Effect of Thermal and Mechanical Deformation of Metamaterial FDM Components

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Abstract - **At Lancaster University, research is currently investigating the use of rapid manufacturing (RM) to realise metamaterials, although key to the success of this project is the development of an understanding of how coated RM parts deform under thermal and mechanical stress. The research in this paper presents a comparison of the thermal and mechanical deformation behaviour of RM coated metamaterials components from a numerical context. The research uses the design of a simple metamaterial unit cell as a test model for both the experimental and finite element method (FEM). The investigation of deformation behaviour of sample Fused Deposition Modelling (FDM) parts manufactured in different orientations and simulated using commercial FEM code means that the FEM analysis can be utilized for design verification of FDM parts. This research contributes to further research into the development of RM metamaterials, specifically design analysis and verification tools for RM materials.**

Keywords – **Fused Deposition Modeling, Rapid Manufacturing, Metamaterials, Finite Element Method**

I. INTRODUCTION

Metamaterials are artificial macroscopic composites with a periodic cellular structure which produce two or more responses not available in nature in response to a specific excitation. Of particular interest are a class of metamaterials which exhibit novel behaviour in the presence of an ElectroMagnetic (EM) wave, termed "Double NeGative materials" (DNG). DNG materials control the phase of the electromagnetic (EM) field to give an effective negative index of refraction, achieved by the DNG presenting a relatively high opposing EM field. Realisation of DNG materials has been achieved using a variety of designs all of which exhibit a resonant behaviour to achieve DNG, via the use of metallic and dielectric components.

In this paper we focus on a class of metamaterials which exhibit a novel response to an EM wave which does not appear in nature. The response of all materials to an EM wave is described through the constitutive relationships:

$$\epsilon_0 \hat{E} + P = \epsilon \hat{E}$$
$$\mu_0 \hat{H} + M = \mu \hat{H} \tag{1}$$

where E and H are the averaged electric and magnetic field, P is the averaged polarization (electric dipole moment density), and M is the averaged magnetization (magnetic dipole moment density). ε and μ are the permittivity and permeability of the material, and define how the material responds to an applied EM field. In most natural materials ε and μ are both positive, but in metamaterials ε and μ are both negative, termed DNG materials. Veselago [1] first proposed that a DNG material can control the phase of the EM field to give an effective negative index of refraction, achieved by the DNG presenting a relatively high opposing EM field.

Realization of DNG materials has been achieved using many techniques, such as: a lattice of split-ring resonators (SRR) and thin wires [2], loaded transmission lines [3], and microspheres [4] to name a few. These metamaterials have been used to construct a range of novel microwave devices such as antennas [5], phase-shifters [6], couplers [7], broadband/compact power-dividers and other devices such as beam steerers, modulators, band-pass filters and lenses. The construct of these materials uses the basic unit cell to form a complex lattice structure, conventional techniques of using SRR and wires to create a unit cell results in an anisotropic material, which proves difficult to manufacture and labour intensive to construct. Rapid Manufacturing (RM) offers the ability to produce the intricate substructure of the unit cell in a repeatable form to construct the lattice structure of the metamaterial. The RM components are then part metalized utilising conventional electroforming techniques to form the completed metamaterial. An added advantage of this technique is that it enables us to realise volumetric isotropic metamaterials, as shown in Figure 1 below.

Fig. 1. Metamaterial consisting of copper coated ABS spheres

The structures shown in Figure 1 consist of a dielectric (acrylonitrile butadiene styrene (ABS)) RM sphere (produced on a Stratasys Fused Deposition Modeller (FDM)), with a partial metallic coating surrounding the outside. The size of the sphere is designed to act as a resonant structure supporting a standing EM wave inside. This resonance acts, just like the SRR, to support an opposing field to the applied field. The interaction of the EM field with the unit cell structure causes distributed heating throughout the whole structure, which could cause deformation to the unit cell. This deformation, if it changes the shape of the resonant structure, could alter the performance of the metamaterial and critically alter the frequency of the resonant mode. If we are to use RM to produce metamaterial devices, we first need to understand the mechanical and thermal deformation that will occur during operation. In this paper we investigate the deformation that would occur during the operation of a metalized RM (ABS from a FDM) unit cell of metamaterial.

