                                case 'No'
                                                    set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                            end
                                        case 'No'
                                            qqq=questdlg('Is it a blind
hole?', ...
                                                'Question', ...
                                                'Yes','No','NO');
                                            switch qqq
                                                case 'Yes'
                                                    set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                case 'No'
                                                    set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                            end
                                    end

                                elseif d>20
                                    msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                                end
                            end
                        else
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
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                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>=10 && d<=20
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
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                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

    elseif c==12
        f=(c-6)/2;
        if a<=f
            if e<=7
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
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                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                            end
                                        end

                                    elseif d>=2 && d<10
                                        qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                            case 'No'
                                                qqq=questdlg('Is it a blind
hole?', ...
                                                    'Question', ...
                                                    'Yes','No','NO');
                                                switch qqq
                                                    case 'Yes'
                                                        set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                    case 'No'
                                                        set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                                end
                                        end

                                    elseif d>=10 && d<=20
                                        qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                qqq=questdlg('Is it a lateral
hole?', ...
                                                    'Question', ...
                                                    'Yes','No','NO');
                                                switch qqq
                                                    case 'Yes'
                                                        set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                                    case 'No'
                                                        set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                                end

                                            case 'No'
                                                qqq=questdlg('Is it a blind
hole?', ...
                                                    'Question', ...
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                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                    end
                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                            end
                        end

                    else
                        if d<0.2
                            msgbox('Input a valid hole diameter!')
                        elseif d>=0.2 && d<2
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    end
                            end

                        elseif d>=2 && d<10
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
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                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                            end

                        elseif d>=10 && d<=20
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    qqq=questdlg('Is it a lateral hole?',
...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    end

                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                    end
                            end

                        elseif d>20
                            msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                        end
                    end

                else
                    set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
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tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

    elseif c==13
        f=(c-6)/2;
        if a<=f
            if e<=7
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
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                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                        end

                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
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                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                            end
                        end

                    else
                        if d<0.2
                            msgbox('Input a valid hole diameter!')
                        elseif d>=0.2 && d<2
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    end
                            end

                        elseif d>=2 && d<10
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                    end
                            end

                        elseif d>=10 && d<=20
```

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                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end
    elseif c==14
        f=(c-6)/2;
        if a<=f
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            if e<=7
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')
popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
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                                                    set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                                end
                                            end

                                        elseif d>=10 && d<=20
                                            qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                                'Question', ...
                                                'Yes','No','NO');
                                            switch qqq
                                                case 'Yes'
                                                    qqq=questdlg('Is it a lateral
hole?', ...
                                                        'Question', ...
                                                        'Yes','No','NO');
                                                    switch qqq
                                                        case 'Yes'
                                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                                        case 'No'
                                                            set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                                    end

                                                case 'No'
                                                    qqq=questdlg('Is it a blind
hole?', ...
                                                        'Question', ...
                                                        'Yes','No','NO');
                                                    switch qqq
                                                        case 'Yes'
                                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                        case 'No'
                                                            set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                                    end
                                            end

                                        elseif d>20
                                            msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                                        end
                                End

                            else
                                if d<0.2
                                    msgbox('Input a valid hole diameter!')
                                elseif d>=0.2 && d<2
                                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                        'Question', ...
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                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                            end
                    end

                elseif d>=2 && d<10
                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                            end
                    end

                elseif d>=10 && d<=20
                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            qqq=questdlg('Is it a lateral hole?',
...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
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remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                End

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end
elseif c==15
        f=(c-8)/2;
        if a<=f
            if e<=10
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')
popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
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                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
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                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                        case 'No'
                                            set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                    end
                                case 'No'
                                    qqq=questdlg('Is it a blind
hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                    end
                            end

                        elseif d>20
                            msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                        end
                end

            else
                if d<0.2
                    msgbox('Input a valid hole diameter!')
                elseif d>=0.2 && d<2
                    qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                            end
                    end
```

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                    elseif d>=2 && d<10
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>=10 && d<=20
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
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                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                            end

