3D PRINTING OF CONTINUOUS FIBRE REINFORCED THERMOPLASTIC COMPOSITES

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ABSTRACT

The idea of using 3D printing technique in manufacturing continuous fibre reinforced composites was proposed and the advantages of using this process in composite structures manufacturing were discussed. 3 point bending specimens were printed out using a commercial composites 3D printer. The flexural strength and modulus were obtained, as well as voids content, in order to evaluate the quality of the printed specimen. A desktop Fusion Deposition Modelling (FDM) printer was modified for continuous fibre reinforced composites printing. Unconventional fibre patterns were designed and printed out. A composites lug structure with curvilinear fibre pattern were manufactured using the continuous fibre 3D printing technique.

1 INTRODUCTION

There is an urgent need for reducing aircraft weight in the demand of less fuel consumption under both economic and environmental considerations. By replacing metallic parts like fuselages, wings and tails panels, with composites material, a large weight saving (about 25,860kg for Boeing 787 [1]) has been achieved and can be transferred into fuel saving. Therefore, the usage of fibre reinforced composites material is significantly increasing [2]. For commercial aircrafts like the Dreamline Boeing 787 and Airbus A350XWB, the usage of advanced composites is up to 50% [2] and 53% [3] by weight respectively, which leads to approximately 20% weight savings and 8,660kg fuel saving over a 10,000km journey [1]. However, there are still many structures on the aircrafts such as joints and lugs, which cannot be replaced by composites material, because fibres have to be cut during processes like drilling and machining resulting in strengths lost. Therefore, the idea of using a 3D printing technique in composites material manufacturing is proposed, which creates an opportunity for broadening the applications of composite material in aircraft structures. Key load carrying structures like joints and lugs can be manufactured using 3D printing technique. Fibre continuity can be maintained, without cutting fibres in the existence of holes or notches. Therefore, the structure and fibre paths need to be optimized so that structure cannot only sustain the specified loading conditions, but also achieve weight reduction compared to metallic structure or conventional fibre reinforced composite structures.

3D printing, also known as Additive Manufacturing (AM), is a manufacturing process for synthesizing a three dimensional object layer by layer. Fusion Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is one of the commonly used extrusion based Additive Manufacturing techniques. In FDM process, a thermoplastic filament is fed into a heated nozzle where the plastic will be melted. Then the melted plastic is extruded from the nozzle by pressure and then becomes solid immediately after cool down. In order to improve the printed part mechanical properties or increase functionalities, some researchers have been adding discontinuous fibres or particles reinforcement into the plastic filament [4-9]. In these researches, thermoplastic filaments were mixed with the discontinuous fibre or particle reinforcements, which were then used in an existing unmodified FDM printer. 3D printed samples with reinforcements were made and the effect of mixing ratio and fibre length were investigated. Depending on the mixing ratio and fibre length, tensile strength was improved by 20~70% while modulus was improved by 30~600%, compared to neat plastic printed parts. Researches have also been focusing on the alignment of short fibre in the printing process [10-12]. A high degree of fibre alignment was observed during the FDM process, which had a positive effect on improving the mechanical properties. Also fibres pulled out were observed in the fractural surface, which indicated a weak interfacial bonding between the fibre reinforcement and the matrix material. Besides investigation on the printing thermoplastic composites, thermoset matrix composite materials were also produced using FDM process. Turri [13] used a dual-cure thermoset resin in printing short carbon reinforced composites. Trask [14] used ultrasound to align short glass fibres in a UV cure resin bath and a laser beam was mounted on a FDM printer to cure the resin.