II. METHODOLOGY

It is possible to solve very large scale and complicated engineering problems by using numerical methods integrated software and computers developed to deal with today's engineering applications. One of these numerical methods is FEM, which is typically used to solve complicated engineering problems in many disciplines of engineering. The method was developed more by engineers using physical insight, than mathematicians using abstract methods. It was first applied to problems of stress analysis and has since been applied to other problems [8].

A. Finite Element Methods: Electromagnetic analysis

The thermal and mechanical forces the metamaterial experiences arise due to the interaction between the macroscopic structure of the unit cell and the applied EM wave. To enable the thermal and stress analysis we must first determine the force the EM wave applies to the whole structure. The energy released into the structure by the EM wave is determined by calculating the time averaged loss density (ρ_v) in the structure:

$$\boldsymbol{\rho}_{\mathbf{v}}(r) = \frac{1}{2}\mathrm{Re}\left(\mathbf{E}(r)\circ\overline{\mathbf{J}}(r) + \left(-\nabla\times\mathbf{E}(r)\right)\circ\overline{\mathbf{H}}(r)\right) \tag{2}$$

where **E** and **H** are the averaged electric field, and magnetic field, r is the spatial coordinate of a given point in the structure, **J** is the current density. The loss density (ρ_v) gives the amount of energy converted to heat at any point in the structure. The loss density is then used as a discrete volume heat source for the Thermal and Stress Analysis.

The loss density is determined using the commercial software package HFSS. HFSS is a 3D full-wave electromagnetic field solver, utilizing the FEM, with adaptive meshing, approach to solve the EM wave-structure interaction. To enable the thermal and stress analysis it is only necessary to simulate a single unit cell of the metamaterial which in our case is the partial copper coated dielectric sphere, as shown in Figure 1. For the simulation the unit cell Figure 2 was discretised into 30K elements, the steady-state loss density was calculated at each element, with a 10W EM plane wave at 10 GHz incident upon the structure. The Loss density simulation results are shown in Figure 3. The linking package e-physics was used to export the 30k data points from HFSS to the thermal and stress analysis software.

B. Finite Element Methods: Thermal and Stress Analysis

In this study, FEM has been applied to investigate the thermal and stress distributions on the copper coated ABS sphere(s) under the high frequency full-wave effect. To achieve this, SolidWorks 3D solid modelling design software, HFFS and ePhysics commercial finite element codes were utilised. The process of the analyses is presented in Figure 2.

In the solid model, the ABS sphere had a diameter of 15 mm and was coated with copper, with a thickness of 0.5 mm and had six equidistant holes each with diameter of 7.5 mm placed around the sphere. After the 3D solid modelling operation in the design software, the

3D model was transferred into the HFSS interface and subsequent high frequency EM wave analysis was conducted using the HFSS software. HFSS is an interactive software package for calculating the EM behaviour of a structure [9]. The analysis was carried out under the assumption of 10W and 10GHz frequency of the EM wave within a vacuum environment – this is representative of the regime of operation of many conventional vacuum technologies. The volume loss density distributions of the model were obtained. Maximum value of 4.2764 e+5 [W m^{-3}] was screened in the simulation and the simulation result for volume loss density is shown in Figure 3.

