The Effect of Powder Recycling in Direct Metal Laser Deposition on Powder and Manufactured Part Characteristics

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ABSTRACT

A potential way of improving the material efficiency and cost effectiveness of the Direct Metal Laser Deposition (DMLD) process is to take powder that is not utilised in each deposition attempt and re-use it in subsequent attempts (powder recycling). Currently, this is not widely implemented for fear of a detrimental effect on part quality.

This study examines how powder recycling, using simple normalisation techniques, affects the powder and the quality of the deposited part. Work was conducted on commercially available DMLD equipment with gas-atomised Waspaloy powder. Powder characteristics such as morphology, size distribution, and purity, and deposited part characteristics such as microstructure and mechanical properties, were quantified for 10 deposition – normalisation - re-use cycles.

The use of normalised powder resulted in successful deposition over all 10 re-cycle stages and did not appear to compromise part integrity. Properties and microstructure, while not completely uniform throughout the 10 cycles, did not vary by large amounts. The powder showed greater variation in size distribution and composition with increasing re-cycle stages. Variations throughout the process, their causes, and the potential benefits of the normalisation procedure used are discussed.

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1.0 INTRODUCTION

Direct Metal Laser Deposition (DMLD) refers to an additive manufacturing process that is achieved by directing a laser beam onto a substrate surface to create a molten pool and delivering powder into it by means of an inert carrier gas [1] to form a deposit. The process parameters of greatest importance are laser power density [2,3], tool feedrate [4], powder delivery rates [4], and process gas flow rates.

Controlling the movement of the weld pool, through either a CNC gantry or robotic system, can facilitate the formation of complex geometries that are metallurgically bonded to the substrate. The deposition of a wide range of ferrous and non-ferrous metallic alloys has been reported [1-3]. Current industrial applications include the repair of turbine engine blade tips using Inconel 625 [5] and the application of wear resistant coatings for Down Hole equipment in the Oil and Gas drilling industry.

DMLD machines, capable of being operated in an industrial environment, are available commercially from several machine manufacturers, such as Trumpf GmbH, Huffman Corp, Optomec Corp, and Reis GmbH. Laser sources used include CO_2, Nd:YAG, Diode and Fibre [6].

There has been steady progress to improve technical aspects and reliability of the DMLD process over the last 10 years, based on increased understanding of thermal and material phenomena [7], the introduction of more advanced control and CAM systems [8], and improved process nozzle design based on understanding of the powder flow [9]. However, acceptance of DMLD for industrial applications is dependent on the optimization of economic as well as technical aspects of the process.

A significant portion of the operating costs of a commercial DMLD machine is for the metal powders used. At current prices, Ni-based super alloy gas atomised powder, of 50 – 100µm diameter, can vary from 25 €/kg for more common compositions up to 250 €/kg when low volumes of non-standard compositions are required. The percentage of the powder leaving the process nozzle that melts to form part of the final part, defined as the powder usage efficiency, can in an industrial system vary from 5 to 70%. It is dependent on the process parameters, the design of the powder delivery nozzle, and the geometry of the deposit being formed. Current practice is to dispose of any unused powder, a practice which is economically and environmentally expensive. This practice is maintained because of the belief that re-use of this powder will result in loss of part quality. W.M.Steen, a pioneer of the DMLD process wrote, “it is unwise to recycle the unused powder because it contains oxides and irregular particles” [10].

It has not been shown if simple shrouding and recycling methods such as filtering and drying are in fact sufficient to allow powder to be reused as a DMLD build material multiple times. The objective of this study is to determine whether the characteristics of collected, unassimilated powder change when it is used multiple times for DMLD with simple filtering and drying methods between deposition attempts and to test if DMLD deposits are affected by using recycled powder.

2.0 EXPERIMENTAL

An overview of the experiment procedure is presented in Figure 1.

