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Fabrication of the Continuous Carbon Fibre Reinforced Plastic Composites by Additive Manufacturing

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ABSTRACT

Additive manufacturing has been adopted in a wide range of industry. However, limited mechanical properties have prevented additive manufacturing from further development in high value applications. Carbon-fibre-reinforced composites are widely used in automobile and aerospace industries due to their improved mechanical properties and reduced weight. The introduction of carbon fibre into additive manufacturing will allow its application across a broader industrial field. In this paper, carbon-fibre-reinforced composite samples were produced by material extrusion and stereolithography. Tensile tests were performed on pure polymer and carbon-fibre-reinforced samples. Experimental results were compared to theoretical ones based on a rule of mixture. Samples produced by material extrusion showed a 73.3 % reduction in elastic modulus compared with theoretical values whereas those produced by stereolithography showed a 42.06% reduction. Micrographs showed that stereolithography samples had better bonding between the matrix and the fibre.

KEY WORDS: Continuous Carbon Fibre; Plastic Composites; Stereolithography (SLA); Material Extrusion (ME), Additive Manufacturing

1. INTRODUCTION

Additive manufacturing (AM) is a novel manufacturing technology which can directly stack materials layer by layer to form parts, enabling complex shapes with high resolution [1]. However, the heterogeneity and poor mechanical property along the layer stacking direction has hindered its progress from printing prototypes to end products in the industry [2]. Carbon fibre reinforced technology is one of the most important areas for manufacturing composites, which has broad application prospects in industries, including aerospace and automotive, which require low weight and high strength [3]. Introducing carbon fibre into AM can improve the mechanical properties of 3D printed parts, enabling high value applications [4].

At present, short-fibre-reinforced composites are widely produced in AM, but with limited improvement in tensile strength in certain direction as the orientation and alignment of short fibres are hard to control. Continuous-fibre-reinforced composites (CFRCs) can effectively improve the overall mechanical properties. Through controlling the distribution and direction of continuous fibres, desired mechanical properties can be achieved. However, issues with poor bonding between the fibre and matrix phases of the resulting composites have remained a challenge in producing additively-manufactured composites [5]. CFRCs have been produced mainly using material extrusion (ME). The first desktop ME machine using continuous carbon fibre was developed by Markforged™ [6]. Other institutions also proposed ME-based methods by infiltrating fibre and plastic in one heated nozzle [7-8]. However, their results demonstrated poor bonding between layers. In this paper, CFRC specimens were fabricated by material extrusion (ME) and Stereolithography (SLA) and evaluated by mechanical testing and microscopic examination.

2. METHODOLOGY

2.1 Specimen Preparation

The tensile test specimens were designed following ASTM D638-02 standard as shown in figure 1[9]. The matrix and fibre material for different types of specimens are given in Table 1 and four types of samples were produced. For SLA samples, matrix was Accura60 resin supplied by 3D Systems™ while reinforcement was carbon fibre filament obtained from Markforged™. For ME samples, matrix was Nylon filament and reinforcement was carbon fibre filament, both of which were supplied by Markforged™.

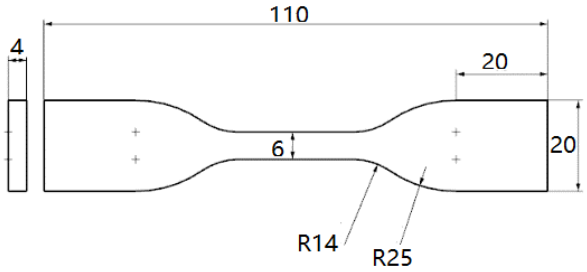

Figure 1: ASTM D638-02a Tensile test specimen sample geometry (dimensions in mm).

