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Characterisation of carbon fibre-reinforced polyamide manufactured by selective laser sintering

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ABSTRACT

Polymers and reinforced plastics are employed in various load-bearing applications, from household objects to aerospace products. These materials are light, strong, and relatively cheap but can be difficult to form into complex geometries. However, the development of additive manufacturing processes has made it easier to manufacture reinforced plastics in complex shapes. The aim of this work was to study the internal features and mechanical properties of carbon fibre-reinforced polyamide (CF/PA12) fabricated with the additive manufacturing technique of selective laser sintering. The test specimens were studied using computed tomography to analyse the internal geometry, and the material proved to be highly porous. Moreover, the test specimens revealed an internal layered structure, which was found to have a great effect on the tensile properties of the material. The results highlight that there is room for further optimisation of the manufacturing parameters for CF/PA12, because the layered structure makes it challenging to design end user parts with acceptable mechanical properties.

1. Introduction

In recent years, a new branch of manufacturing techniques, called additive manufacturing (AM), has evolved from rapid prototyping, which has been around since the 1980's [1]. In AM, small portions of material are added layer by layer to create the end product instead of removing material from a larger bulk. The AM technique has significant advantages over classical manufacturing methods, and designers can create parts with any geometry without being restricted by the limitations of milling, lathing, and moulding. There are several materials available for AM, such as a variety of plastics with and without reinforcement fillers and a selection of metallic alloys.

Selective laser sintering (SLS) is an AM method that is based on the powder-bed technique. In SLS, powder is raked in thin layers over a build table that moves downwards in steps, and lasers melt a portion of the added layer according to the geometry of the part to be built. This creates a thin slice of the part and fuses this section to that beneath it. Today, the technique has advanced to a point where the produced parts no longer serve only as prototypes but possess material properties that are suitable for end user products [2].

One of the new SLS materials being developed for end user parts is carbon fibre-reinforced polyamide (CF/PA12). The material itself is well known in the industry and has been used for many years for fabricating complex and light parts by injection moulding [3]. The material in its raw form is a powder consisting of polyamide spherical particles with diameters in the range of 50 μm mixed with carbon fibres of diameter 10 μm and length 100–200 μm. The fibres normally undergo chemical treatments before they are blended with the polyamide to achieve greater adhesion between the fibres and the plastic matrix. A higher percentage of fibres increases the strength of the material. Yan et al. found that a fibre percentage of approximately 40% was suitable for the SLS process and that higher percentages caused problems when applying new coats of powder layers [4].

The mechanical properties of the material are generally strengthened by the fibres, making it stiffer, stronger, and lighter. However, the material properties are influenced by the fibre orientation. For example, in injection-moulded parts, the fibres themselves align along the melt flow direction, increasing the material strength in that direction but decreasing the strength in other directions [5]. The inhomogeneity in the material strength can restrict the part designs suitable for injection moulding, because the options for the melt flow directions are limited.

Abbreviations: CF/PA12, carbon fibre–reinforced polyamide; SLS, selective laser sintering; CFRP, carbon fibre–reinforced polymer; CT, computed tomography.

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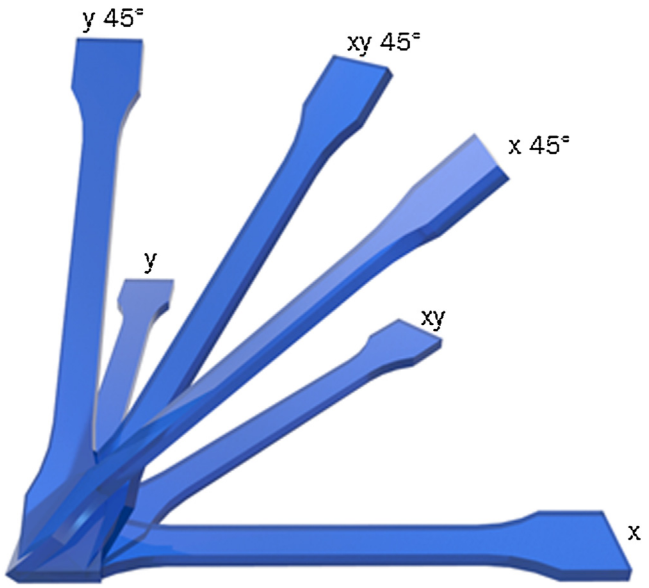

Fig. 1. The manufacturing orientation of the tensile bars in the build chamber. The powder spreading rake travels in the *x*-direction.

