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Research

Preparation and Properties of 3D Printing High Performance Polymer Composite for Aerospace Application

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Abstract: Composite materials are essential material for aircraft structures. Their main advantage is connected to the possibility of deeply reducing weight and costs by maintaining high performances in terms of strength and security. In this study, dumbbell shaped nylon-6 (PA-6)/carbon nanotube (CNT) composite wires were prepared using nylon as matrix and carbon nanotubes as reinforcement by twin-screw extruder. The prepared PA-6/CNT composite wires were printed into dumbbell shaped spline test pieces using a raised 3D printer through melt deposition molding. The properties of nylon-carbon nanotube composite were tested, and the effects of different proportions of carbon nanotubes on the properties of nylon-carbon nanotube composite were studied. The experimental results reveled that CNTs effectively enhanced the mechanical properties of nylon-6, such as the tensile strength and Young's modulus. When the mass fraction of CNTs is 0.2%, the tensile strength is the highest, which is 165% higher than pure nylon. When the mass fraction of CNTs is 1%, the Young's modulus is the highest, which is 83% higher than pure nylon. The addition of carbon nanotubes also increased the melting point of nylon-6. This study has important theoretical significance and engineering value for the application of non-metallic matrix composite in the aerospace industry.

Keywards: Polymer Composite; Carbon Nanotube (CNT); Nylon-6; 3D Printing; Aerospace

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1. Introduction

Composite materials are made by combining two or more natural or artificial elements with different physical or chemical properties that, as a result of molecular pairing, are much stronger [1,2]. Composite materials not only retain the unique advantages of each component material, but also complement each other, so that it can play a better role in the application field, and bring maximum benefits [3,4]. Composite materials are widely used in the aerospace industry such as military aircraft, civil aircraft, rockets, and missiles, because of their high strength to weight ratio, corrosion resistance, heat conduction, vibration reduction, high temperature resistance, high degree of freedom design, and easy machinability [5-7]. According to the properties of the composite prepared by us, its applications are determined. For example, reinforcements with good conductivity can be used in on-board electronic components. The products made of non-metallic materials with good mechanical properties such as nylon and other materials, have high specific modulus, strength, and higher fatigue strength. Non-metallic matrix composite for aviation are used for large-scale loadbearing structural parts, aircraft internal parts, and electronic components [8,9]. In conclusion, composite material is essential for modern aircraft manufacturing [10,11].

3D printing is different from the traditional manufacturing industry, which needs to design molds, saving time and economic cost to a great extent [12,13]. 3D printing (3DP) belongs to additive manufacturing, which belongs to a group of technologies that enable digital fabrication [14,15]. Its raw materials consist of filaments, powder plastics, resins, and metals. It is based on digital models, and products are produced by layer-by-layer printing. 3D printing has high flexibility and reduced material loss in production (just change the digital model to process articles of any shape) [16,17]. 3D printing technology has shown promising application advantages in many fields such as medicine and pharmaceuticals, warships, electronics, aviation, and aerospace manufacturing that has brought positive influence in promoting industry development and innovation [18,19].

2. Experiment

2.1 Experimental Materials and Equipment

The materials and equipment used in this experiment is shown in Tables 1 and 2.

Table 1. Experimental Materials

Material	Manufacturer
Nylon-6	Yuyao Chihong Plastic Chemical Co., Ltd.
Carbon Nanotube (CNT)	Shenzhen Suiheng Technology Co., Ltd.
Polyvinyl alcohol	Deli Group Co., Ltd.

Table 2. Experimental Equipment

Equipment name	Manufacturer
Raise3D Pro2	Shanghai Fuzhi Information Technology Co., Ltd.
Electric heating blast drying oven	Changge Yingong Machinery Manufacturing Co., Ltd.
Computerized tensile testing machine	Shanghai Songdun Instrument Manufacturing Co.,Ltd.
Muffle furnace SY-MF-700	Hebi Robot Instrument Manufacturing Co., Ltd.
Electronic balance	Shanghai Lichen Bangxi Co., Ltd.
Twin screw extruder equipment	Taizhou Kedi Electrical Equipment Co., Ltd.

