Comparison of strength of 3D printing objects using short fiber and continuous long fiber

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Abstract. In this research, composite materials were used to improve the strength of FDM 3D printed objects. The nanocomposites made from polylactic acid as matrix and multi-wall carbon nanotube as filler, short carbon fiber reinforced composite and continuous carbon fiber reinforced composite were prepared, and tensile test was carried out. As a result, the continuous fiber reinforced material exhibited tensile strength of about 7 times and elastic modulus about 5 times that of the other two materials. The strength was greatly improved by using the continuous fiber. The fracture surface after the test was observed using a scanning electron microscope. The result of observation shows that adhesion between the laminated layers and the relationship between the fiber and the matrix are bad, and improving these are necessary to increase strength.

Comparing those materials, it is possible to improve the strength in some degree by using short fiber while maintaining ease of printing. On the other hand, by using continuous fiber it can be achieved significant strength improvement while printing was complicated.

1. Introduction

In recent years, 3D printers have attracted attention as multi-product small-volume production technology. 3D printing is one of Additive Manufacturing (AM) technology [1]. In modelling by 3D printers, the original three-dimensional shape (usually 3D CAD data) is divided into two-dimensional layers with constant thickness. The 3D printer makes and stacks the layers to create the original three-dimensional shape. By using a 3D printer, it is possible without metal mould to make complex parts which was difficult to shape with conventional processes. In other words, it is possible to reduce the time and cost to make metal mould so it is suitable for small lot production.

Depending on the forming method of each layer, 3D printers can be classified into various types. For example, there are Stereo Lithography (STL) which curing a photo-curable resin with laser, Selective Laser Sintering (SLS) which sintering a powder, Fused Deposition Modelling (FDM) which laminates thermoplastics, etc. Among them, we focused on FDM. The FDM uses thermoplastics formed into a wire shape which is called filament. The printer melts filament and extrudes it onto a forming table to create a three-dimensional object. The FDM has some advantages. Firstly, it have a simple mechanism that melt and extrude resin. It does not require expensive parts such as laser, so that the FDM system is relatively inexpensive. Secondly, thermoplastics can be used. The photo-curable resins used in the STL are inferior in strength and durability and the powder materials used in the SLS are difficult to handle. However, the thermoplastics used in FDM has enough strength and durability and it is easy to handle. Therefore, it is possible to manufacturing not only prototypes but practical parts easily.
However, the objects made by FDM does not have enough strength for mechanical parts. Therefore, we try to improve strength by adding carbon nanotube (CNT). The CNT has good mechanical property and can improve strength. It is also possible to impart functionality such as conductivity by adding CNT [2]. As another method, fiber reinforced composites are tried. In some examples, the strength of 3D printed objects is improved by using carbon fiber with excellent specific strength [3, 4]. Depending on the length of the carbon fiber, it can be divided into short fiber and continuous fiber. In this study, we compared 3D printed objects using MWCNT, continuous carbon fiber and short carbon fiber and consider strength and usefulness of them.

2. Introduction

2.1. Material
It is used that polylactic acid (PLA, REVOIDE 110, Zhejiang Hisun Biomaterials Co., Ltd.) as a matrix and multi-wall carbon nanotube (MWCNT, NC 7000 TM, NANOCYL SA.) as filler to make PLA/MWCNT nanocomposite. These materials were kneaded using a twin-screw kneading extruder (ZSK 18 MEGAlab, Coperion Gmbh) and formed into filament with 1.75 mm in diameter. The mass concentration of MWCNT were 0 (neat PLA), 0.5, 1.0, 2.0 and 3.0 wt%.

Commercial materials were used to prepare test pieces made from continuous carbon fiber reinforced thermoplastic (continuous CFRTP) and short carbon fiber reinforced thermoplastic (short CFRTP). The short carbon fiber reinforced composite (ONYX, Markforged), neat resin (NYLON, Markforged) and continuous carbon fiber reinforced composite (carbon fiber, Markforged) was used.

