IOP Conference Series: Materials Science and Engineering

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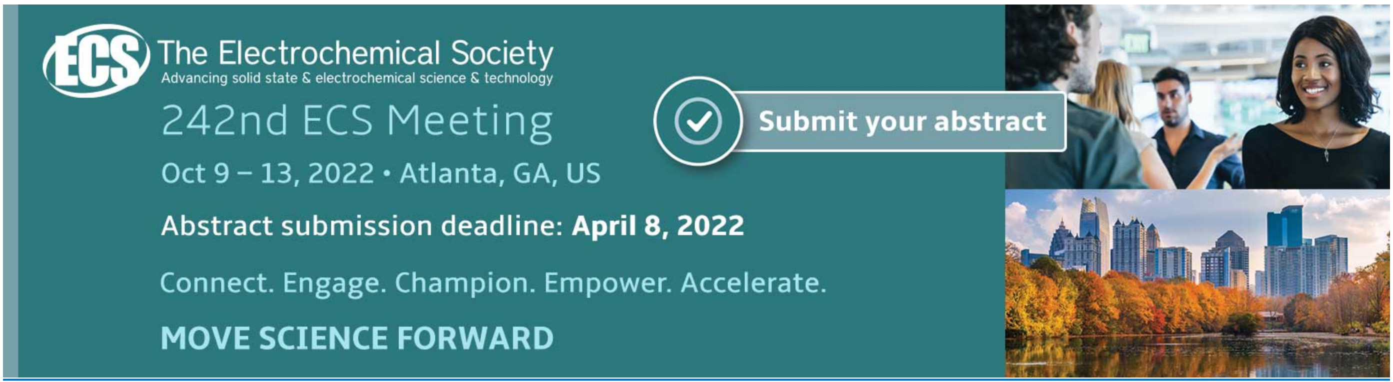
To cite this article: Sadik L. Omairey *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1226** 012003



Design against distortion for aerospace-grade additively manufactured parts - PADICTON

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Abstract. Additive manufacturing (AM) is a computer-controlled 3D printing process with increasing demand in the aerospace sector. This manufacturing process offers the production of lighter components, design flexibility, reduced labour effort and material cost, as well as decreased waste generation compared with subtractive manufacturing. Additionally, AM can provide parts availability at the point of use, significantly improving the supply chain. However, producing advanced high-temperature AM thermoplastic components remains a challenging task as these require a high-temperature build chamber environment that is prone to producing parts with thermal stresses and warpage. PADICTON project aims to develop a tool capable of accurately and rapidly predicting and correcting such distortions, offering improved quality of the produced parts and minimising rejection rates. Creating this tool requires conducting a comprehensive mechanical and thermal characterisation campaign to optimise the print parameters and part geometry. In this study, the concept of the project and the findings of the initial mechanical and optical characterisation tests for two AM processes, namely fused deposition modelling and selective laser sintering, are presented and discussed.

Keywords: Aerospace; Additive manufacturing; Polymers; Thermoplastic; Characterisation.

1. Introduction

Additive manufacturing (AM) has greatly influenced product design, manufacturing, and assembly compared to conventional subtractive manufacturing processes. Hence, AM has rapidly become a strategic technology that will generate revenue throughout the aerospace supply chain [1]. For thermoplastic-based AM, the two main processes are material extrusion-based 3D printing techniques, such as fused deposition modelling (FDM), where a solid thermoplastic material is extruded through a hot nozzle, see Figure 1(a) and selective laser sintering (SLS). SLS uses a laser scan as the power source to sinter powdered material aiming the laser automatically at points in polymer powder bed defined by a 3D model, thus bonding the material together to create a solid structure, see Figure 1(b).