2.2 Pure Nylon-6 Tensile Spline 3D Printing

The extruder machine was set up to make the pure nylon tensile spline. The data used to prepare nylon wire is drawn in Table 3. Once finished, it was put into an electric blast drying box, and dried it for more than four hours to prepare pure nylon wire (Figure 1. a).

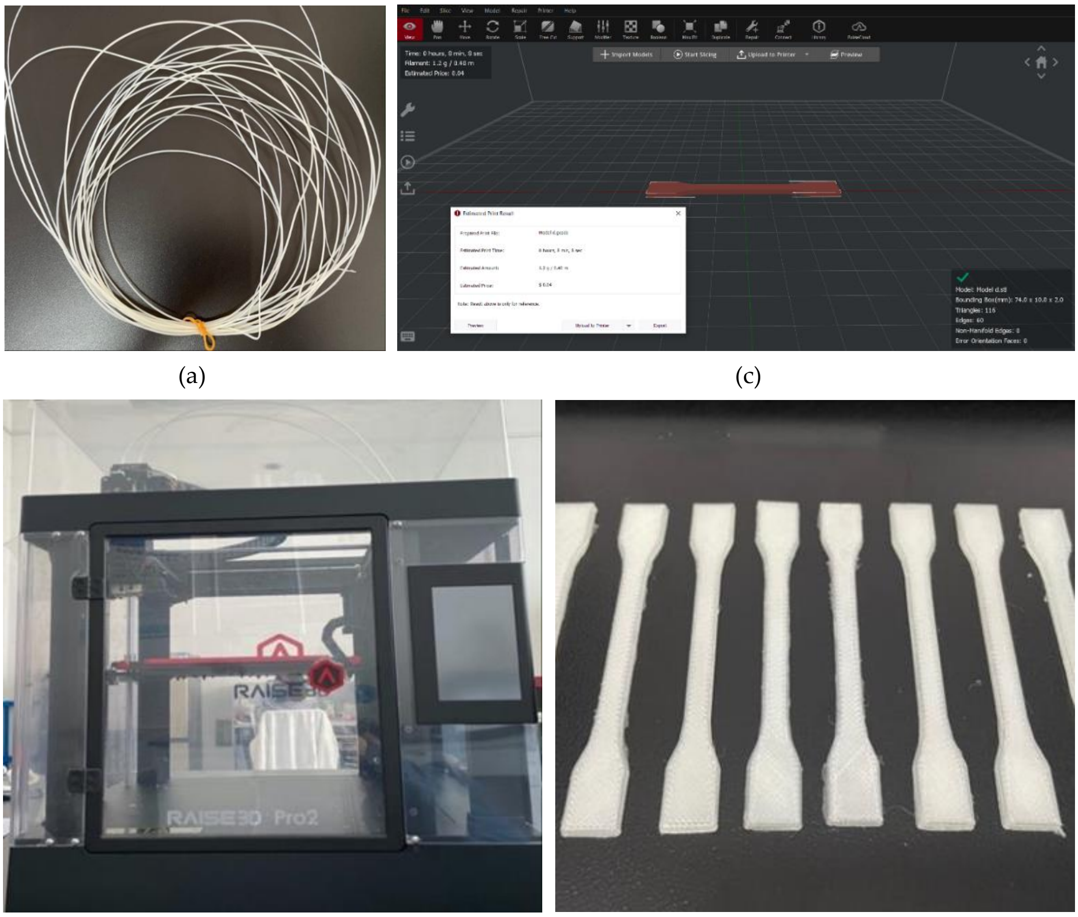
Table 3. Data used in extruder machine to make nylon-6 wire

Process Parameters	Values
Spindle speed	25 rpm
Feeding port speed	16 rpm
Temperature control zone 1	180^0C
Temperature control zone 2	190^0C
Temperature control zone 3	200^0C
Die zone 1	210^0C

Printed nylon-6 wire and CAD 3D model placed into the 3D printer to print the nylon-6 tensile spline. The data were used to the 3D printer to print nylon-6 tensile spline are shown in Table 4.