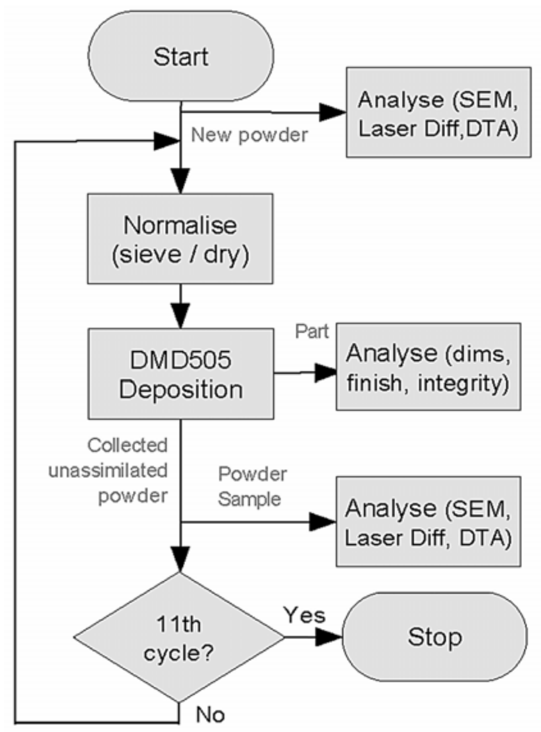


Figure 1: Outline of the steps undertaken during the experiment

Deposition was undertaken by TWI using a Trumpf/POM DMD505 system. The DMD505 comprises a 2 kW CO_2 laser and has a single cantilever 5-axis Cartesian gantry system with a processing envelope of 2 m (x), 1.1 m (y) and 0.75 m (z). It has a CNC control system, a powder feed system, a powder delivery nozzle, a patented feedback and control system. Figure 2 shows the system installed at TWI's Technology Centre in Yorkshire.

Figure 2: The Trumpf DMD505 Laser LDMD system installed at TWI's Technology Centre in Sheffield

The system uses an integrated process control system to ensure a good quality deposit. The two components of this system are active height control and a facility to link laser power and tool feedrate. For this project, only the latter component, known as 'Tip Control', was employed. This permitted the reduction of laser power during the speed ramp-up and ramp-down associated with table movement during starting and stopping.

For this experiment, a POM designed process head with a powder spot diameter at the work piece of 4 mm was used. Work was conducted in an Argon atmosphere containing less than 10ppm Oxygen. Gas-atomised Waspaloy® powder, with a nominal size distribution of 50 – 125 micrometers, supplied by Sandvik Osprey Ltd was used as the deposition material. The substrate material was INCONEL 718. The process parameters employed were developed by TWI through a separate project with Rolls Royce. The diameter of the laser beam at the workpiece was approximately 0.5mm.

Two thin sample walls (vertically aligned tracks), consisting of 50 deposition tracks of Waspaloy, 40mm long, were deposited onto the INCO 718 plate at each recycle stage. After the two sample walls were formed, deposition of solid blocks was undertaken to ensure that enough 'used' powder was processed and available for recycling at each stage,. After each deposition run, any powder in the process chamber that was not melted was collected and a simple normalisation process of mechanically sieving the powder to remove any over (>150 um diameter) or under (<50 um) sized particles and of drying it in an open atmosphere oven at 383 K for 24 hrs was used. Sample walls were made from powder that had been recycled up to 10 times. Sample nomenclature is explained in Table 1.

Table 1: Explanation of sample nomenclature

Description	Name	Description	Name
As received powder	P-1	Wall made from as received powder	W-1
Normalised powder	P0	Wall made from normalized powder	W0
Powder used once	P1	Wall made from powder recycled once	W1
Powder used twice	P2	Wall made from powder recycled twice	W2
Powder used 3 times	P3	Wall made from powder recycled 3 times	W3
Powder used 4 times	P4	Wall made from powder recycled 4 times	W4
Powder used 5 times	P5	Wall made from powder recycled 5 times	W5
Powder used 6 times	P6	Wall made from powder recycled 6 times	W6
Powder used 7 times	P7	Wall made from powder recycled 7 times	W7
Powder used 8 times	P8	Wall made from powder recycled 8 times	W8
Powder used 9 times	P9	Wall made from powder recycled 9 times	W9
Powder used 10 times	P10	Wall made from powder recycled 10 times	W10