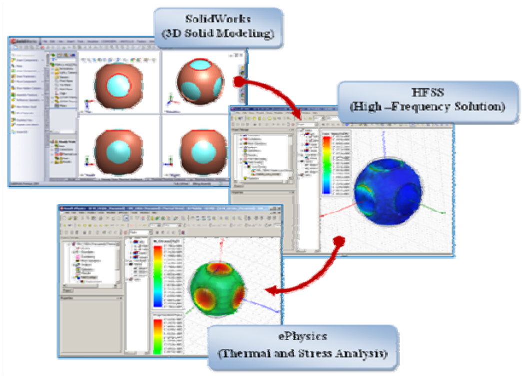


Fig. 2. Process of creating CAD, applying EM field and subsequent thermal and stress analyses

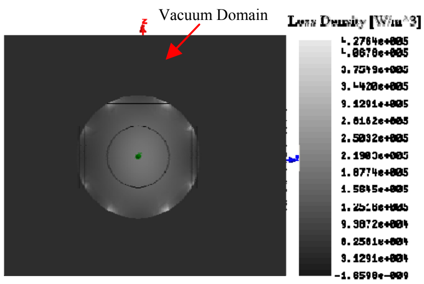


Fig. 3. HFSS analysis result: the volume loss density (Centre cross section plot of the model)

Within the total analysis process, the calculated behaviour results was subsequently utilised in the ePhysics software by using direct links without any data losses for thermal and stress analysis. The software is designed to work in a standalone mode or coupled with HFSS high-frequency solution sequences. The software's generalised, finite element based field solvers enable the user to simulate thermal and structural fields in virtually any type of device. It is expected that the user draws the structure and specifies all relevant material characteristics, boundary conditions and sources. ePhysics then generates the necessary field solutions and computes the requested quantities of interest [10].

Within the ePhysics software, firstly the static thermal analysis was utilised. The heat source was linked from HFSS generated result files. An ambient temperature of 20 °C was assumed in the analysis. To simulate a vacuum environment, radiation heat transfer parameters for copper and ABS were used. Radiation parameters of the copper and ABS emissivity were assumed as 0.07 and 0.8 respectively. 3D, linear and isotropic material model assumptions were utilised for both the thermal and stress analyses. Some of the properties of the materials are given in Table 1.

TABLE I
MECHANICAL PROPERTIES OF THE MATERIALS

Properties		Copper	ABS
Young Modulus	[GPa]	120	2
Poisson rate	[-]	0.38	0.394
Emissivity	[-]	0.07	0.8
Thermal Expansion Ceff.	[-]	1.77e-5	5.2e-5
Thermal conductivity	[W.m^{-1}.C^{-1}]	400	0.2256
Specific Heat	[J.Kg^{-1}. C^{-1}]	385	1386
Mass Density	[Kg.m^{-3}]	8933	1020
Relative Permeability	[-]	0.99991	1
Relative Permittivity	[-]	1	2.8

The HFSS mesh functions were used for the mesh construction of the model and the all ePhysics analyses were generated with the same mesh structure by linking each other. Tetrahedral elements were used in the mesh construction of the model and total elements of 27277 were obtained. After solving, the process, a maximum temperature of 7.6404e+1 °C was obtained. The temperature centre cross section and 3D result plots of the ePhysics thermal analysis is presented in Figure 4.

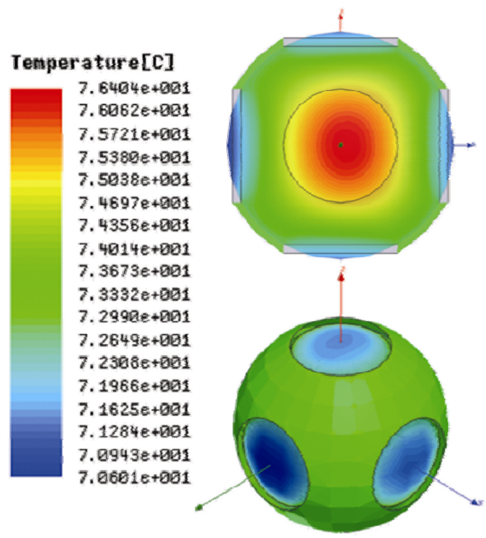


Fig. 4. Static Thermal Analysis: Temperature distributions (Centre cross section and 3D plots)

To investigate the stress distribution and deformation behaviour of the model under the calculated temperature effect, thermal stress analysis was utilised within the ePhysics software. Thermal analysis results were the basis for stress analysis. The software uses a direct link to get thermal results for stress analysis. According to the stress analysis results, a maximum Von Mises stress of 2.2939e+8 Pa was obtained. In addition to this, the deformation results presented a maximum displacement of 2.6547e-5 m. The stress and deformation plots are given in Figure 5 and Figure 6 respectively.