Table 4. Data used in 3D printing machine to print nylon-6 tensile spline

Process Parameters	Values
Left nozzle temperature	250^0C
Hot bed temperature	70^0C
Rising temperature	250^0C



Time: 0 hours, 0 min, 0 sec
Filament: 1.2 g / 0.40 m
Estimated Price: 0.04

Model: Model d.stl
Bounding Box(mm): 74.0 x 10.0 x 2.0
Triangles: 116
Edges: 60
Non-Manifold Edges: 0
Error Orientation Faces: 0

(a) (c)

(b) (d)

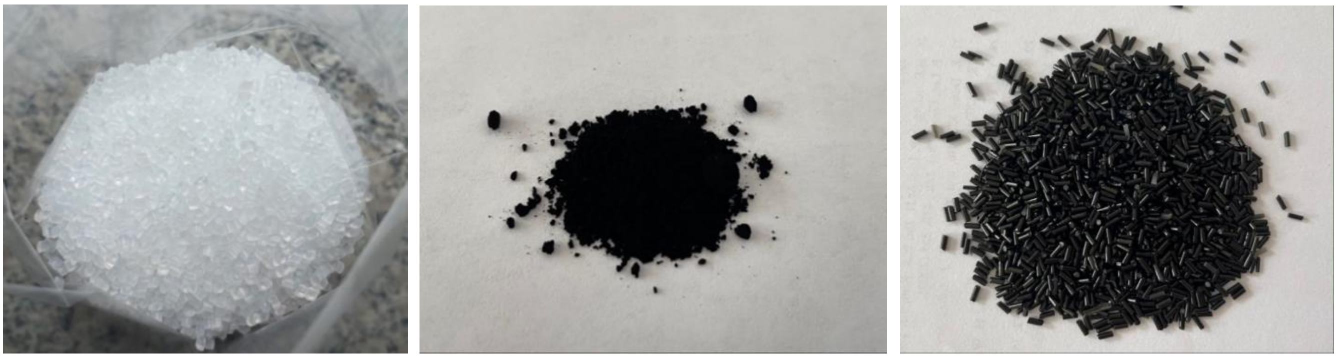
Figure 1. Pure nylon tensile spline 3D printing: (a) Pure nylon wire, (b) 3D printer, (c) Specimen modelling process in CAD software, (d) Pure nylon-6 tensile parts

2.3 Preparation of nylon-6/CNT Composite

To prepare the nylon-6/CNT composite, 198g nylon-6 particles and 2g CNT materials were weighed. Added a proper amount of nylon-6 particles in the left inlet and a proper amount of carbon nanotube materials in the right inlet. The right discharge port extruded the mixed composite wire. Data used in the extruder equipment to prepare the nylon-6/CNT Composite is shown in the Table 5.

Table 5. Data used in extruder machine to prepare the composite

Process Parameters	Values
Spindle speed	25 rpm
Feeding port 1 speed	16 rpm
Feeding port 2 speed	10 rpm
Temperature control zone 1	200^0C
Temperature control zone 2	210^0C
Temperature control zone 3	220^0C
Nose zone 1	230^0C



(a) (b) (c)

Figure 2. Preparation of nylon-6/CNT Composite: (a) Four crystal morphologies of carbon crystals (b) Multi-walled CNT (c) Composite particles

2.4 3D Printing Composite Tensile Spline

After cleaning, the prepared nylon-6/CNT composite particles were placed into an extruder to extrude the wire rod. The data used to prepare nylon-6/CNT composite wire is drawn in Table 6. Once finished, dried it for more than four hours to prepare the composite wire (Figure 3. a).

Table 6. Data used to extruder machine to make nylon-6/CNT composite wire

Process Parameters	Values
Temperature control zone 1	190^{0}C
Temperature control zone 2	200^{0}C
Temperature control zone 3	210^{0}C
Head zone 1	225^{0}C

Placed the prepared nylon-6/CNT composite wire into a 3D printer for printing and CATIA 3D model to print the nylon-6/CNTs tensile spline. The data used to print the nylon-6/CNT composite tensile spline is shown in Table 7.