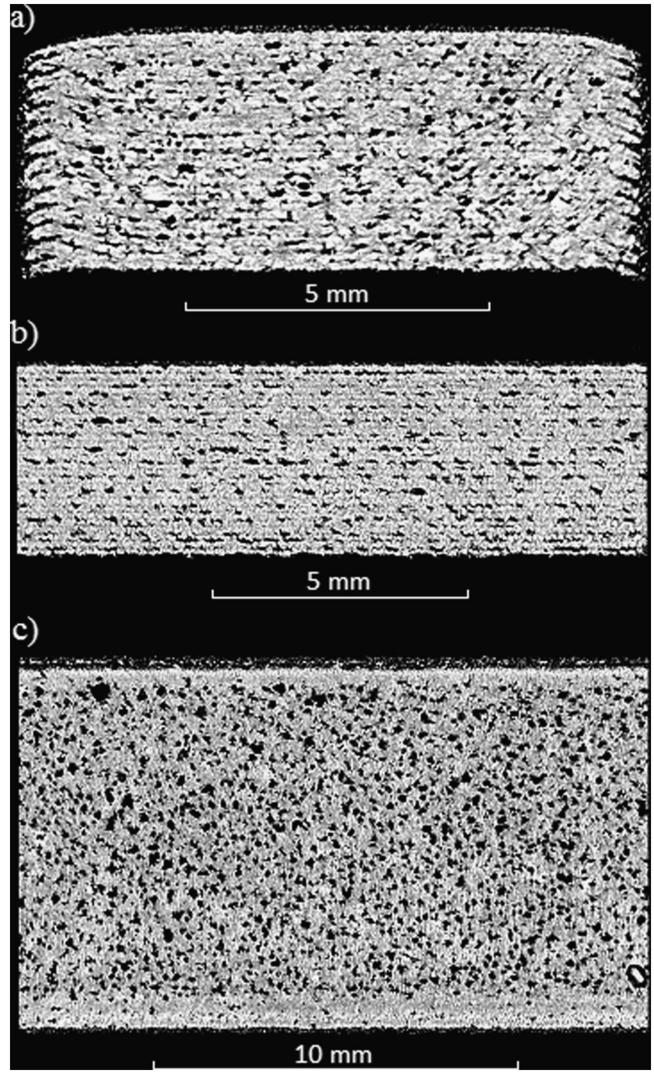

Fig. 2. Cross sections from a *y* direction tensile bar (a) cross section normal to the build direction. (b) cross section from the centre of the tensile bar, showing a layered structure that continues throughout the specimen. (c) cross section along the fusing area of two build layers.

SLS could prove to be a powerful alternative manufacturing method in which the fibre alignment could be controlled more effectively. CF/PA12 parts built by SLS exhibit different material properties in different directions, and there are claims that this is linked to the fibre orientation in the material. It is thought that the fibres align themselves along the direction in which the powder is spread in the build chamber, i.e. the *x*-direction. However, the SLS process is a complex method with a large number of parameters that affect the outcome of the produced material, such as powder composition, laser beam settings, temperature of the powder bed, and powder layer thickness. Moreover, there have been reports of porosity in other carbon fibre–reinforced polymers (CFRPs) manufactured by SLS, such as in the PA12 material studied by Van Hooreweder et al [6]. The group compared the mechanical properties of SLS parts and injection-moulded parts that used the same material and found that the SLS parts were weaker. They also detected porosity in the SLS parts by examining their cross sections and postulated that the porosity was homogenous throughout the samples. Other studies on SLS parts have also indicated that porosity is caused by this process [7,8].

To study complex materials such as CFRPs, there is a need to investigate their internal features in a non-destructive manner. It has been recognised that computed tomography (CT) is particularly suited for analysing complex parts built by AM methods [9]. The use of industrial CT systems has escalated in recent years, and as the complexity of parts increases, new reliable non-destructive methods of investigation have become necessary. CT has proved to be an effective tool for studying composite materials, as has been shown by Meneghetti et al. [10]. among others.

The aim of this work was to characterise carbon fibre-reinforced polyamide parts manufactured by SLS, to broaden our understanding of CF/PA12 and its properties.

2. Materials and methods

The SLS system used in this study was from one of the major equipment manufacturers in the area (EOS P396), using the recommended parameters set by the equipment manufacturer. The CF/PA12 material analysed was also one of their products and is marketed as having 'outstanding mechanical properties characterised by extreme stiffness and strength'. The material is known to exhibit variations in properties depending on the build direction in the SLS build chamber.

Tensile bars complying with ISO-527 [11] were built in six directions in the build chamber: *x*, *y*, *xy*, *x* 45°, *y* 45°, and *xy* 45°. The bars labelled 45° had a 45° tilt angle with respect to the *z*-axis of the build chamber, as illustrated in Fig. 1, whereas the *x*, *y*, and *xy* tensile bars were built in the plane of the build table. Three tensile bars was built in each build direction. The thickness of the bars was 4 mm, and that of a newly spread powder layer was 0.15 mm. Therefore, each of the non-tilted and tilted bars was built up by approximately 27 and 800 powder layers, respectively.

The tensile bars were built using the cross-directional laser sweep technique. The laser starts each layer by melting the contour of the part slice and then alternatively sweeps along the *x*- and *y*-directions to fill the slice. Thus, if the first layer was melted along the *x*-direction, the next layer will be melted along the *y*-direction.

The tensile bars were examined in the state 'as delivered', which meant that they had been exposed to a light abrasive treatment using glass beads. A 20 × 40 × 5 mm piece of standard PA12 was also fabricated, using SLS, as a reference object for porosity studies.