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INVESTIGATION OF FIBER REINFORCED COMPOSITE USING MULTI-MATERIAL 3D PRINTING

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Abstract

Fiber reinforced composite materials have been commonly fabricated by laying and curing the stiff and high strength fibers within tough matrix to enhance the elastic modulus. The strength and elasticity of the fiber reinforced polymers are dependent on the intrinsic mechanical properties of matrix and fiber, the fiber layup pattern as well as the volume percentage of the matrix and fiber. In this paper, the effects of these factors on the 3D printed fiber reinforced composite materials were investigated. The fiber reinforced polymers were fabricated using multi-material inkjet printer with rubbery material as matrix and rigid strong polymer as the fiber reinforcement. Two types of fiber layup configurations and fiber/matrix volume ratios were designed for this study. The experimental result shows that both tensile strength and elastic modulus of the fiber reinforced polymers could be largely enhanced by varying the fiber/matrix ratio and layup pattern.

Introduction

One of the recent development in AM technology is the modelling and fabrication of multi-material component. These developments include synthesizing composite materials using nano-particles and fillers suitable for various AM processing [1-3], or selective laser melting of different metal alloys across layers [4], and 3D inkjet printing of different UV curable photopolymers with the control of depositing selective materials on a droplet scale [5]. This has opened many potentials to utilize the ability to fabricate composite models with complex geometry, without the need of tooling.

There is an increasing trend in the AM research field to strengthen the considerably weak 3D printed polymers through adding in fibers into the feedstock [6-8]. Fibers as reinforcement in composite material has been one of the most commonly use material in the aerospace and defense industry, owing to its high strength, modulus, stiffness and lightweight [9]. In general, the load sharing between the matrix and the reinforcing fiber is critical in understanding the mechanical behavior of a composite. Reinforcement is usually made up of stiffer and stronger material, than the matrix. Thus, reinforcement in the composite could bear a relatively high proportion of externally applied load. The mechanical properties of a fiber reinforced composite are dependent on the volume fraction of the matrix/fiber, shape and orientation of the fiber reinforcement.

In this paper, we aim to investigate the effects of these factors on the 3D printed fiber reinforced composite materials. The fiber reinforced polymers were fabricated using multi-material inkjet printer with rubbery material as matrix and rigid strong polymer as the fiber reinforcement. Two types of fiber layup configurations and fiber/matrix volume ratios were designed to understand the effects on the mechanical performance and the failure mechanism.

Experimental Method

PolyJet 3D printing technology was chosen to fabricate the fiber reinforced composite structure due to its capability to fabricate multi-material component with great controllability. PolyJet 3DP is a material jetting technology that is capable to deposit two or more distinct materials in addition to a support material, simultaneously in high speed. The photopolymers are immediately cured by UV light upon printing. Through manual control of the microstructure and composition of different materials, new types of composite can also be fabricated. Similar to conventional fiber reinforced laminates, long fiber reinforcement can be precisely designed and fabricated using the multi-material PolyJet to obtain wider range of elasticity and tensile strength.

In this research, the matrix of the composite was chosen to be TangoPlus (FLX930), a rubbery flexible material while the stiff Digital ABS (RGD515 and RGD535) was used as the fiber reinforcement material. Digital ABS material has high impact resistance and high elastic modulus while TangoPlus has much lower elastic modulus and toughness but high elongation at break. Thus, high strength Digital ABS is chosen to reinforce and to bear the most of the load of the elastomer TangoPlus.

The fiber reinforced polymers was modelled based on the common continuous fiber composite which involves fibers being in the form of plies, or laminae [10]. Each lamina has thousands of fibers with the same orientation along its thickness in the plane of the sheet and the composite is made up of laminae such that the fibers are oriented differently among the laminae. In this study, two types of fiber configurations were designed using Autodesk Inventor: crisscross (C) which has biaxial-fibers oriented at ±45° (with respect to the loading direction) in every plies, and angle-ply laminates of +45° and -45° (A), as shown in Figure 1. Each structure consists of 4 plies and each ply has a thickness of 0.8 mm. In all configurations, the continuous fiber reinforcements are in the cylindrical shape with 0.5 mm diameter. Both configurations were designed in fiber volume fraction of 10% (I) and 20% (II) to investigate the effects of reinforcement volume on the mechanical properties of the composite.