Table 7. The data used to 3D printing machine to print nylon-6/CNT composite tensile spline

Process Parameters	Values
Left nozzle temperature	250^{0}C
Hot bed temperature	50^{0}C
Rising temperature	250^{0}C

2.5 Injection Molding Composite Tensile Splines

To prepare injection molding composite tensile spline, placed the composite materials to injection molding machine, started injection molding, waited for several seconds, and after successful injection molding took off the injection tensile parts. By changing the ratio of nylon-6 particles to carbon nanotubes, prepared the injection molded test pieces with mass fractions of 0%, 0.1%, 0.2%, 0.5% and 1%.

(a) (b)

Figure 3. 3D Printing composite tensile spline (a) Nylon-6/CNT composite wire (b) Composite 3D printed tensile parts

By changing the ratio of nylon 6 particles to carbon nanotubes, the above steps were repeated to prepare 3D printed test pieces and injection molded test pieces with mass fractions of 0.1%, 0.2% and 0.5%.

2.6 Mechanical Properties Test

Tensile tests were carried out on the prepared pure nylon tensile parts (Figure 4. a), nylon-6/CNT composite tensile parts (Figure 4. b), and injection molded composite tensile parts. Clamped both sides of the dumbbell piece to the upper and lower jaws of the tensile testing machine (Figure 4. c). Set the parameters to the control section. When the experiment finished, calculated the physical parameters tensile strength, elongation at break, Young's modulus to draw the diagrams.

(a) (b)

Figure 4. Mechanical properties test: (a) Pure nylon-6 tensile parts (b) Nylon-6/CNT composite tensile parts

3. Results and Discussion

The data in the tensile testing machine were copied to the computer, sorted in excel, and the stress and strain was calculated. The maximum stress-tensile strength was obtained by sorting, and the corresponding maximum strain-elongation at break recorded. The image was drawn using Origin-2018 software, with strain as abscissa and stress as ordinate, and the following image has generated. As shown in Figure 5, the five curves represent the stress and strain of 3D printed test pieces with carbon nanotubes of 0%, 0.1%, 0.2%, 0.5%, and 1% respectively. It can be seen from the Figure that with the addition of carbon nanotubes, the composite has greater tensile strength than pure nylon, and the stress required for breaking is greater, among which the nylon-6/CNT composite with mass fraction of 0.2% has the highest tensile strength.

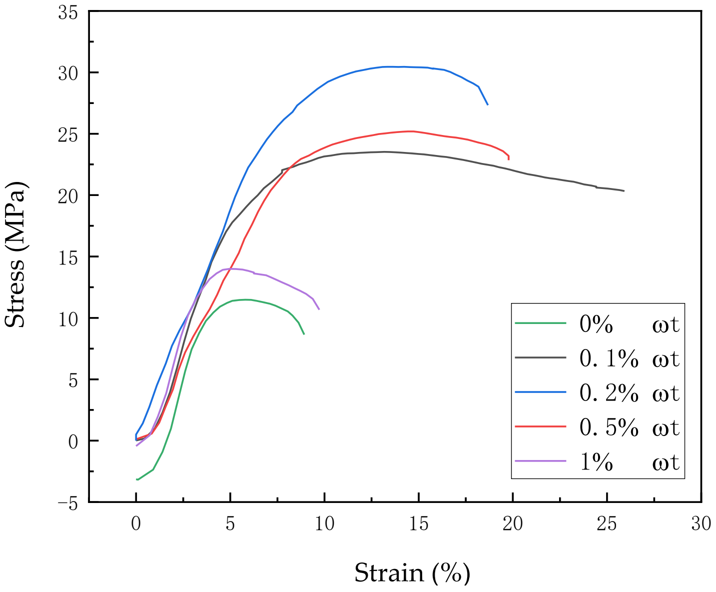


Figure 5. Stress-strain diagram of PA-6/CNT composite with different mass fractions

3.1 Tensile Strength

Figure 6 is the tensile strength curve of PA-6/CNT composite with different mass fractions. It's clearly seen from the Figure 6 that the tensile strength of composite after adding carbon nanotubes is higher than that of pure nylon in different proportions, and it gradually increases with the increase of the proportion of carbon nanotubes. The tensile strength is the highest when the proportion of carbon nanotubes is 0.2% is about 41.762 MPa, but the tensile strength decreases when the proportion of carbon nanotubes continues to increase. Therefore, proper content of carbon nanotubes can effectively enhance the mechanical strength of nylon. After adding carbon nanotubes, the tensile strength can be increased by up to 165%.