Although 3D printed short fibre reinforced polymer composites show some improvements compared to neat printed plastics, the mechanical properties are still not comparable to that manufactured by conventional continuous fibre reinforced composites processes like Prepreg/Autoclave and RTM. Since fibres are the primary load carrying part in composites, maintaining their continuity would significantly increase the mechanical properties of the structure. Some researchers are working in the field of 3D printing of continuous fibre reinforced composites. Jones [15] and Downes [16] attempted to use 3D printed continuous glass fibre reinforced biodegradable polymer composites in the application of human bone replacement. A technology called MDM modeller was developed, which combined a form of FDM and thermoplastic tow placement or tap laying. A glass fibre tow was passed through a bath of molten polycaprolactone (PLC) to form tow-preg and then was fed into the MDM machine. Tensile test specimens with 19 layers (10 longitudinal and 9 transvers) were manufactured and tested, which resulted in 168MPa and 11.55GPa for tensile strength and Young's modulus respectively. Low fibre volume fraction (27%) and high voids content (11-19%) could be the reason for the low mechanical properties. A poor wetting was also observed inside the fibre tow. Namiki [17] and Matsuzaki [18] developed an in-nozzle impregnation 3D printing process which was able to produce continuous reinforced composites. The continuous fibre reinforcement and the thermoplastic resin filament were supplied to the print head separately. The plastic filament was fed by drive gears and a stepping motor, while fibres were automatically supplied by the movement of the plastic filament. The fibres were impregnated inside the nozzle by the melted thermoplastic. Two types of reinforcements were used: carbon fibre tow and twisted jute-fibre yarns, and PLA filament was used as the matrix material. A large diameter nozzle (1.4mm) was used to prevent clogging of the fibres, and the diameter of the filament was 1.85mm. A very low fibre volume fraction was achieved, 6.6% for carbon fibre reinforced PLA and 6.1% for jute-fibre reinforced PLA. Test results showed that the tensile strength and modulus of the carbon fibre reinforced PLA were 599% and 435% of those of the neat PLA samples. Voids and poor bonding between PLA resin and carbon fibres were observed from the fracture surface. A similar in-nozzle impregnation FDM process was developed by Tian [19,20]. 1k dry carbon fibre bundle and PLA filament were used as reinforcement and matrix materials. The carbon fibre and PLA filament were fed into the extrusion head separately. The PLA filament was heated up and melted by a liquefier for fibre impregnation. A 2mm diameter nozzle was used and the PLA filament diameter was 1.75mm. The effects of process parameters on the composites properties were investigated. A maximum fibre content of 27wt% was obtained and an average flexural strength of 335MPa and modulus of 30GPa were achieved. Li [21] also used an in-nozzle impregnation method for continuous carbon fibre composites printing, but carbon fibres was pre-processed in a PLA and methylene dichloride solution in order to improve the weak bonding in the interface between the fibres and the PLA matrix. 13.8% and 164% improvements in tensile strength and flexural strengths were obtained, compared to original carbon fibre reinforced samples. The Markforged printer, which is a commercially available continuous fibre reinforced composites 3D printer, was used in Klift's [22] and Carey's [23] research. Continuous carbon fibres and Nylon were used as reinforcement and matrix material. A higher fibre volume fraction 34.5% was obtained and the ultimate tensile strength of specimens was 464.4MPa. In Gerguri's research [24], bicycle lugs were printed out using the Markforged printer, as shown in Figure 1. Among these studies, fibres were embedded inside the printed plastic parts. They are more likely to be 3D printed plastic with some fibre reinforcement, rather than a real composites structure. The advantage of using the anisotropic properties of the fibres has not been explored. The fibre path design like the joint in Figure 1, where fibres stop at the edge of a hole or simply going around it, certainly is not the best way of using continuous fibres.

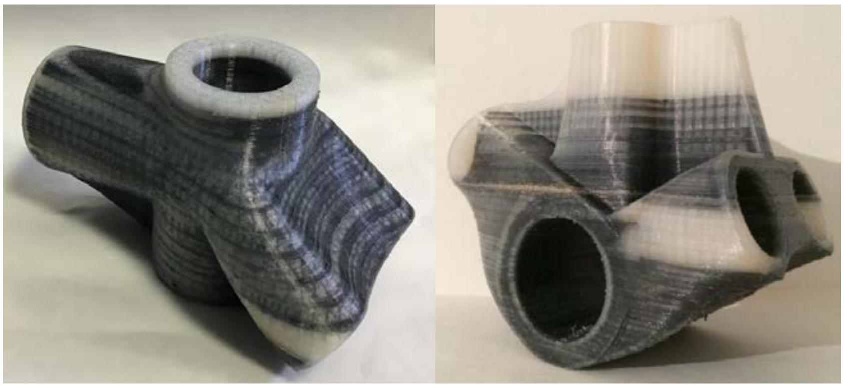

Figure 1 3D printed bicycle lugs reinforced with continuous carbon fibre [24]