Powder and deposit analysis was performed by the University of Manchester. Powder, size distribution was determined using a Malvern Matersizer Microplus laser diffractometer and a Hall Flow meter was used to characterise flow. The deposits were subjected to Vickers microhardness (measured using a 100 g load), optical microscopy, and surface profile analysis using a laser triangulation scanning system. X-ray diffraction and a FEI Sirion FEGSEM (Field Emission Gun Scanning Electron Microscope), coupled with a Roentec Quantax Energy Dispersive X-Ray Spectroscopy (EDS) system, was used to examine the crystallography, metallurgy and elemental consistency of both the powder and the deposits.

3.0 RESULTS AND DISCUSSION

3.1 Powder

Particle size analysis showed that the distribution remained Gaussian as the number of powder recycling iterations increased. Figure 3 shows that a marginal decrease in mean particle size may have occurred but experimental variance makes it difficult to be certain.

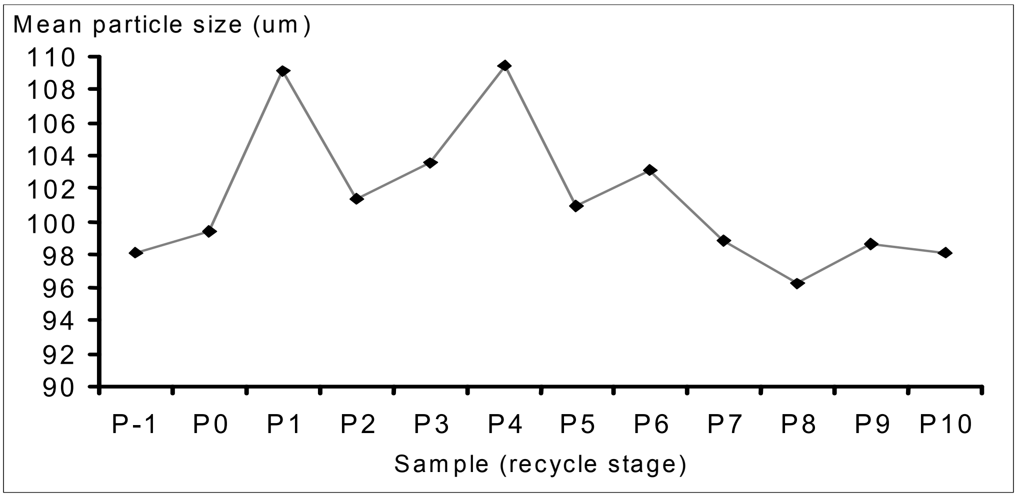


Figure 3: Effect of powder recycling on powder size when processed by LDMD

Figure 4 illustrates the likelihood of a marginal decrease in flow times as powder goes through increasing deposition and normalisation cycles. This indicated that some change occurred to either the particles' shape and surface finish or size distribution, however SEM results indicated that no significant change did in fact occur to the surface morphology. SEM micrographs of powder after the final processing iteration illustrate the spherical shape of the gas-atomised powder (see Figure 5). Porosity was present within the powder but the volume fraction of this did not increase with the number of recycling stages. This porosity was attributed to the atomisation process.