                        elseif d>20
                            msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                        end
                    end

                else
                    set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
            end

        elseif c==16
            f=(c-8)/2;
            if a<=f
                if e<=10
                    if (get(handles.radiobutton30,'Value') ~= 0)
                        contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                        switch popupmenu9value
                            case 'Select Tapping'
                                msgbox('Select tapping!')
                            case 'M2'
                                set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                            case 'M4'
                                set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                            otherwise
                                if d<0.2
                                    msgbox('Input a valid hole diameter!')
                                elseif d>=0.2 && d<2
                                    qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                        case 'No'
                                            qqq=questdlg('Is it a blind
hole?', ...
                                                'Question', ...
                                                'Yes','No','NO');
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                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                        end
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                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                            end
                        End

                    else
                        if d<0.2
                            msgbox('Input a valid hole diameter!')
                        elseif d>=0.2 && d<2
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    end
                            end

                        elseif d>=2 && d<10
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
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                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                            end

                        elseif d>=10 && d<=20
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    qqq=questdlg('Is it a lateral hole?',
...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    end

                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                    end
                            end

                        elseif d>20
                            msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                        end
                    end
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            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

    elseif c==17
        f=(c-8)/2;
        if a<=f
            if e<=10
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')
    popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
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                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                        end

                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
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difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                    end

                                elseif d>20
                                    msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                                end
                            end

                        else
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                        end
                                end
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                    elseif d>=10 && d<=20
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                End

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end
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    elseif c==18
        f=(c-8)/2;
        if a<=f
            if e<=10
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
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                                                    set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                case 'No'
                                                    set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                                end
                                            end

                                        elseif d>=10 && d<=20
                                            qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                                'Question', ...
                                                'Yes','No','NO');
                                            switch qqq
                                                case 'Yes'
                                                    qqq=questdlg('Is it a lateral
hole?', ...
                                                        'Question', ...
                                                        'Yes','No','NO');
                                                    switch qqq
                                                        case 'Yes'
                                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                                        case 'No'
                                                            set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                                    end

                                                case 'No'
                                                    qqq=questdlg('Is it a blind
hole?', ...
                                                        'Question', ...
                                                        'Yes','No','NO');
                                                    switch qqq
                                                        case 'Yes'
                                                            set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                        case 'No'
                                                            set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                                    end
                                            end

                                        elseif d>20
                                            msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                                        end



                                end
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                else
                    if d<0.2
                        msgbox('Input a valid hole diameter!')
                    elseif d>=0.2 && d<2
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                end
                        end

                    elseif d>=2 && d<10
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>=10 && d<=20
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
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                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

    elseif c==19
        f=(c-8)/2;
        if a<=f
            if e<=10
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
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                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end
```

```
                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                        end

                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                            end
                        end

                    else
                        if d<0.2
                            msgbox('Input a valid hole diameter!')
                        elseif d>=0.2 && d<2
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                case 'No'
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                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                end
                            end

                        elseif d>=2 && d<10
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                case 'No'
                                    qqq=questdlg('Is it a blind hole?', ...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                    end
                            end

                        elseif d>=10 && d<=20
                            qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    qqq=questdlg('Is it a lateral hole?',
...
                                        'Question', ...
                                        'Yes','No','NO');
                                    switch qqq
                                        case 'Yes'
                                            set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                        case 'No'
                                            set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    end
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                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>20
                        msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                    end
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
            end

        else
            set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
        end

    elseif c==20
        f=(c-8)/2;
        if a<=f
            if e<=10
                if (get(handles.radiobutton30,'Value') ~= 0)
                    contents=get(handles.popupmenu9,'String')

popupmenu9value=contents{get(handles.popupmenu9,'Value')}
                    switch popupmenu9value
                        case 'Select Tapping'
                            msgbox('Select tapping!')
                        case 'M2'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        case 'M4'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used
further machining will be needed to achieve the desired tapping.')
                        otherwise
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 2:1?', ...
```

```
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use EDM drill due to fine feature
identification.')
                                        end
                                end

                            elseif d>=2 && d<10
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:4?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                            case 'No'
                                                set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                        end
                                end

                            elseif d>=10 && d<=20
                                qqq=questdlg('Is maximum ratio of hole
diameter to hole length 1:3?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        qqq=questdlg('Is it a lateral
hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
```