In this study, continuous fibre reinforced composites were produced by 3D printing technique. A MarkTwo printer was used to print out the specimen for mechanical testing. Flexural strength and modulus were obtained to evaluate the quality of the printed specimen. The cross section of the specimens was examined using an optical microscope, and the voids content was estimated using the cross section microscope images. A lug structure was chosen to demonstrate the idea of using 3D printing technique in composites manufacturing. Unconventional fibre patterns were design and a composites lug specimen was printed by a modified FDM printer.

2 EXPERIMENTAL PROCEDURES

2.1 Materials

In the present research, continuous carbon fibre reinforced Nylon filaments and continuous glass fibre reinforced Nylon filaments from Markforged® have been used, which are pre-impregnated prepreg materials. The diameter of both filaments is 0.4mm. A 1.75mm diameter Nylon filament (Markforged®) without any reinforcement is also used in printing out the bottom substrate for fibre filament to be laid on, and top surface to finish with.

2.2 Experimental platform

The MarkTwo printer (Markforged, Inc., USA) was used to produce specimens for the mechanical testing. There are two nozzles mounted on the print head, one for Nylon filament and one for fibre filament. The web based software of the MarkTwo printer is called Eiger, which serves the function of slicing the print part into layers and generates printing file for the printing process, like heating nozzle, feeding filament, movement of nozzle and so on. A 3D part was first created by any CAD software and then imported into the Eiger software. Several parameters can be modified in the software, including fibre types, fibre fill type, fibre layers, fill pattern etc. There are two options of fibre fill types can be chosen in the software. One is "isotropic fibre", and the other is "concentric fibre". The isotropic fibre fill means that all fibres will be placed as straight lines in the assigned direction from 0° to 180°continuously, while in the concentric fibre fill, fibres will be placed in concentric rounds as the shape of the edge.

2.3 Specimen characterization

3 point bending test was chosen to examine the mechanical properties of the printed continuous fibre reinforced composites. Specimens with a size of 38.4×13×1 mm was printed out and tested. The span was set to be 32mm according to the ASTM Standard D7264. An Instron testing machine was use to perform the test, and 1mm/min was chosen for the testing speed. The maximum flexural stress was calculated by equation 1. For the 3 point bending test, five specimens were printed to calculate the average flexural stress and modulus.

$$\sigma = \frac{3PL}{2bh^2} \tag{1}$$

2.4 Morphological studies

The cross section morphology of the 3D printed composites were examined using an optical microscope. Specimens with the same dimensions as the 3 point bending test were printed out and cut in the middle. Then the samples were embedded in epoxy resin. After the resin was cured, the samples with the cross section surface were sanded and polished to be observed under the optical microscope. Microscopic pictures of the cross section were taken. The voids content was estimated by adjusting the colour threshold using the ImageJ software.

3 RESULTS AND DISSCUSSION

3.1 Mechanical properties

Two groups of specimens were prepared for testing. One was 5 carbon fibre layers and 3 Nylon layers, and the other was 6 carbon fibre layers and 2 Nylon layers. All the fibres were in the longitudinal direction in each the specimen. The stress and strain curves of both groups are presented in Figure 2 and 3. The average maximum flexural strength for the 5 carbon fibre layers specimens is 297.67MPa, while for the 6 carbon fibre layers, it is 395.61MPa. The flexural modulus were obtained by measuring the linear part of the slope of the stress and strain curve, and they are 17.80GPa and 29.91GPa respectively.