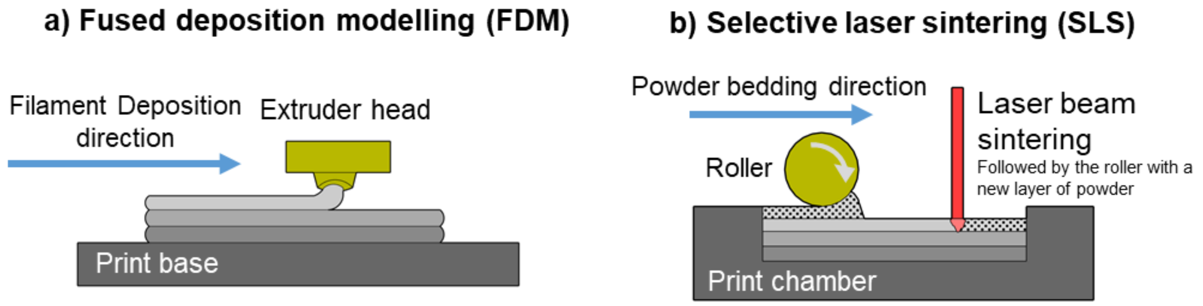

Figure 1. An illustration of FDM and SLS AM processes.

AM is known for its several advantages such as reduced lead times, complex designs manufacturing, easy customisation of part geometry through CAD designs and less material wastage. Nonetheless, there are industrial challenges that need to be resolved, namely lower part quality compared to other manufacturing processes, slow build rates, interactive trial and error process for final part design optimisation, high production costs and post-processing requirements.

PADICTON project [2] answers the scope of JTI-CS2-2018-CFP09-AIR-02-75 on the topic “Design Against Distortion: Part distortion prediction, design for minimised distortion, additive manufactured polymer aerospace parts”. This project is fully in line with the topic request to develop rapid methods to predict material degradation, crystallinity and distortion of additive manufactured PEKK or PEEK parts, with or without fibre reinforcement, as well as to develop methods and tools for topology and shape optimisation accounting for distortion. This will be achieved by developing accurate and functional distortion prediction models for AM of polymeric parts. These models will be integrated into design tools and, more precisely, into Digimat-AM [3]. On the other hand, Apex Generative Design [4] will be used for the process optimisation of the produced part designs. As part of the project, demonstrator CAD models generated and printed using the tool will be compared with conventional CAD designs to assess the benefits of the developed tool in terms of dimensional accuracy, structural quality, and weight reduction. Developing such simulation tools to predict and mitigate part shrinkage, warpage and realise the impact of design decisions on the manufacturing process before the part is being printed will unlock the full value of additive manufacturing.

Still, there are several challenges related to the development of the process simulation which are the complex thermo-mechanical loadings that occur during the layer-by-layer deposition of the material and the successive cooling of the part, as well as the thermal history of the material deposition that generates differential shrinkage between adjacent beads or layers which affects the end tolerances of the part. Overall, modelling the printing process requires taking into account the material state evolution, modelling the stress build-up, and stress relaxation over time. Furthermore, numerical predictions of warpage and shrinkage need to account for the process parameters, the material characteristics and the printing strategy (part orientation, toolpath, supports etc.). In PADICTON, one of the methods used to quantify AM induced distortions in FDM and high temperature SLS is through process simulation. Apart from a rapid approach, fast enough to be integrated into topology and shape optimisation, a "reference" high-fidelity multiscale approach is also used, illustrated in Figure 2:

Step 1: Solve a fully coupled thermomechanical problem of the FDM and the SLS process to identify the warpage and shrinkage behaviour of the printed material accounting for thermal exchanges inside the printer build (conduction, convection and radiation). These simulations use data obtained from the thermal and mechanical characterisation campaign conducted by TWI Ltd [5] and Brunel Composites Centre [6].

Step 2: Load the toolpath issued from the manufacturing processing software and extract information about the deposition sequence.

Step 3: Micromechanics modelling of the heterogeneous material microstructure as a function of the toolpath (e.g., porosity volume fraction and orientation) and predict the resulting warpage and shrinkage induced by the printing process.

Step 4: Based on this high-fidelity modelling, develop a simplified, rapid simulation approach that can be integrated with a generative design approach will be employed to optimise the weight and allow rapid manufacturability.