Sample Code	Sample type	Matrix Material	Fibre Material
SLA-P	Pure Samples by SLA	Accura60 Resin	N/A
SLA-C	Composite samples by SLA	Accura60 Resin	Carbon Fibre
ME-P	Pure Samples by ME	Nylon	N/A
ME-C	Composite sample by ME	Nylon	Carbon Fibre

Table 1: Sample code and material specification

ME-P and ME-C samples were manufactured using a Markforged™ MarkTwo machine. The printer adopts a double nozzle structure with one for nylon and the other for continuous carbon fibre. ME-P samples were printed using Nylon filament only (single nozzle). The layer height was 0.125mm as fixed in Eiger software for composite. The infill density was set to be 100% with standard rectangular fill pattern which has strength in all directions. ME-C samples were produced using the same settings for the matrix part and 3 layers of fibre were centre-positioned.

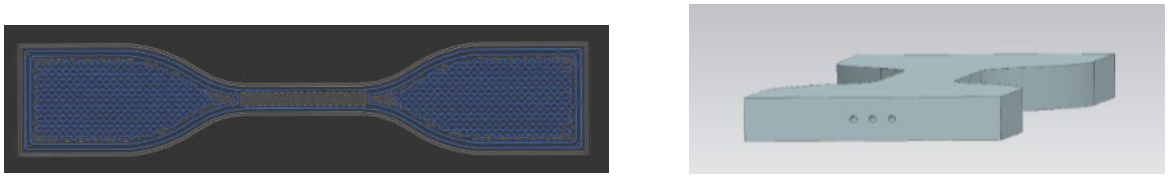

Figure 2: (a) 2D plane view of fibre distribution of ME-C sample;
(b) Cross Section view of SLA-C matrix sample

Pure SLA samples were manufactured using Accura60 resin on a Viper SLA System from 3D Systems™. Samples were cleaned using IPA and post-cured for 40 minutes using a UV oven. For SLA composite samples, three holes with a diameter of 0.6 mmm were included in the specimens. The holes were 1.5 mm apart and evenly distributed in the gauge section for the tensile specimens. The number of holes and their positions were chosen as it was an initial study. Further investigation on the number of carbon fibre and its distribution will be carried on. The carbon fibre filaments, with a diameter of 0.375 mm, were coated with resin and slotted into the holes. The whole composite was post-cured for 80 minutes.

2.2 Testing

Tensile tests were performed on an Instron 3369 machine with a 50 kN load cell. Tensile test specimens based on the two AM methods were tested to failure with a loading rate of 5 mm/min. A Zeiss™ Primotech optical imaging microscope was used to analyse the fracture surface of tested specimens. One side of the fracture surface was polished using a Buehler EcoMet™ Manual Grinder Polisher with a 600-grit sandpaper to obtain a flat surface. A Hitachi TM3030 Tabletop scanning electron microscope with 5-15 kV accelerating voltage was used to investigate the fibre-matrix interface. Specimens were coated in platinum using the Quorum Q150R Rotary Pumped Sputter Coater for greater electrical conductivity to get clearer images.

2.3 Theoretical Calculation

To predict the strength of fibre-reinforced samples, the following assumptions were made:

- The fibres are assumed to be uniformly arranged and distributed within the matrix.
- The fibre-matrix interface is assumed to be perfectly bonded.
- The load is evenly distributed between the fibres through the gauge section.
- The applied load is parallel to the direction of fibres.

The theoretical cross section of the gauge section for ME-C and SLA-C are shown in Figure 3(a) and Figure 3(b) The diameter of the carbon-fibre strand was measured as 0.375 mm using a micrometre.

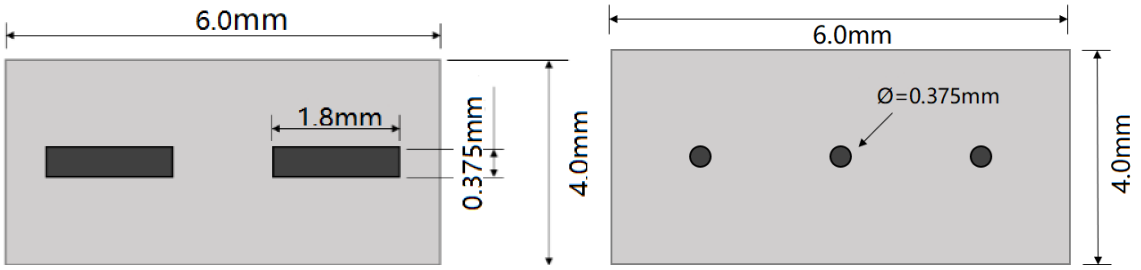

Figure 3: Assumed cross section views of the gauge sections of (a) ME-C and SLA-C samples.