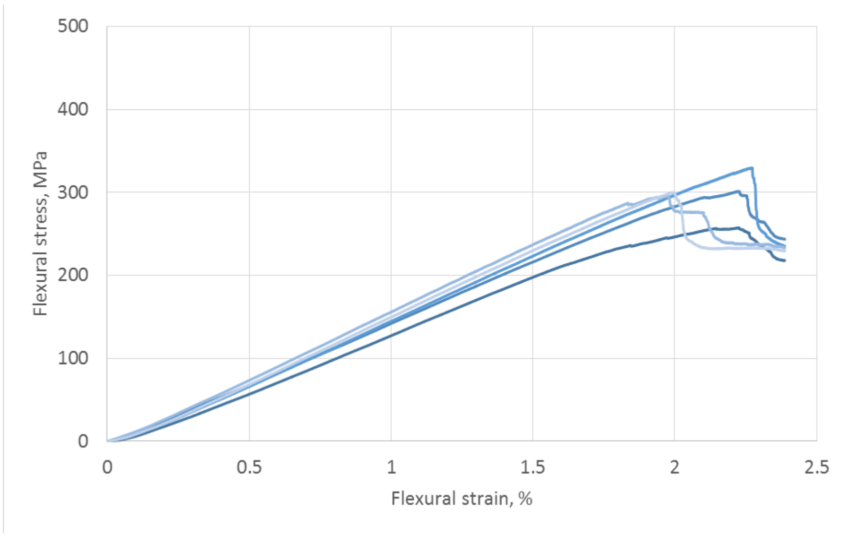

Figure 2: Flexural stress and strain curve of the 5 carbon fibre layers and 3 Nylon layers specimens

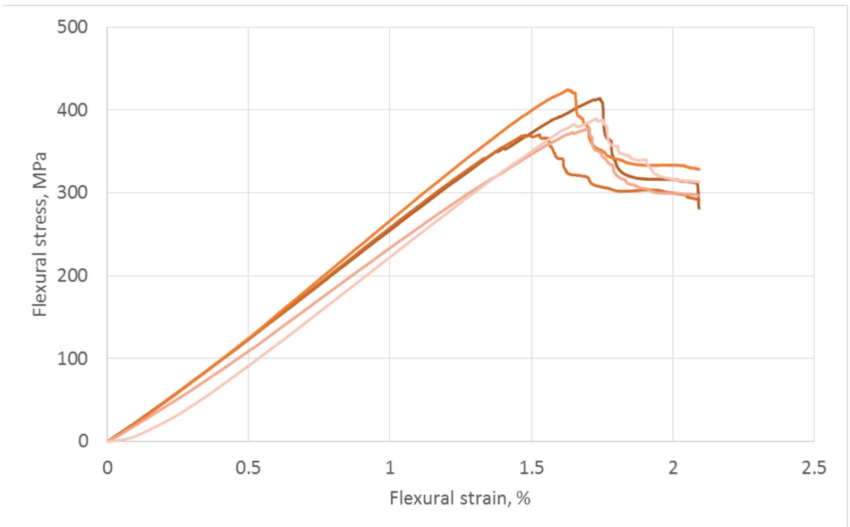

Figure 3: Flexural stress and strain curve of the 6 carbon fibre layers and 2 Nylon layers specimens

It is easy to anticipate that the 6 carbon fibre layers specimens resulted in a higher flexural stress and modulus, because of the higher fibre volume fraction. Also, a lower failure strain was observed in the 6 carbon fibre layers specimen. The mechanical properties of the printed continuous fibre reinforced composites resulted in a much higher value than pure Nylon plastic [25], however, it is still much lower than composites manufactured by conventional processes like autoclave process. The fibre volume fraction of the printed specimens were relative low, because there were some extra Nylon layers on top and bottom. Since the Nylon layer did not contribute much in strength, in order to make a more reasonable comparison with the conventional composites material, a new flexural strength of the printed carbon layers part was calculated by excluding the Nylon layer thickness. The fibre volume fraction for the carbon fibre layers would be 50% according to the Marforged data sheet [25]. Figure 4 compares the flexural properties of the 3D printed composites with that manufactured in an autoclave using commercial T300 carbon/epoxy prepreg with a 60% fibre volume fraction[26]. Despite that epoxy matrix has a better performance than the Nylon, the flexural strength of the 3D printed carbon part is only one third of the properties of composites manufactured by conventional process.