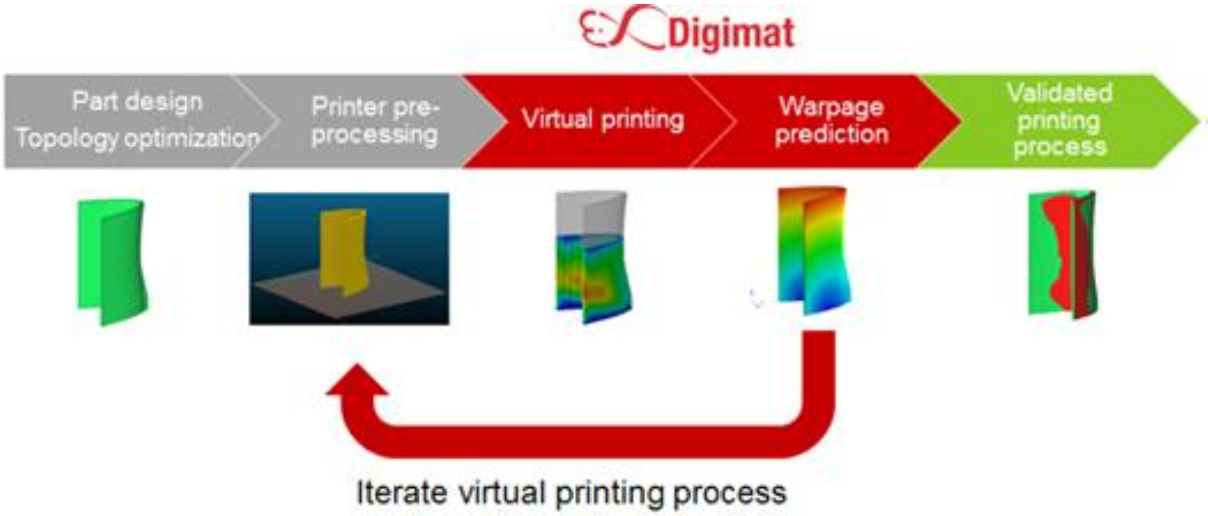

Figure 2. PADICTON simulation approach for optimal printing and distortion minimisation [3].

This prediction model will be based on a high-fidelity reference process simulation. This modelling method will rely on fully coupled thermomechanical analysis, equilibrating the displacements and temperature fields every time a piece of polymer filament is extruded and deposited or sintered. To achieve this simulation and obtain accurate predictions, thermal and mechanical characterisation of each simulated material is required. In this paper, the initial findings from the microscopic examination and mechanical characterisation for FDM and SLS materials (part of the testing campaign of PADICTON project) are presented in the following sections.

2. Processes and materials

The prediction model developed as part of the project will be based on a high-fidelity reference process simulation method for commercial grades of engineering thermoplastics. In this work, two additive manufacturing system processes are chosen, each used to examine two materials; these are the FDM and SLS processes, which are presented herewith.

2.1. Fused Deposition Modelling

FDM is a 3D printing process that uses a continuous filament of thermoplastic material fed through a heated printer extruder head and deposited to form layers. The viscous material solidifies on the build plate, which allows the build-up of a part with dimensional accuracies typically in the order of 100 µm [7]. The most commonly used thermoplastics for this process are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), with typical bulk strengths between 30–100 MPa and elastic moduli in the range of 1.3–3.6 GPa. However, the mechanical properties of 3D printed parts can deviate significantly from the material bulk properties due to the specifics of how a structure is formed on the meso-scale during printing [8]. To maximise the mechanical performance of printed parts, the key elements of the printing process and how these affect the final print quality must be understood. Turner et al. [7] provided an extensive review of FDM process modelling, including the flow and thermal dynamics of the melt, the extrusion process and the bonding (melt fusing) process between successive layers of material. Temperature, viscosity and surface energy of the melt play an important role in how the material flows through the nozzle and, more importantly, how the final interface between the beads is formed.