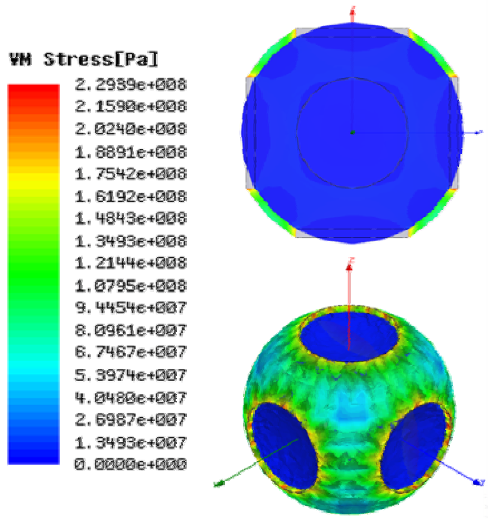


Fig. 5. Thermal Stress Analysis: Stress distributions (Centre cross section and 3D plots)

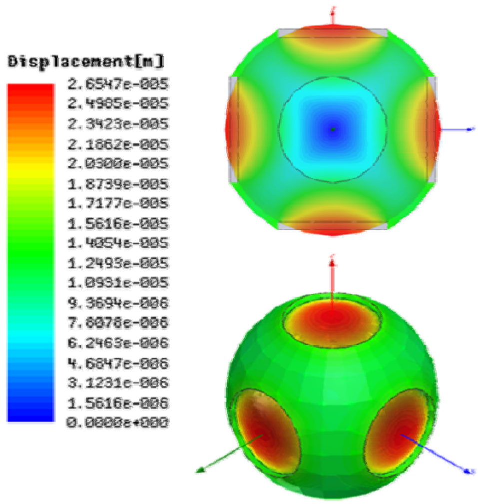
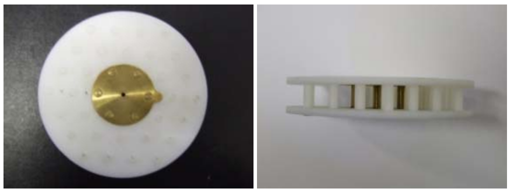


Fig. 6. Thermal Stress Analysis: Deformation distributions (Centre cross section and 3D plots)

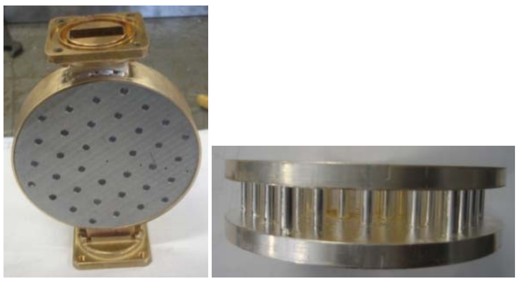
C. Using RM as an Enabling Tool

RM applications of additive manufacturing technologies lend themselves extremely well to the generation of very complex 3D geometries, and therefore are entirely suited to the types of structures required in EM and microwave applications [11], which are typically low volume (between nine and eighteen individual components), can produce these components in reduced timescales and are typically more cost effective than conventional manufacturing routes (e.g. see Figure 7 for RM and Figure 8 for conventionally manufactured photonic band gap (PBG) structures). However, the surface irregularities (poor surface finish on non-post-processed components due to inherent stair-stepping) can be problematic to EM applications where smooth surfaces are a requirement. These issues have been addressed to some extent by optimizing the orientation deposition of the material through development of deposition algorithms, in order to reduce the negative surface qualities [12; 13], however, these surface irregularities are never fully eradicated and it is inevitable that a degree of surface roughness will remain.