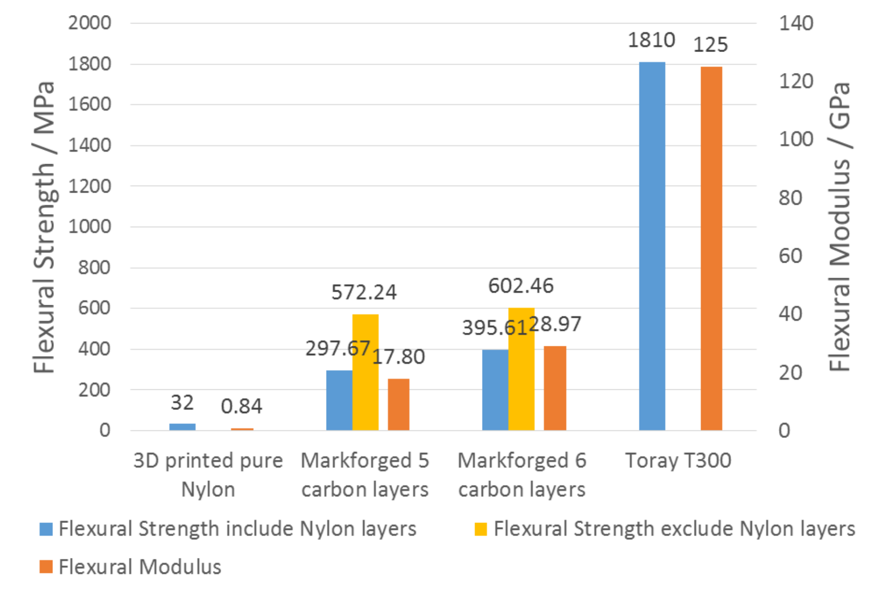

Figure 4 Flexural strength and modulus comparison between 3D printed composites and conventional composites

3.2 Microstructural analysis

Figure 5 shows the optical microscope picture of the 3D printed continuous fibre reinforced composites cross section. The black part around is pure Nylon layers. The light white dots represent carbon fibres, and the light grey area is the Nylon matrix material. Large area of voids were found both in 5 carbon fibre layers specimens and 6 carbon fibre layers ones. Interface between filaments and layers was not clear, which indicated a good bonding between filaments and layers. However, layers debonding was also observed on the sides of the specimens. A full size cross section picture was taken in order to estimate the voids content across the whole area, as shown in Figure 6. A threshold was chosen carefully in order to identify the voids area, which was marked in red. Since the Nylon layers around has a similar color as the voids, only those areas inside the fibre layers were accounted as voids when estimating the voids content. A voids content of 7~12% was obtained from the optical microscope pictures. Such high voids content can be the reason for its low mechanical properties, compared to conventional composite material (around 1% voids content).