All the specimens were printed in the Singapore Centre for 3D Printing (SC3DP) Lab at NTU using an Objet500 Connex3 multi-material 3D printer from Stratasys with 'glossy' surface finishing. The specimens were orientated longitudinally along the X-axis of the printing head. After the printing job was done, support materials were removed manually by hand. The leftover support materials on the tensile specimens were cleaned using the recommended water jet cleaning machine. Figure 2 shows the 3D printed specimens for all 4 configurations: AI, AII, CI and CII.

The size and geometry of the specimens, as well as the testing setup were in accordance to the ASTM D-412 which defines the standard tensile test method for vulcanized rubber and elastomers. Uniaxial tensile tests were performed using a Shimadzu AGS-10kNXD universal testing machine, with a 10kN load cell and constant crosshead speed of 5mm/min. Stress-strain curves of various specimens were directly measured and calculated in the integrated Shimadzu Trapezium X testing software. In addition to the crosshead displacement, the strain was also obtained from the displacement measured using a non-contact extensometer, TRViewX, during testing.

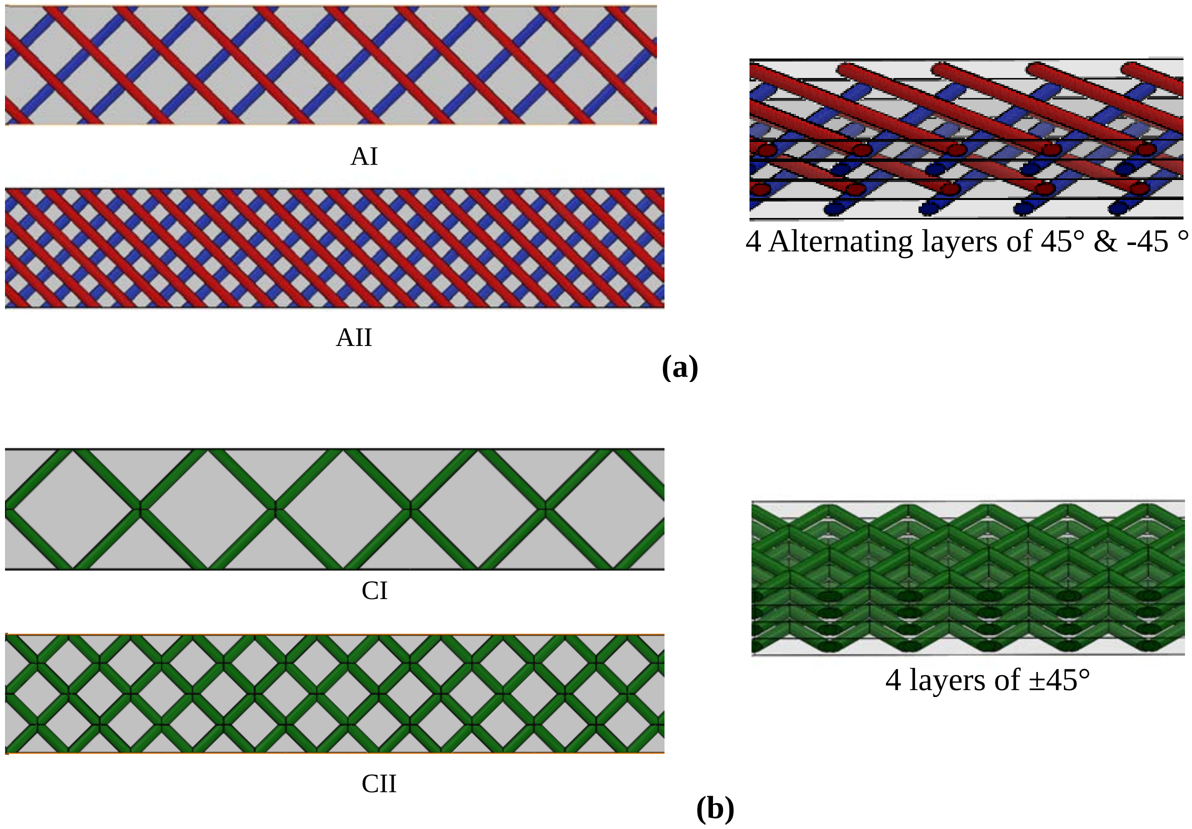

Figure 1. The design configurations for (a) alternated 45° plies (A) structure in 10% and 20% fiber volume ratio, (b) criss-cross (C) structure in 10% and 20% fiber volume ratio