(a) (b)

Fig. 7. RM produced PBG structure: (a) plan view (b) end elevation



(a) (b)

Fig. 8. Conventionally manufactured and assembled PBG structure: (a) plan view (b) end elevation

As part of this larger research agenda, it was therefore a requirement that some physical or chemical post-processing be undertaken to smooth the surface of these RM components in order that the copper metallization process be successfully achieved [11]. Optimization of the chemical smoothing process was enabled through a series of experiments where small ABS slabs, built in three differing orientations on the FDM equipment, were introduced to Iso Propyl Alcohol (IPA) and Acetone baths for a varying sequence of times. The IPA was observed to have no significant effect on the surface quality of the ABS components (up to dipping timescales of 30 mins), whereas the Acetone reacted favourably giving a smooth surface with minimal material degradation at optimized dipping times of 2 mins [14].

III. RESULTS

The results of the HFSS simulation of the Loss Density shown in Figure 3, show that the greatest loss of energy from the EM wave occurs at the iris boundaries between the copper outer coating and the ABS substructure with a peak value of 427 Kw m^{-3}, whereas the Loss Density on-axis going only through the ABS part of the cell is coolest at the edge of the structure and rising towards the centre of the cell. The ePhysics simulation for the temperature distribution calculated from the Loss Density, shown in Figure 4, demonstrates that the copper coating has a uniform temperature distribution. The RM ABS component exhibits an almost Gaussian temperature distribution with the peak in the centre of the ABS.

The stress distribution, shown in Figure 5, demonstrates that the maximum stress occurs in a localized region around the iris boundary between the copper and the ABS substructure, with a peak value of 229 MPa, which is below the elastic limit of ABS which is 250 MPa. The resulting deformation of the ABS is approximately 26 μm, which occurs in the centre of the iris.

IV. DISCUSSION AND FURTHER WORK

The physical EM trials using these RM produced spheres and other components are ongoing and are the subject of further research, alongside further research on the chemical surface smoothing of RM generated structures. Initial indications show that the utilization of RM technology is beneficial and will have a significant impact in reducing the time taken to conduct physical trials with differing geometries, thereby allowing for the optimization of the entire process.

V. CONCLUSION

The results of the Thermal Loss simulations give expected results the increase in loss at the iris is expect, as the sharp boundary between the two media results in a peak in the electric field, which results in higher losses occurring in that region. In terms of the temperature distribution the copper iris although having a higher loss tangent has a much higher thermal conductivity than the ABS and is able to conduct the heat away efficiently, yield a low uniform temperature. The ABS at the center of the structure has a much lower thermal conductivity and is surrounded by ABS which is also being heated resulting in a peak temperature at the centre of the structure, uniformly distributed over the ABS substructure. The peak temperature of 76 C is well below the minimum soft point of ABS which is 88 C.

The maximum deformation of 26 μm of the ABS that results from the heating may appear to be negligible, but in fact could dominate the behavior of the structure. The metamaterial properties are determined by the resonant frequency of the structure which is determined by the precise diameter of the ABS sphere. The authors of [15] considered the effect of disorder on a 2D form of the structure considered here, finding that a variation 40 μm at 9 GHz caused a detuning of the structure of 40 MHz, which in our case would be enough to stop the structure behaving like a metamaterial. Although the structure considered here has a maximum deformation of 26 μm, the frequency of operation is higher at 10 GHz, this higher frequency reduces the size of any variation required to cause detuning compared to the results of [15]. To fully understand the effect this would have, more research is required, although one could envisage the case where the heating causes a small deformation that detunes the structure. The applied EM wave will then not interact with the detuned structure; this may in fact lead to a form of self regulation, which needs to be investigated further.

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