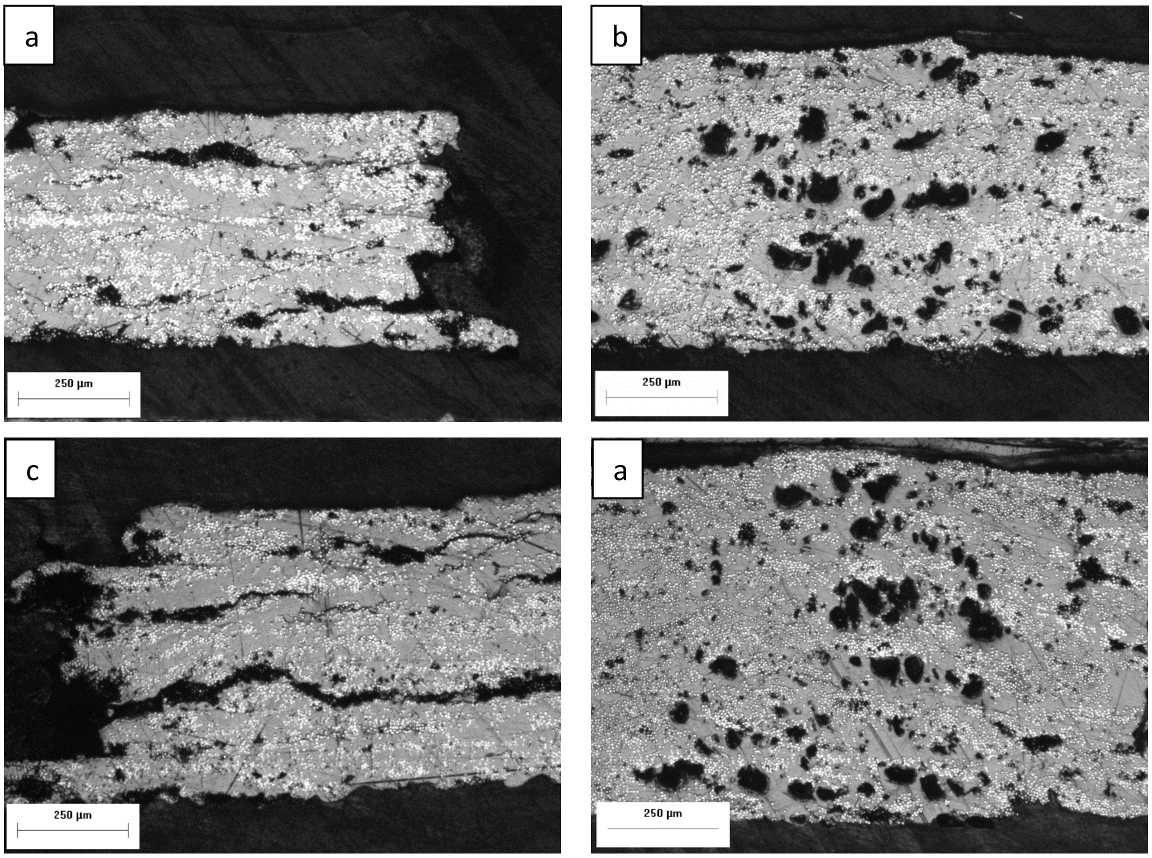

Figure 5 The 3D printed composites specimens cross section optical microscope picture: (a) 5 carbon fibre layers specimen side, (b) 5 carbon fibre layers specimen middle, (c) 6 carbon fibre layers specimen side, (d) 6 carbon fibre layers specimen middle.

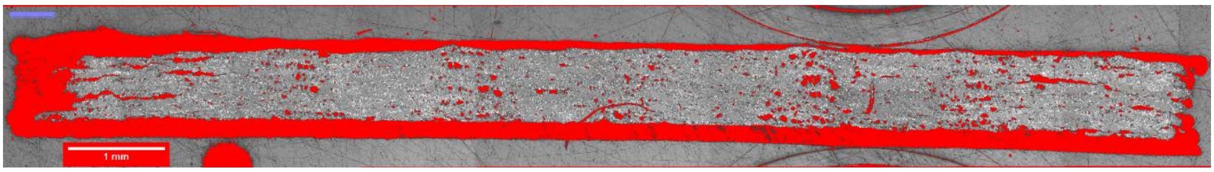

Figure 6 Full size cross section microscope picture

3.2 3D printing composites lug structure

One main advantage of using 3D printing technique in composites manufacturing is realizing fibre steering within a ply of a composites structure by accurate depositing the fire during the process. Strength and stiffness of the structure can be tailored and optimized by the designer for different requirements and conditions. Structures like aircraft lugs and joints can be one of the applications. In conventional composites manufacturing processes, uni-directional fibres or woven fabrics are commonly used. Fibres have to be cut during processes like drilling and machining in the existence of holes or notches, which would dramatically weaken the strength of the structure. By using 3D printing technique to lay down continuous fibres without cutting, composite materials can potentially be used in highly loaded structures like lugs and joints. Thus, in this study, a lug shape specimen was manufactured using the 3D printed technique to demonstrate the potential application.