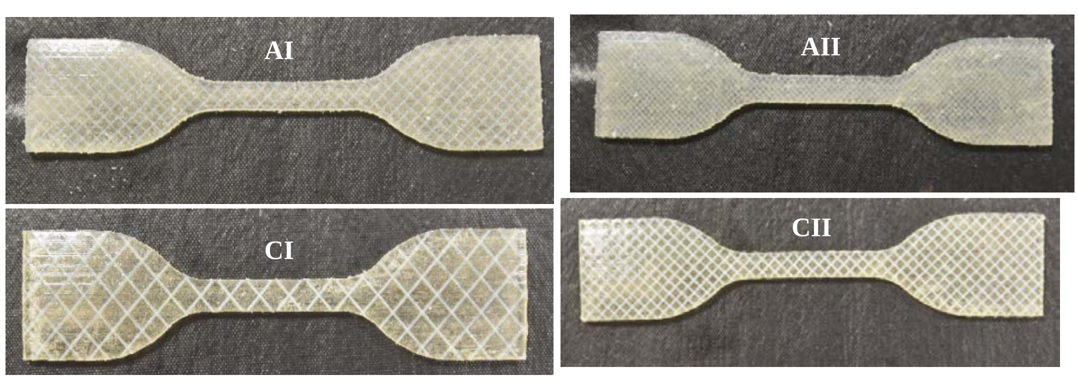

Figure 2. 3D printed specimens of various configurations: AI, AII, CI and CII

Results and Discussion

Using the displacement data from the extensometer, the typical stress-strain curves of the Tango and various configurations of ABS reinforced Tango composite, AI, AII, CI and CII are shown in Figure 3. Figure 4, Figure 5 and Figure 6 show the mean elastic modulus and the elongation at break, respectively. It is observed that the pure Tango has the lowest elastic modulus. The ABS fiber reinforcement increases the elastic modulus significantly. Both AI and CI, which possess 10% reinforcement volume fraction exhibit similar elastic modulus and elongation at break but AI has nearly double tensile strength as compared to CI. On the other hand, even though both AII and CII have the same reinforcement volume fraction of 20%, their mechanical properties under tensile loading do not behave the same way. The elastic modulus of CII is about 1.7 times higher than that of AII while the elongation at break at about 0.7MPa stress for AII is 1.7 times longer than that for CII. Elastic modulus of CII is It is also noticeable that AII is able to maintain its high elongation like its matrix material, TangoPlus while having higher elastic modulus and tensile strength. The higher elongation and high tensile strength of CII and AII mainly attribute to the effectiveness of the high stiffness ABS fiber for crack arresting and blunting. Due to the fiber orientation, CI has the least number of continuous fibers in either +45° or -45° in each ply while AI and CII have the same number of continuous fibers in each ply. AII has the highest number of fiber reinforcements in each ply. It therefore implies that the shorter the distance in between the fibers (i.e., the higher number of fibers) in each ply, the greater the elongation at break.