In PADICTON project, two high-performance thermoplastic FDM materials are investigated, ULTEM™ 1010 and Antero 800NA. However, this paper focuses on ULTEM™ 1010. This material is a high-performance polyetherimide (PEI) thermoplastic that offers excellent strength, thermal stability and the ability to withstand steam autoclaving. Additionally, ULTEM™ 1010 offers high heat and chemical resistance, making it a material of choice for many aerospace and automotive applications. In this study, microscopy and tensile tests are conducted for different print groups of this material and findings are presented in Section 3.

2.2. Selective Laser Sintering

The SLS additive manufacturing technique uses a laser as the power source to sinter powdered material aiming the laser automatically at points in the polymer powder bed defined by a 3D model, fusing the material together to create a solid structure. As a layer is sintered, the powder bed is lowered by one layer thickness, and a new layer of the powder material is applied on top, see Figure 1. The process is repeated until the part is completed. Finally, the completed parts are extracted from the chamber once cooled down, and a percentage of the unsintered powder is recycled for further use.

In PADICTON, a reinforced and non-reinforced SLS material system are being investigated; these are the Fibre Filled HT-23, and PA 2241 FR. The scope of this paper covers microscopy and tensile tests for the Fibre Filled HT-23 material, which is based on a Polyetherketoneketone (PEKK) resin with 23% Carbon Fiber compounded in and ground to a fine powder. The comparative results are presented in Section 3.

3. Results and discussions

As part of this study, optical microscopy and tensile tests were conducted for the two selected 3D printed thermoplastic materials. These are presented and discussed herewith. Given the nature of 3D printing, these tests were conducted for different print orientations to simulate the process accurately. The examined print orientations are illustrated in Figure 3.

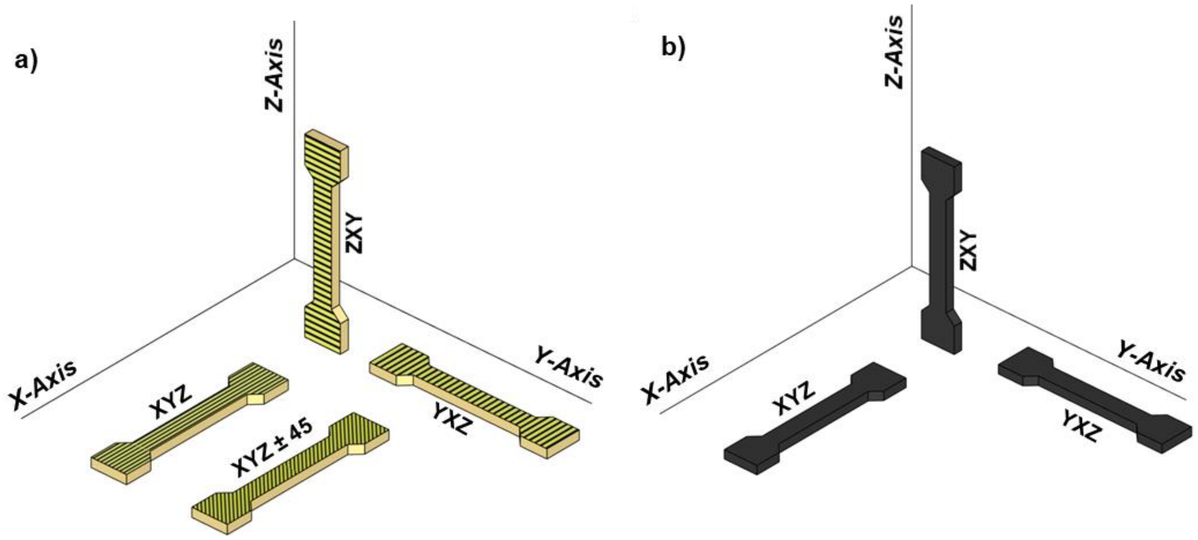

Figure 3. Investigated printed orientations for a) FDM and b) SLS materials.