The volume fraction of matrix and fibre can be calculated, and the theoretical strength and modulus can be determined using a rule of mixture.

3. Results and discussion

3.1 Tensile Test

According to Figures 4 (a) and (b), the stress at 0.03 strain is about 14 MPa for pure ME sample, and 30 MPa for ME composite piece. By obtaining the average value of multiple effective parts, the mean modulus is 0.486 GPa for the pure ME piece, and 1.023 GPa for ME composite piece. Continuous fibre increased the elastic modulus by 1.1 times (110.49%), but greatly reduced the elongation at break. Carbon fibre has a lower elongation-to-break compared to pure nylon, resulting in a much more brittle nature of composite sample. Figures 4(c) and 4(d) show that the stress at 0.03 strain is about 21 MPa for pure SLA piece, and about 27 MPa for the composite piece. The mean modulus is 0.726 GPa for the pure SLA piece, and 0.898 GPa for SLA composite piece. Continuous fibres increased the elastic modulus by 23.69%.

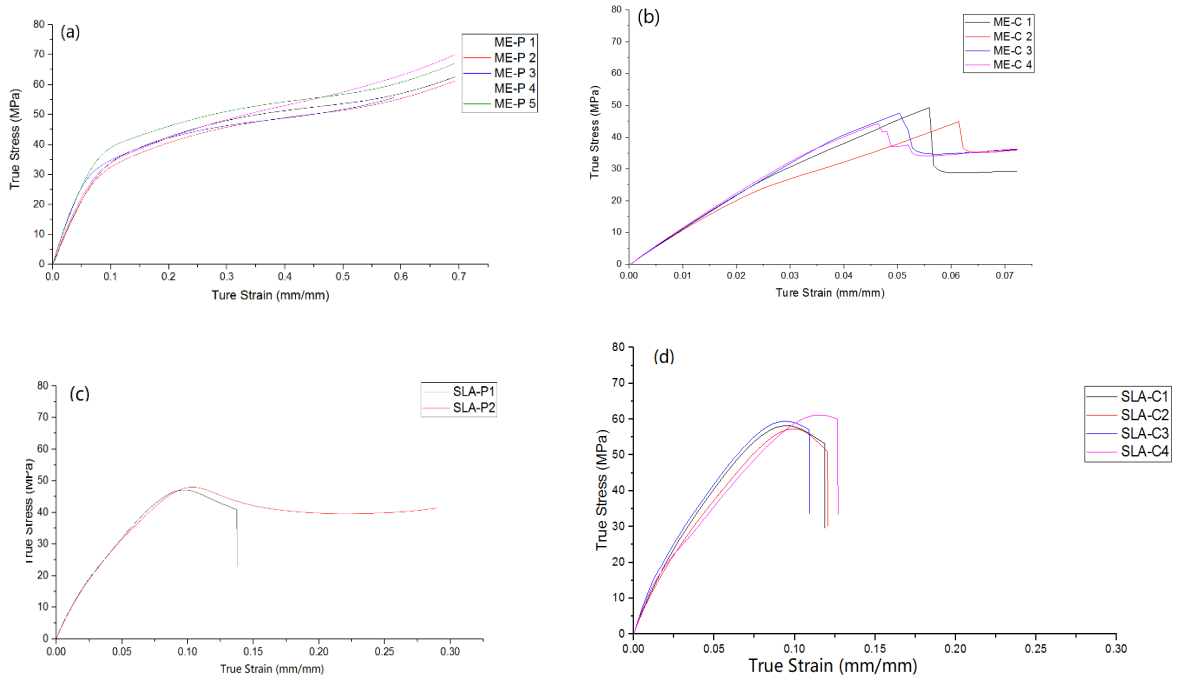

Figure 4: (a) True stress vs. true strain for ME-P sample; (b) True stress vs. true strain for ME-C sample; (c) True stress vs. true strain for SLA-P sample; (d) True stress vs. true strain for SLA-C sample

According to the rule of mixture, the enhancement of mechanical properties of fibre composites has a direct relationship with the proportion of continuous fibres. Since the elastic modulus of fibre material is much higher than that of a matrix material, the higher the fibre content the higher the increase in elastic modulus of the composite. Using obtained experiment data, the elastic modulus of composite material can be predicted, and results are shown in Table 2.