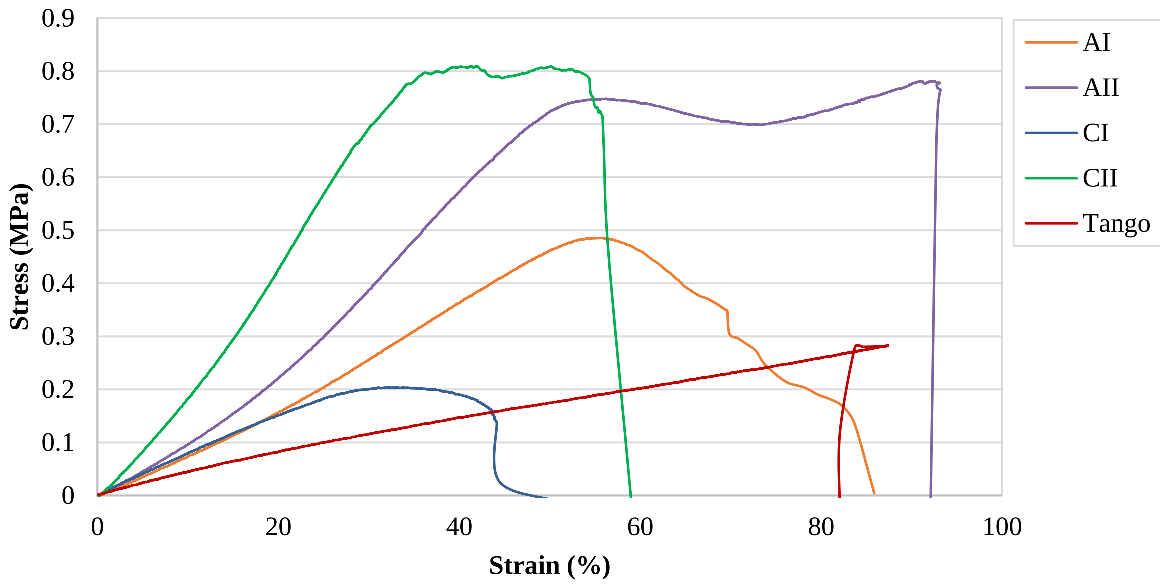

Figure 3. Typical stress-strain curves of Tango, AI, AII, CI and CII

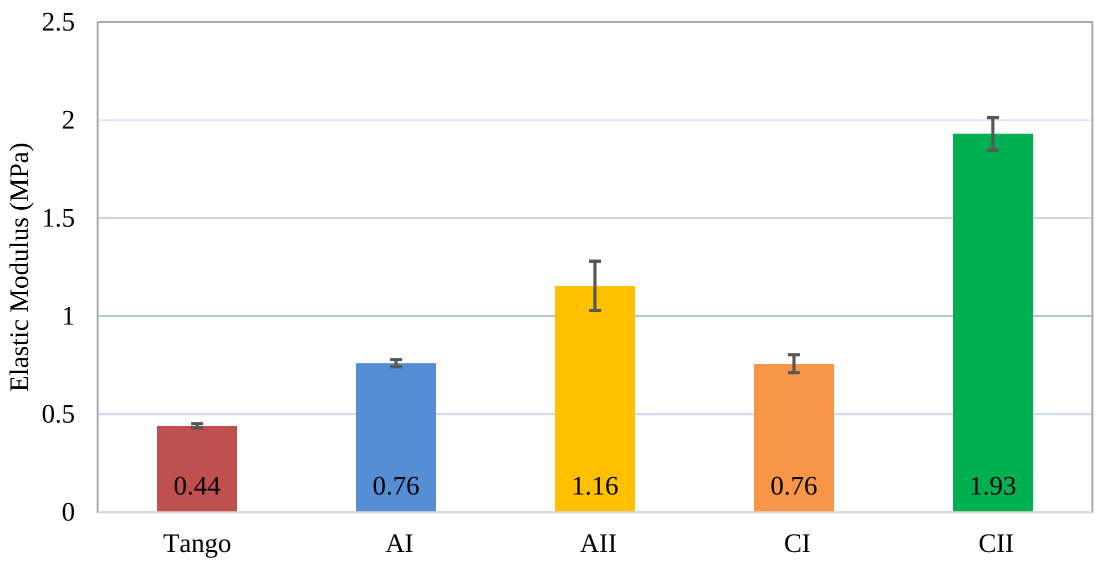

Figure 4. Mean elastic modulus of Tango material and 4 configurations (error bars denote the standard deviation)

Upon applying the tensile load, pure TangoPlus material extended till crack formation before final rupture. However, for the reinforced specimens, we clearly see that the influence of the stiffer ABS reinforcement in postponing the crack growth by arresting the crack. Cracks typically initiated at the weaker matrix zone at both edges and the cracks did not cause immediate rupture as they were arrested by fibers. The relatively poor mechanical performance of CI could be affected by the fiber placement especially at the edges, which might have resulted in crack initiation and quicker rupture at a lower strength as compared to the Tango matrix.