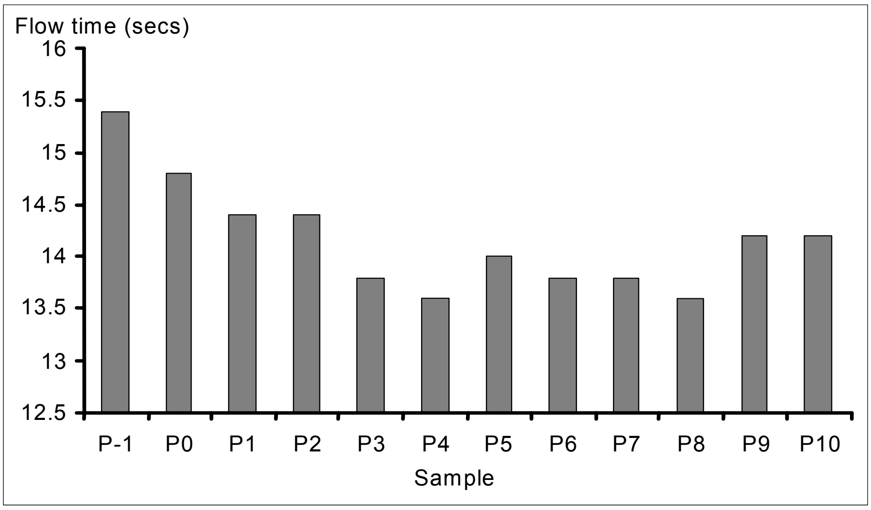
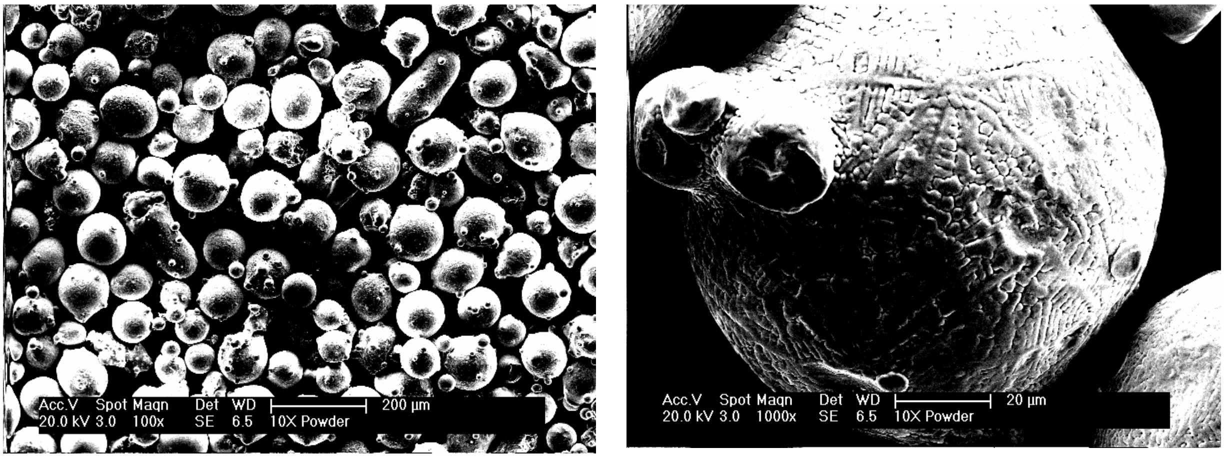


Figure 4: Effect of recycling powder processed by LDMD on powder flow rates; measured using a Hall Flow Meter



a) 100x magnification b) 1000x magnification

Figure 5: SEM images of gas atomised Waspaloy powder recycled 10 times (sample P10) through the LDMD process

XRD analysis revealed an austenitic, face centred cubic structure. XRD results also indicated that no change in the crystalline composition of the surface of powder particles with repeated recycling and no build-up of contaminants to levels detectable by the equipment occurred. This implies that the inert gas shield from both the chamber and the nozzle gases prevented oxidation or carburisation.

3.2 Deposit

Wall thickness remained constant at 0.6 mm throughout the experiment. However, both the sidewall surface roughness (Ra, measured across the tracks) and deposit centre-line Vickers microhardness did vary. The former increased from 8.5 µm for deposit W-1 to 19 µm for deposit W10. The latter decreased from 370 kg/mm^2 for deposit W0 to 330 kg/mm^2 for W2, after which it remained approximately constant through to deposit W10.

Examination by optical microscopy revealed that the sample microstructure was consistent throughout the experiment with no cracking at the deposit/substrate interface or between deposit passes. Figure 6 presents a cross section from deposit W8. The intralayer porosity observed within the deposits can be attributed to either the DMLD process parameters or the gas atomised powders or a combination of the two. Subsequent optimisation has greatly reduced this issue.