```
                                                    set(handles.edit9,
'String', 'Recommended manufacturing technique is CNC machining.
Otherwise, if SLM is used a support structure will have to be added to
hold the lateral hole from collapsing. Hence, the user must acknowledge
the necessity to remove the support structures which might not be easily
accessible or require further machining.')
                                                case 'No'
                                                    set(handles.edit9,
'String', 'Recommended to use SLM or CNC machining, because no
limitation is identified for manufacturing this feature.')
                                            end
                                        case 'No'
                                            qqq=questdlg('Is it a blind
hole?', ...
                                                'Question', ...
                                                'Yes','No','NO');
                                            switch qqq
                                                case 'Yes'
                                                    set(handles.edit9,
'String', 'Recommended manufacturing technique is SLM or die sink EDM.
Otherwise,  it is difficult for a cutting tool to reach higher depth
that is not within the standard ratio of hole diameter to depth.')
                                                case 'No'
                                                    set(handles.edit9,
'String', 'Recommended to use SLM or Wire EDM, Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                                            end
                                    end

                                elseif d>20
                                    msgbox('Refer to pocket feature, or
enter a value for hole diameter between 1 and 20 mm!')
                                end
                            end

                        else
                            if d<0.2
                                msgbox('Input a valid hole diameter!')
                            elseif d>=0.2 && d<2
                                qqq=questdlg('Is maximum ratio of hole diameter
to hole length 2:1?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                    case 'No'
                                        qqq=questdlg('Is it a blind hole?', ...
                                            'Question', ...
                                            'Yes','No','NO');
                                        switch qqq
                                            case 'Yes'
                                                set(handles.edit9, 'String',
'Feature is difficult to manufacture.')
                                            case 'No'
                                                set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                                        end
                                end

                            elseif d>=2 && d<10
```

```
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:4?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                end
                        end

                    elseif d>=10 && d<=20
                        qqq=questdlg('Is maximum ratio of hole diameter
to hole length 1:3?', ...
                            'Question', ...
                            'Yes','No','NO');
                        switch qqq
                            case 'Yes'
                                qqq=questdlg('Is it a lateral hole?',
...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                                end

                            case 'No'
                                qqq=questdlg('Is it a blind hole?', ...
                                    'Question', ...
                                    'Yes','No','NO');
                                switch qqq
                                    case 'Yes'
                                        set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                    case 'No'
                                        set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
```

```
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                                    end
                                end

                            elseif d>20
                                msgbox('Refer to pocket feature, or enter a
value for hole diameter between 1 and 20 mm!')
                            end
                        end

                else
                    set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut length. Therefore length
out of range is difficult to manufacture.')
                end

            else
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is SLM. Otherwise when using CNC machining, standard cutting
tools are used to reach the desired undercut depth. Therefore depth out
of range is difficult to manufacture.')
            end

        elseif c>20
            msgbox('Enter a value for hole diameter between 10 and 20 mm!')
        end

        %tapping
    elseif (get(handles.radiobutton30,'Value') ~= 0)
        contents=get(handles.popupmenu9,'String')
        popupmenu9value=contents{get(handles.popupmenu9,'Value')}
        switch popupmenu9value
            case 'Select Tapping'
                msgbox('Select tapping!')
            case 'M2'
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is CNC machining. Otherwise, if SLM is used further machining
will be needed to achieve the desired tapping.')
            case 'M4'
                set(handles.edit9, 'String', 'Recommended manufacturing
technique is CNC machining. Otherwise, if SLM is used further machining
will be needed to achieve the desired tapping.')
            otherwise
                if d<0.2
                    msgbox('Input a valid hole diameter!')
                elseif d>=0.2 && d<2
                    qqq=questdlg('Is maximum ratio of hole diameter to hole
length 2:1?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String', 'Recommended to use
EDM drill due to fine feature identification.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String', 'Feature is
difficult to manufacture.')
```