3.1. Optical microscopy

Optical microscopy is used to examine the microstructure of the 3D prints for different printing orientations and sections. The samples were sectioned and mounted in resin to ensure easy handling during the microscopy analysis, and avoid damaging and contaminating the material voids with debris while polishing. Images scaling from 1mm to 200μm were captured using the Leica DM6000 optical microscope.

Microscopy images were conducted for printed tensile dog-bone samples, sectioned at a longitudinal and transverse axis, see Figure 4. For the ULTEM™ 1010 material, printing orientation having deposition in the X direction only (XYZ prints) is showcased in this study. Whilst for SLS material, standard XYZ printing orientation is presented.

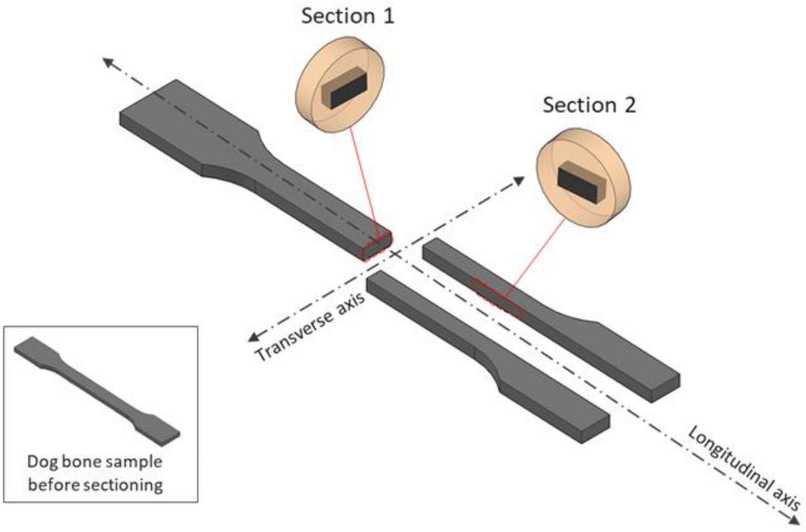

Figure 4. Schematic drawing of Section 1 and Section 2 taken from the sample.

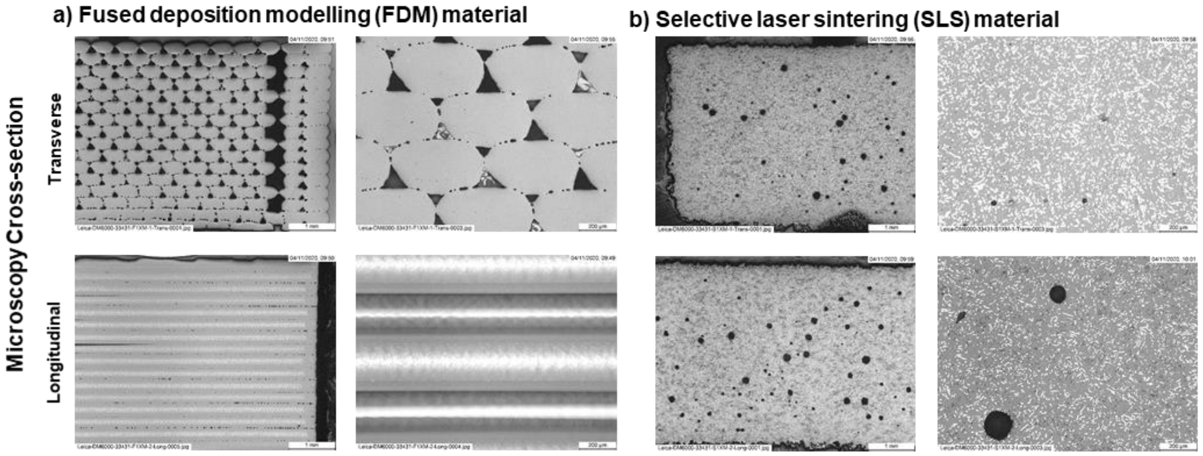

Figure 5. Micrographs with a magnification scale of 1mm and 200μm at the transverse and longitudinal direction for a) FDM material with Deposition along the X-Axis (XYZ prints), b) SLS material with standard printing orientation.