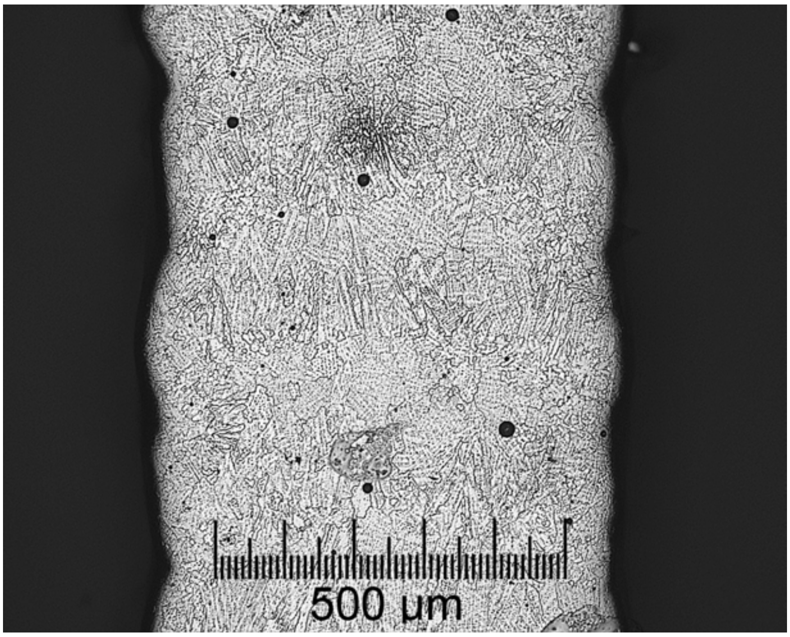
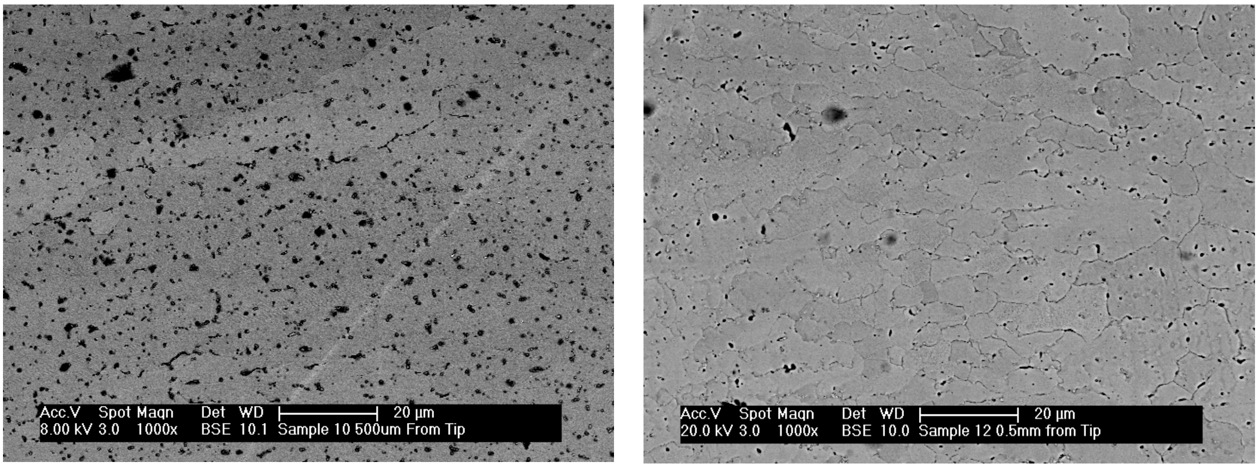


Figure 6: Optical microscopy cross section of DMLD deposit formed using powder recycled 8 times (W8); etched with Kallings Reagant

Back scattered electron (BSE) SEM images from the centre line of the deposits showed that for deposits W0 and W2, relatively coarse but evenly distributed carbides were observed with some concentration at grain boundaries. However, for deposits W4 to W10, the carbides formed are of the same distribution but of smaller size, see Figure 7. EDS confirmed that the elemental composition did not vary significantly throughout the deposit. Oxygen content remained constant at between 1.5 and 2.0 wt% for all the deposits.