Although the commercial Markforged printer was capable of printing continuous fibre composites, the design freedom was limited to the only two fibre fill options (straight and concentric circles). In order to freely design the fibre path, an open sourced Velleman K8400 RepRap printer was modified and used in this part of the study. The material is not limited to thermoplastic prepreg tow like the Markforged printer, but also thermoplastic commingled fibre yarns and co-extrusion of dry fibres and thermoplastics.

The lug was designed under two loading conditions, which were pin load tension and compression. The fibre path design philosophy was that the fibre continuity should be maintained while the structure could survive the given loading conditions. An unconventional fibre pattern was designed as shown in Figure 7(a). It consists of 6 different layer patterns, which were created under considerations for different loading conditions. A specimen of these 6 layers was printed using glass fibre reinforce Nylon, as shown in Figure 7(b). The unconventional pattern can be clearly seen by the partially transparent specimen under the light, which matches with the design in Figure 7(a). Finally, a lug specimen with total 24 layers was printed out using carbon fibre reinforced Nylon. The resulted thickness of the specimen was 4.05mm.

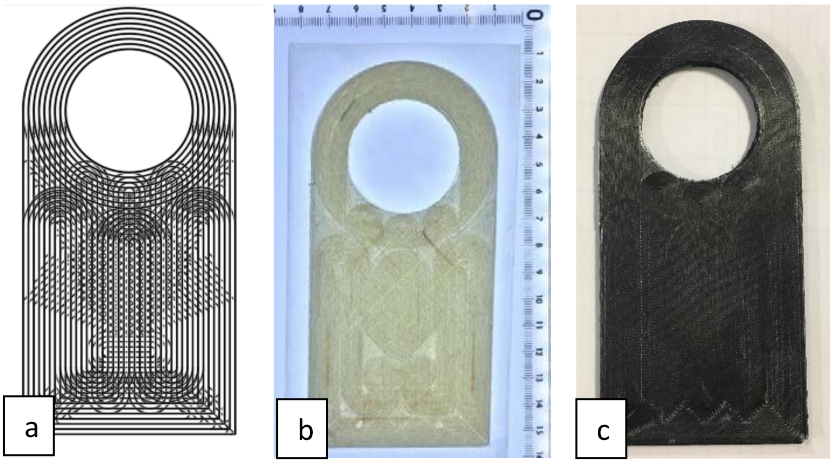

Figure 7 (a) Overlap view of the 6 patterns; (b) the specimen with 6 layers glass fibre reinforce Nylon; (c) the lug specimen with 24 layers carbon fibre reinforced Nylon.

4 CONCLUSION AND FUTURE WORK

Two desktop FDM printers were used to produce continuous fibre reinforced composites. Specimens printed by the Markforged printer were tested in the three point bending test. The flexural strength and modulus of the 3D printed continuous fibre reinforced composites were resulted in a much higher value than the pure printed plastic, but only one third of the properties of the composites material manufactured by conventional processes like prepreg/autoclave. The micro-structure of the printed sample cross-sections were examined by using an optical microscope. A voids content of over 10% was found in the commercial printer printed specimens. The high voids content and low fibre volume fraction are the cause of poor mechanical properties compared to that of conventional carbon fibre reinforced composites material.

The advantage of using 3D printing technique in continuous fibre reinforced composites manufacturing was discussed. With this technique, fibre path tailoring can be achieved. Composite materials can be potentially used in key load carrying structures like aircraft joints and lugs. An open-sourced FDM 3D printer was modified to produce the lug specimen. 6 fibre patterns were designed under the consideration of the given loading conditions. A 24 layers lug structure was successfully manufactured to demonstrate the process. Even though these fibre patterns are only preliminary design, they cannot be produced by any other conventional composites manufacturing process.

In order to improve the quality of the printed composites, a compaction system is under design. A compaction pressure can be beneficial for reducing the voids content and prevent debonding between layers. Post-treatment like reconsolidation using a hot press might also be favourable for improving the quality. A stronger matrix material like PEEK will be furtherly investigated for this process, if the printed part wants to be used in highly loaded applications like aircraft lug structures. Fibre paths optimization and stress analysis are required in the future research, and mechanical testing will be performed to furtherly support the concept.

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