The micrographs for ULTEM™ 1010 illustrated in Figure 5(a) show the presence of voids between neighbouring filaments. These voids are driven by the defined offset distance between the filaments, following the printer's toolpath parameters and the layer to filament depth ratio. However, it is important to note that the settings used to represent the maximum possible print infill. It is also observed in the transverse microscopy cross-section that although print layer thickness is a constant print parameter for all layers, the lower layers of the print appear to be more compact. This is caused by weight and heat build-up that deforms the shape of the deposited layers as printing progresses.

In addition to voids, porosity is observed around the bond line of the deposited filaments. Their presence is not limited to the transverse direction, but is confirmed to occur along the entire length of the filaments, as seen in the longitudinal microscopy cross-sections in Figure 5(a). Although these materials are supplied in sealed containers, the observed porosity could be a result of moisture in the raw material or inside the print chamber. Further work is ongoing to identify any trace of moisture in the material before printing.

As for the SLS material, the micrographs illustrated in Figure 5(b) are largely homogenous. Still, they indicate a consistent presence of dispersed voids in all cross-sections, the largest of which appears to be smaller than 100μm with a semi-spherical shape based on the available longitudinal and transverse cross-sections. These voids likely correspond to unsintered powder, which was washed out after sectioning and polishing, thus, leaving these empty voids. It is also noted that short fibres are randomly distributed in the sintered material with no indicative alignment to a particular direction. This is expected given that the powder is distributed by a roller, and fibres are relatively short to follow the laying direction.

3.2.Tensile test

3D printed thermoplastic materials were tested under tensile loading following BS ISO 527. The test was used to obtain Young’s modulus and ultimate tensile strength (UTS) values for each group of specimens. An Instron 5567A B723 instrument was used to perform the tensile tests at ambient 23℃±2℃. Extensometers were mounted on the specimens to conduct strain measurements. The test was conducted with a displacement rate of 1 mm/min. In total, twenty FDM samples were tested, five from each of the XYZ, XYZ and XYZ±45 orientations. In the case of the SLS material, fifteen samples were tested, five for each of the XYZ, YXZ and ZXY orientations. These tested specimens were printed to size with no machining required, and their print orientation are illustrated in Figure 6.