2.2. 3D printing
Tensile test pieces were made by 3D printing. SCOVOO X9 (Abee Co.) was used for printing of PLA/MWCNT nanocomposite and Markforged X7 (Markforged Inc.) was used for printing of continuous and short CFRTP. The test piece shape is shown in Fig. 1 (a) and (b). The specimen shape is different due to the limitation by the performance of the 3D printer. For PLA/MWCNT, smaller one was chosen to avoid warp and print quickly. The PLA/MWCNT has three outer walls and fills inside alternately at 45 degrees and -45 degrees. As shown in fig. 2, in the continuous CFRTP, carbon fibers oriented in the load direction were printed in the center and the outside was covered with neat resin (NYLON) or short fiber reinforced composite (ONYX). The short CFRTP was printed in the same way as the PLA composite using the short fiber reinforced composite (ONYX).

![Figure 1. Dimension and shape of specimen (mm)](image)

![Figure 2. Continuous carbon fiber reinforced thermo-plastic](image)
2.3. Tensile test
A tensile test was carried out using the prepared test piece. A universal testing machine (Auto graph AG-1 100 kN, Shimadzu Co.) was used for the test. The crosshead speed was set to 1 mm / min. In order to measure the strain, non-contact digital video extensometer (TRviewX 240S, Shimadzu Co.) and crosshead displacement was used.

2.4. Image observation
Image observation of the fracture surface was carried out. The scanning electron microscope (JSM-7001FD, JEOL Ltd.) was used. Trimming, marking and colour adjustment were performed on the image using painting software.

2.5. Observation of carbon fiber
The 3D printed object using carbon fiber were heated in an electric muffle furnace to remove the matrix. Heating was carried out at 550 °C for 30 minutes. The volume contents of the fiber were measured by comparing the weights before and after. The remaining carbon fiber was taken out and the fiber length was measured by an optical microscope.

3. Results and discussion
3.1. Mechanical properties
The stress-strain diagram of the PLA/MWCNT composite is shown in the fig. 3. In PLA/MWCNT, the stress increased almost linearly until fracture. The breaking strain was about 1 ~ 2%, and no stress reduction was occurred. Compared with neat PLA, the elastic modulus was not greatly improved but the tensile strength was improved and increased by 48% when 1wt% of MWCNT is added. In that case, the tensile strength was 53 MPa and the Young's modulus was 3 GPa. Until 1 wt%, the tensile strength was improved as more CNT is added, but strength was decreased when 3wt% was added. It is because the aggregation of MWCNT. The aggregations are considered to act as internal defects of the material. The cross section of the PLA/MWCNT specimen is shown in the fig. 4. Using a microtome (RMD-5, Nihon Microtome Laboratory, Inc.), a thin piece was cut out from the cross section of the test piece and photographed with a microscope. The white spots are voids and the black spots are aggregates. As a result of measuring the area using the image processing software, both the area and the number of the aggregates increased with the increase of the addition amount of MWCNT. The image of the specimen fracture surface is shown in the fig. 5. In the SEM image, it was confirmed that the MWCNTs were dispersed, but there are some aggregates. Several voids were generated. These were made when overlaying. There was no crack between the laminated layers, and the interlayer adhesion may be good.