Sample	Volume Fraction of Matrix	Volume Fraction of Fibre	Elastic Modulus of Matrix (GPa)	Elastic Modulus of Fibre (GPa) [10]	Theoretical Elastic Modulus of Composite (GPa)	Experimental Elastic Modulus of Composite GPa)
ME-C	0.94375	5.625×10^{-2}	0.486	60	3.833	1.023
SLA-C	0.9862	1.380×10^{-2}	0.726	60	1.55	0.898

Table 2. Theoretical and experimental tensile strength of SLA-C and ME-C samples

As observed from Table 2, there is an obvious deviation between theoretical and experimental results for ME-based composite samples. There is a 73.3% reduction in the real elastic modulus compared to the calculated result. One reason might be the insufficient bonding of matrix and carbon fibre. Also, the infill density of fibre might not be 100% and the fibre distribution is not uniform. SLA-based composite samples showed a 42.06% reduction, which is less than the ME samples.

3.4 Microscopic examination

As can be seen from Figures 5(a) and 5(b), the fracture surface of ME samples displayed a rough surface with stretched matrix, which indicated a ductile failure mode. At the interface, the number of voids were presented between the fibre and matrix layers, resulting in high porosity and hence a reduction in mechanical performance of the composite specimens. The voids indicated the insufficient bonding between fibre and matrix. One reason might be the infill density was not 100% and the printed fibre was not uniformly distributed.

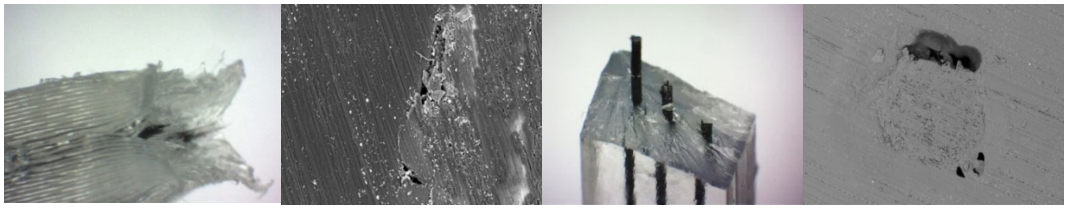

Figure 5: Fracture sections of ME-C samples (a and b) and SLA-C samples (c and d).

According to Figures 5(c) and 5(d), the flat and smooth fracture surface shows a clear manifestation of brittle failure mode. It is clear that the fibres broke with different protrusion lengths. Due to the nature of the material, the matrix cracked first and the remain stress led to the facture of fibre. The fracture surface suggests that both fibre pull-out and interface debonding occurred. Comparing Figures 5(d) and (5)b, less voids were observed in SLA-C sample, indicating a better intra-surface bonding,

4. Conclusion

Composite samples based on two AM methods were fabricated. Tensile test and microscopic analysis were carried out. The increase of elastic modulus after embedding carbon fibre is 110.49% and 23.69% for ME and SLA based composite samples, respectively. Compared with theoretical result, experimental results demonstrated a 73.3% lower tensile modulus for ME samples and a 42.06% lower tensile modulus for SLA samples. The microscopic analysis suggested a presence of porosity at the fibre-matrix interface of the composite specimens produced by both SLA and ME while SLA samples have a less percentage of porosity. It is inferred that the interfacial bonding quality between fibre and matrix is one of the main reasons for the change of mechanical properties. The weak fibre-matrix bonding could compromise tensile properties. Compared to commercially available composite ME based machine, SLA technology showed promising results for composite manufacturing, and further investigation is ongoing.

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