The above results indicate that recycling powder to form deposits did affect their characteristics, albeit in an insignificant manner. However, further work is required to confirm this initial finding.



a) Sample W2 b) Sample W4

Figure 7: Back Scattered SEM images of a DMLD deposit formed using powder recycled 2 (sample W2) and 4 (sample 4) times; etched with Kallings Reagant

3.3 Process

In order to understand the process and explain the changes to powder and deposits it is necessary to consider the possible routes that feed powder could take. Powder entering the process work area could either become assimilated into the melt pool, interact with the laser beam or heated substrate but not fuse with the substrate, interact with the laser beam and vaporise, or interact with neither the laser beam nor hot substrate.

The relative weighting of each of these fractions is dependent on nozzle design and process parameters such as process gas flow speeds, process specific energy (beam power / (traverse speed × beam diameter)) and powder mass flow rate. For this experiment, a high proportion of powder interacted with neither the laser beam nor hot substrate, which was reflected in the low powder usage efficiency (calculated to be less than 5%).

This unchanged powder may have hidden changes produced by powder that had been altered during a deposition attempt and then recycled. Using a powder nozzle with increased efficiency would increase the fraction of the powder that interacts with the laser beam and may therefore give more significant changes in powder and deposit properties with stage of recycling. This is the subject of further study.

4.0 CONCLUSIONS

This study examined the effects of reusing Waspaloy powder during the DMLD process. The machine used was a Trumpf/POM DMD 505. The process nozzle used had a powder focus diameter of 4mm at the workpiece. A CO_2 laser having a beam diameter at the work piece of 0.5mm was used.

Tests showed that recycling the powder up to 10 times produced only very minor changes in the surface crystalline structure and composition, morphology and surface texture of the powder. Flowability showed a slight tendency to increase as the powder went through more deposition-recycle cycles and there were small changes in size distribution. Using recycled powder did not introduce a measurable level of contaminant elements into the deposited walls or cause the emergence of new phases. All deposits were of a desired shape having a good metallic bond between the successive deposit layers and at the deposit/substrate interface. Deposit microhardness decreased and surface roughness increased as the powder used underwent further recycling iterations. Powder usage efficiency for the current study was approximately 5%. The effect of recycling on powder and deposit characteristics may become more apparent at higher usage efficiencies. Nevertheless, these initial results give no indication that using recycled powder is not viable or that it leads to part contamination, reduced process efficiency or major changes in microstructure.

5.0 ACKNOWLEDGEMENTS

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MEETING DISCUSSION – PAPER NO: 18

Author: P. Carroll

Discusser: B. Bodger

Question: Is your "recycled" powder 100% recycled or mixed with some virgin material?

Response: At this stage, 100% recycled. Current/future work will examine mixing.

Discusser: D. Dicus

Question: 1. Assuming that the powder size distribution changes with each use, how would you propose to introduce the powder that has been through previous processes into the supply stream for subsequent builds? 2. Have you estimated the economic impact of recycling the use of powder on the laser deposition process?

Response: 1. The process, depending on application, may be durable enough to deal with size changes. If "normalization" is required, additional "virgin" powder of correct size can be added. This results in production with powder of various re-use iterations difficult for Q.A. 2. Not yet, This is being dealt with on particular applications, case-by-case. As suggested by discusser, true benefit may be less than envisaged!

Discusser: L. Pambaguian

Question: Do you foresee any problem linked to the long term storage of your powders?

Response: Yes! Current practice in R & D is to store, sieve, etc. correctly. In my experience, this is not the case in a production repair job shop. I think this approach is changing. As repairs become more advanced/complex materials, this will become an issue.

Discusser: X. Wu

Question: Do you have evidence that recycled powder cannot be used for non-critical component?

Response: No. Current work is an initial study only. This was made clear in talk/presentation. Further mechanical testing with various process set-ups and powders will examine this. Furthermore, mechanical testing may not be required if engine, abrade or burner rig tests are going to be made.