\[\text{Figure 3. Stress-strain curve of PLA/MWCNT} \quad \text{Figure 4. Aggregates and voids}\]
As a result of the measurement, the weighted average fiber length of the short carbon fiber was 0.13 mm. The stress strain diagram of short CFRTP (ONYX) is shown in the fig. 6 (dashed Line). At first, it showed a linear relationship and the elastic modulus was 2 GPa. But the gradient decreased from about 1% strain, and finally the breaking strain reached 10%. The tensile strength was 45.5 MPa. This is lower than the neat resin material (NYLON) that is described in the catalogue. The fracture surface is shown in the fig. 7 and fig. 8. There were some fiber which was pulled out of the matrix in fig. 8. This indicates poor adhesion between the fiber and the matrix. It is thought that this is the cause of the deterioration of the mechanical properties of the short CFRTP. In addition, as shown in fig. 7, the fracture surface has a step for each laminated layer. This is because adhesion between the laminated layers was poor. It also affected the mechanical properties. With the short carbon fiber reinforced material, it was seemed that the fiber orientation was different for each laminated layer in fig. 8, and the fiber were oriented along the resin extrusion direction. It is because the short fiber dispersed in the material are oriented in one direction through the process of forming filaments and extruding from the nozzle.
The stress-strain diagram of the continuous fiber reinforced material is shown in the fig. 6 (solid line). Looking at the stress-strain diagram, the slope varies at 0.5% strain. Also, the curve was disturbed around 3 – 4% strain. In the continuous CFRTP, the continuous fiber reinforced material is covered with a neat resin or a short fiber reinforced material to improve surface roughness and so on. It is thought that the change and disorder of the inclination occurred due to breakage of the interface between the fiber and the matrix and peeling of the interface between the outer layer and the strong central layer. The test piece after the test is shown in the fig. 9. The specimen did not break completely and the center continuous reinforcing fiber part and the outer peripheral part peeled at the boundary. This material had tensile strength of 341 MPa and elastic modulus of 10 GPa. These were much higher than that of short CFRTP. However, as mentioned above, the adhesion between the layers are weak, and destruction has also occurred from there. By improving this, it is considered that the mechanical properties of this material can be further improved.

3.2. Comparison by material

The tensile strength and elastic modulus of each material prepared in this study are shown in the fig. 10. The continuous CFRTP has the strongest elastic modulus and tensile strength. The FDM 3D printer extrudes the material little by little while moving the nozzle, so it can control the internal structure. For example, it is possible to place a lot of fiber where the stress concentrates or align fiber along load direction. Therefore, using in the FDM, parts with high mechanical properties can be manufactured. However, to use continuous fiber reinforced material in 3D printer, modified equipment must be used. It require special nozzle to extrude fiber and mechanism to cut fiber.

The short CFRTP and PLA/MWCNT are inferior in mechanical properties compared to the continuous. But they can be printed with conventional 3D printers without special modifying. Especially the nanocomposites demonstrate its effect by adding a small amount. The mass concentration of fiber was 35.7 wt% for continuous CFRTP and 14.3 wt% for short CFRTP, but MWCNT was 3wt% or less. Generally, the smaller the amount of reinforcement, the more easy to print. In fact the PLA/MWCNT nanocomposite can be printed with commercially available 3D printer without special modified in this study. Continuous fiber and short fiber material should each have merits and demerits and should be used properly.

![Figure 9. The broken specimen (continuous CFRTP)](image)

![Figure 10. The tensile strength and elastic module](image)
4. Conclusion

In this paper, mechanical properties of 3D printed object using PLA/MWCNT nanocomposite, short CFRTP and continuous CFRTP were evaluated. Nano fiber and short fiber were mixed in the filaments and replace the conventional neat filament. The continuous fiber was mixed with the resin at the nozzle. Experimental results show that the continuous fiber reinforced material has a tensile strength of 341 MPa, a short fiber of 47 MPa and a nanocomposite of 53 MPa. The elastic modulus was about 10 GPa for continuous fiber, about 2 GPa for short fiber and about 3 GPa for nanocomposite. By observation of the fracture surface, it was shown that adhesion between layers and interfacial strength between fiber and matrix affects strength in fiber reinforced materials. And in the nanocomposite, strength decreases due to formation of aggregates. Continuous fiber reinforced materials are superior in strength, but it require special equipment to print. However, nanomaterials improve strength and can be replaced from neat materials without modification. By properly using both, it leads to the manufacture of better parts.

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