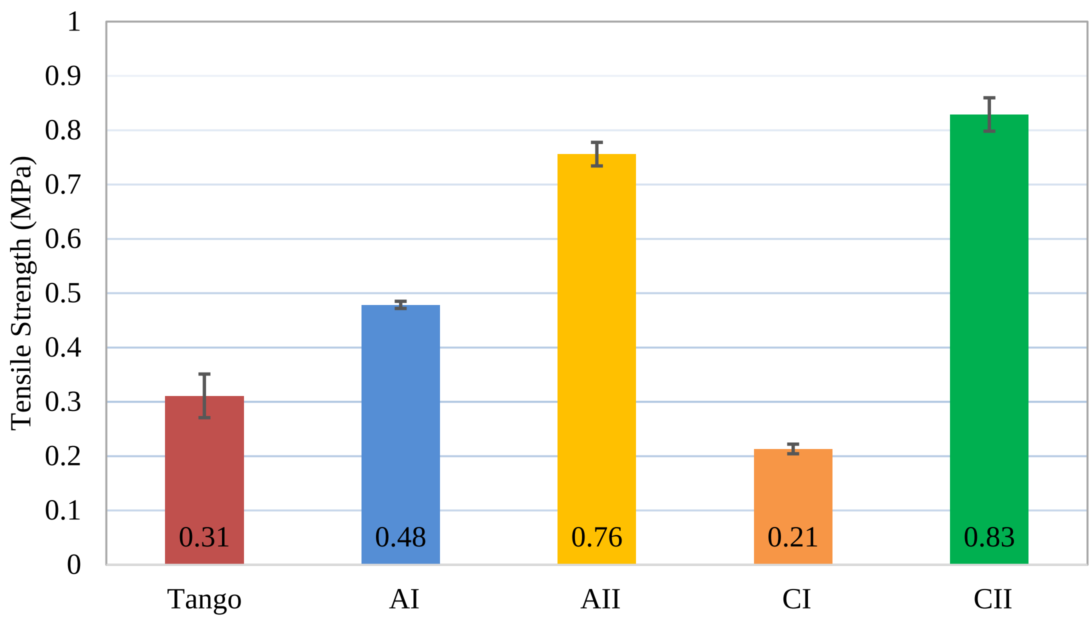

Figure 5. Tensile strength of Tango material and 4 configurations (error bars denote the standard deviation)

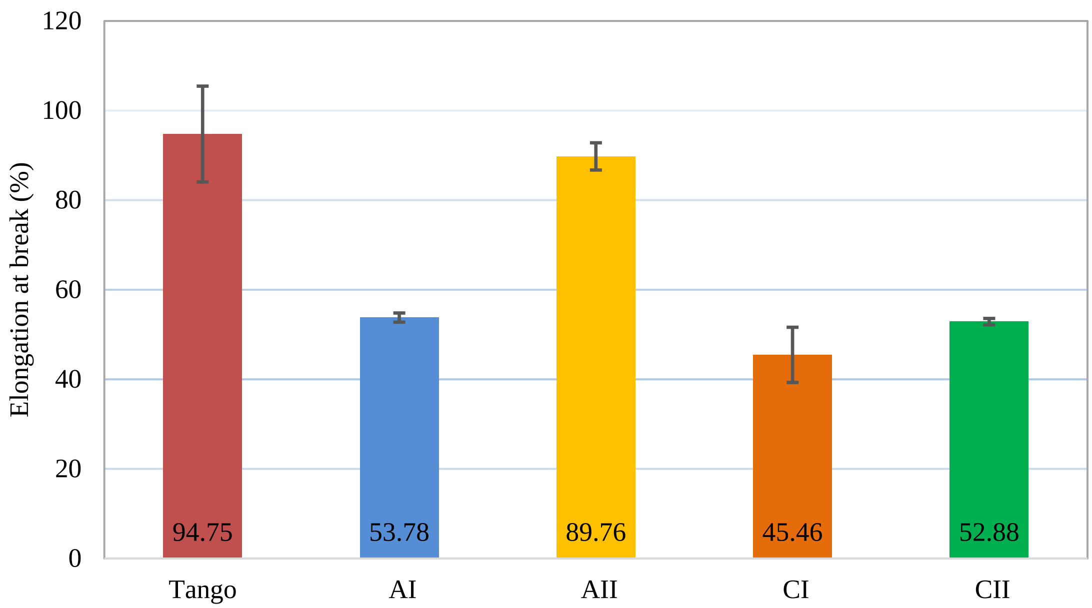

Figure 6. Elongation at break of Tango material and 4 configurations (error bars denote the standard deviation)

Conclusion and Future Works

In conclusion, the fiber reinforced polymers fabricated using multi-material inkjet printer with rubbery material as matrix and rigid strong polymer as the fiber reinforcement were found to be feasible to produce materials that have higher strength with high elongation properties. Two types of fiber layup configurations and fiber/matrix volume ratios have been designed for this study and the experimental result shows that both tensile strength, elastic modulus as well as elongation at break of the fiber reinforced polymers could be varied and controlled by varying the fiber/matrix ratio and fiber layup pattern. The fracture of the structure was also shown to be affected by the fiber layup pattern as well as the density of the fibers across each ply. These designs have shown the possibility to have combination of high strength and stiffness from the fiber and of elasticity from the matrix. The fibers also help to prevent sudden failure or rupture by slowing down the crack propagation. For the future works, quasi-isotropic laminates could be considered for isotropic properties.

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