```
                            case 'No'
                                set(handles.edit9, 'String',
'Recommended to use EDM drill due to fine feature identification.')
                            end
                    end

                elseif d>=2 && d<10
                    qqq=questdlg('Is maximum ratio of hole diameter to hole
length 1:4?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String', 'Recommended to use
SLM or CNC machining, because no limitation is identified for
manufacturing this feature.')
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                            end
                    end

                elseif d>=10 && d<=20
                    qqq=questdlg('Is maximum ratio of hole diameter to hole
length 1:3?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            qqq=questdlg('Is it a lateral hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is CNC machining. Otherwise, if SLM
is used a support structure will have to be added to hold the lateral
hole from collapsing. Hence, the user must acknowledge the necessity to
remove the support structures which might not be easily accessible or
require further machining.')
                                case 'No'
                                    set(handles.edit9, 'String',
'Recommended to use SLM or CNC machining, because no limitation is
identified for manufacturing this feature.')
                            end
                        case 'No'
                            qqq=questdlg('Is it a blind hole?', ...
                                'Question', ...
                                'Yes','No','NO');
                            switch qqq
                                case 'Yes'
                                    set(handles.edit9, 'String',
'Recommended manufacturing technique is SLM or die sink EDM. Otherwise,
```

```
it is difficult for a cutting tool to reach higher depth that is not
within the standard ratio of hole diameter to depth.')
                            case 'No'
                                set(handles.edit9, 'String',
'Recommended to use SLM or Wire EDM, Otherwise,  it is difficult for a
cutting tool to reach higher depth that is not within the standard ratio
of hole diameter to depth.')
                            end
                end

            elseif d>20
                msgbox('Refer to pocket feature, or enter a value for
hole diameter between 1 and 20 mm!')
            end
    End

    % %         ratio
elseif (get(handles.radiobutton30,'Value') == 0)
    if d<0.2
        msgbox('Input a valid hole diameter!')
    elseif d>=0.2 && d<2
        qqq=questdlg('Is maximum ratio of hole diameter to hole length
2:1?', ...
            'Question', ...
            'Yes','No','NO');
        switch qqq
            case 'Yes'
                set(handles.edit9, 'String', 'Recommended to use EDM
drill due to fine feature identification.')
            case 'No'
                qqq=questdlg('Is it a blind hole?', ...
                    'Question', ...
                    'Yes','No','NO');
                switch qqq
                    case 'Yes'
                        set(handles.edit9, 'String', 'Feature is
difficult to manufacture.')
                    case 'No'
                        set(handles.edit9, 'String', 'Recommended to use
EDM drill due to fine feature identification.')
                end
        end

    elseif d>=2 && d<10
        qqq=questdlg('Is maximum ratio of hole diameter to hole length
1:4?', ...
            'Question', ...
            'Yes','No','NO');
        switch qqq
            case 'Yes'
                set(handles.edit9, 'String', 'Recommended to use SLM or
CNC machining, because no limitation is identified for manufacturing
this feature.')
            case 'No'
                qqq=questdlg('Is it a blind hole?', ...
                    'Question', ...
                    'Yes','No','NO');
                switch qqq
                    case 'Yes'
                        set(handles.edit9, 'String', 'Recommended
manufacturing technique is SLM or die sink EDM. Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                    case 'No'
```

```
                        set(handles.edit9, 'String', 'Recommended to use
SLM or Wire EDM, Otherwise,  it is difficult for a cutting tool to reach
higher depth that is not within the standard ratio of hole diameter to
depth.')
                end
            end

        elseif d>=10 && d<=20
            qqq=questdlg('Is maximum ratio of hole diameter to hole length
1:3?', ...
                'Question', ...
                'Yes','No','NO');
            switch qqq
                case 'Yes'
                    qqq=questdlg('Is it a lateral hole?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is CNC machining. Otherwise, if SLM is used a
support structure will have to be added to hold the lateral hole from
collapsing. Hence, the user must acknowledge the necessity to remove the
support structures which might not be easily accessible or require
further machining.')
                        case 'No'
                            set(handles.edit9, 'String', 'Recommended to use
SLM or CNC machining, because no limitation is identified for
manufacturing this feature.')
                    end