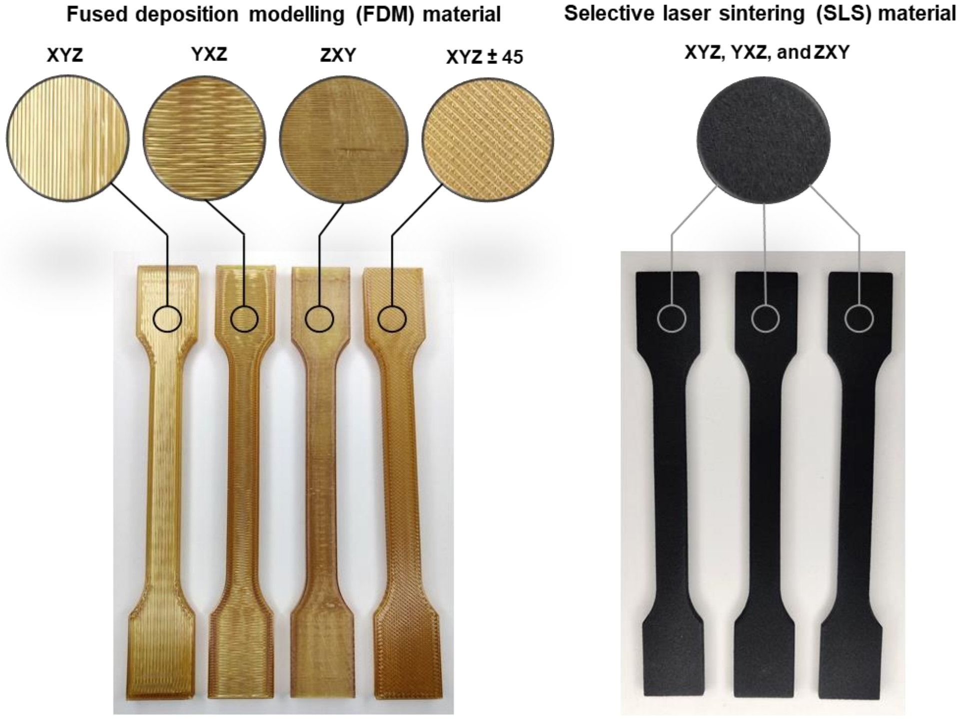

Figure 6. An illustration of the seven print-to-test tensile dog bone specimens for FDM and SLS materials.

For ULTEM™ 1010, the Young's modulus and UTS results showed consistency across the five test specimens for each group. The UTS values for the group having a deposition in the X direction only (XYZ prints) were approximately 46% higher than the other two groups' average because the tensile load path is aligned with the deposited continuous long filaments. In contrast, YXZ and ZXY prints showed lower properties because deposition layers are transverse to the path of the applied load. Another contributor to the lower performance in these directions is the microscopic porosity observed between the filaments' interfaces along these layers. In terms of Young's modulus, the extent of difference between XYZ and the other orientations is less than the UTS, indicating the material stiffness is not fundamentally affected by print orientation.

Similar to FDM, good consistency is observed for the Young's modulus and UTS values across the five specimens of each group of the SLS HT-23 material. The highest Young's modulus and UTS results were obtained from the standard print orientations (XYZ and YXZ), compared to an approximately 19% lower UTS for the ZXY prints as more layers were subject to tensile load.

From the above, it can be seen that the difference in the UTS for the SLS samples is significantly lower than the difference obtained between the different FDM prints. This supports the SLS microstructure observations, where the build is generally homogenous in all directions, offering relatively more isotropic bulk properties for the sintered material compared with the toolpath-dependant FDM prints.

4. Conclusions

PADICTON project aims to respond to the challenges associated with AM. As part of the project, an experimental campaign was carried out to develop and validate a simulation tool for the accurate prediction and prevention of distortion in AM parts. The fused deposition modelling and selective laser sintering AM techniques were considered for the development of this distortion prediction tool.

In this study, optical microscopy and tensile testing for materials printed with FDM and SLS are reported. Optical microscopy was conducted to provide an insight into the printed microstructure. In the case of FDM, the filaments were consistent. Yet, voids and porosity were observed between the filaments and the interfaces. It is understood that voids between the filaments are caused by the toolpath defined by the printer's parameters. However, further work is undergoing to investigate the presence of moisture that might have resulted in the porosity at the interfaces. In contrast, the optical microscopy of the SLS material showed a homogeneous structure with randomly distributed voids caused by unsintered powder. The tensile strength test showed good consistency across the tested specimens of each group. For the FDM material, it was observed that prints with filaments aligned along the loading direction (XYZ) offer the highest average values of Young's modulus and UTS. In the case of the SLS material, both in-plane prints (XYZ and YXZ) showed similar properties. However, lower values were demonstrated from the out-of-plane prints (ZXY), due to the layers being along the transverse direction of the applied load.

Further to the above-presented findings, more testing, including thermal conductivity, DSC, DMA, TMA, pvT, FTIR, and surface roughness, are underway to complete an extensive mechanical and thermal characterisation experimental campaign that will be used to develop and validate the distortion prediction simulation tool for PADICTON project.

Acknowledgements

The authors would like to acknowledge the PADICTON partners, namely FDM Digital Solutions, e-Xstream Engineering, part of Hexagon Manufacturing Intelligence, AMendate, as well as the Topic Manager of the project, Airbus, for their assistance and encouragement towards the realisation of the activities. In addition, the consortium would like to express its gratitude to EOS for their technical support. Furthermore, the activities of PADICTON project have received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement number 864819.

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