                case 'No'
                    qqq=questdlg('Is it a blind hole?', ...
                        'Question', ...
                        'Yes','No','NO');
                    switch qqq
                        case 'Yes'
                            set(handles.edit9, 'String', 'Recommended
manufacturing technique is SLM or die sink EDM. Otherwise,  it is
difficult for a cutting tool to reach higher depth that is not within
the standard ratio of hole diameter to depth.')
                        case 'No'
                            set(handles.edit9, 'String', 'Recommended to use
SLM or Wire EDM, Otherwise,  it is difficult for a cutting tool to reach
higher depth that is not within the standard ratio of hole diameter to
depth.')
                    end
            end

        elseif d>20
            msgbox('Refer to pocket feature, or enter a value for hole
diameter between 1 and 20 mm!')
        end
end




global x %slot
global y %pocket
global z %boxx
global yy %pattern
```

```
global rech1
global number
rech1=get(handles.edit9,'string');
if number==1
    close(window2)
    if x==1
        close (window2)
        slot_num
    elseif y==1
        close (window2)
        pocket_num
    elseif z==1
        close (window2)
        boss_num
    elseif yy==1
        close (window2)
        pattern_num
    else
        Reccomendation
    end

elseif number>1 && number<=5
    close(window2)
    h_d_1
elseif x==1
    close (window2)
    slot_num
elseif y==1
    close (window2)
    pocket_num
elseif z==1
    close (window2)
    boss_num
elseif yy==1
    close (window2)
    pattern_num
end
```

(iv) Recommendation page

```
function pushbutton1_Callback(hObject, eventdata, handles)
global rech1
global rech2
global rech3
global rech4
global rech5
set(handles.uipanel1,'visible','on');
set(handles.text62,'string',rech1);
set(handles.text8,'string',rech2);
set(handles.text63,'string',rech3);
set(handles.text10,'string',rech4);
set(handles.text64,'string',rech5);
set(handles.uipanel10,'visible','off');
set(handles.uipanel11,'visible','off');
set(handles.uipanel22,'visible','off');
set(handles.uipanel23,'visible','off');

function pushbutton2_Callback(hObject, eventdata, handles)
global recs1
global recs2
global recs3
global recs4
```

```
global recs5
set(handles.uipanel1,'visible','on');
set(handles.uipanel10,'visible','on');
set(handles.text71,'string',recs1);
set(handles.text69,'string',recs2);
set(handles.text72,'string',recs3);
set(handles.text74,'string',recs4);
set(handles.text73,'string',recs5);
set(handles.uipanel11,'visible','off');
set(handles.uipanel22,'visible','off');
set(handles.uipanel23,'visible','off');

function pushbutton3_Callback(hObject, eventdata, handles)
global recp1
global recp2
global recp3
global recp4
global recp5
set(handles.uipanel1,'visible','on');
set(handles.uipanel10,'visible','on');
set(handles.uipanel11,'visible','on');
set(handles.text78,'string',recp1);
set(handles.text80,'string',recp2);
set(handles.text85,'string',recp3);
set(handles.text76,'string',recp4);
set(handles.text77,'string',recp5);
set(handles.uipanel22,'visible','off');
set(handles.uipanel23,'visible','off');

function pushbutton4_Callback(hObject, eventdata, handles)
global recb1
global recb2
global recb3
global recb4
global recb5
set(handles.uipanel1,'visible','on');
set(handles.uipanel10,'visible','on');
set(handles.uipanel11,'visible','on');

set(handles.uipanel22,'visible','on');
set(handles.text116,'string',recb1);
set(handles.text115,'string',recb2);
set(handles.text113,'string',recb3);
set(handles.text118,'string',recb4);
set(handles.text117,'string',recb5);
set(handles.uipanel23,'visible','off');

function pushbutton5_Callback(hObject, eventdata, handles)
global recpn1
global recpn2
global recpn3
global recpn4
global recpn5
set(handles.uipanel1,'visible','on');
set(handles.uipanel11,'visible','on');
set(handles.uipanel10,'visible','on');
set(handles.uipanel22,'visible','on');
set(handles.uipanel23,'visible','on');
set(handles.text126,'string',recpn1);
set(handles.text125,'string',recpn2);
set(handles.text123,'string',recpn3);
set(handles.text128,'string',recpn4);
set(handles.text127,'string',recpn5);
```

```
function pushbutton6_Callback(hObject, eventdata, handles)
```

Appendix G.

Feature-Based Manufacturability Assessment System (FBMAS) flowchart.