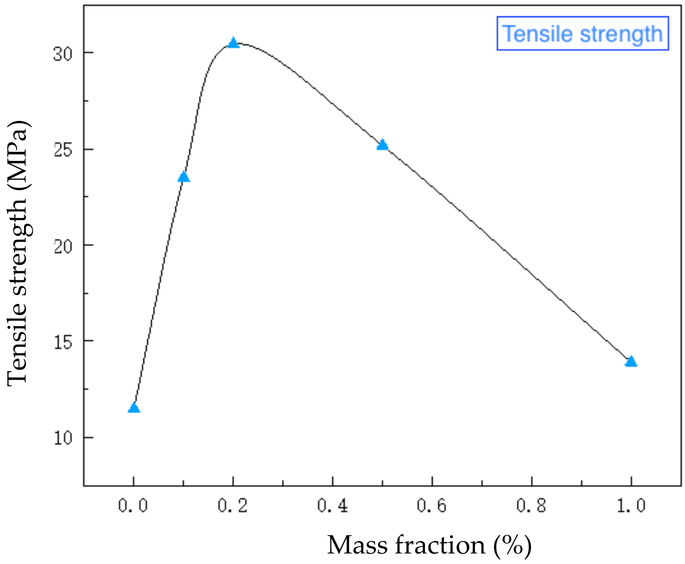


Figure 6. Tensile strength of 3D printed PA-6/CNT composite with different mass fractions

Figure 7 shows the effect of different carbon nanotube content on tensile strength in injection molding. As well as the tensile strength of injection molding and 3D printing, the graph shows that after adding carbon nanotube materials, the tensile strength of composite materials with two manufacturing processes exceeds that of nylon, and when the mass fraction of carbon nanotubes is constant, the tensile strength of injection molding parts is higher than that of 3D printing process. It can be seen from the Figure 7 that the tensile strength of composite with mass fraction of 0.2% is the highest, but the tensile strength tends to decline after the proportion of carbon nanotubes continues to increase. Among them, the tensile strength of pure nylon injection-molded tensile parts is 28.474 MPa, and the tensile strength of 0.2% composite is 41.762 MPa. Experiments show that the tensile strength can be increased by 46.7% after adding carbon nanotubes.

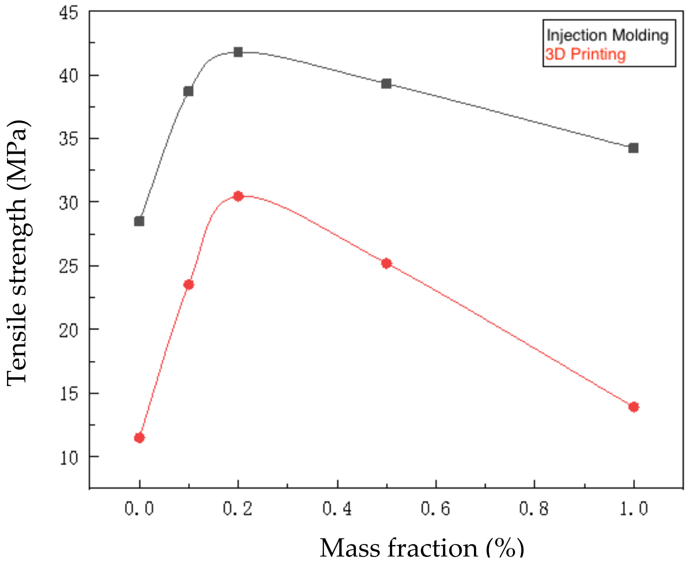


Figure 7. Comparison of tensile strength between 3D printing and injection molding

3.2 Elongation at Break

Figure 8 shows the elongation at break of PA-6/CNT composite with different mass fractions. Elongation at break refers to the ratio of deformation degree to original length when tensile parts are broken. It's clearly seen from the Figure 7 that as the carbon nanotube content increases, the amount of deformation when the composite material is broken gradually increases. When the mass fraction reaches about 0.5%, the elongation at break reaches the maximum, and then decreases with the increase of carbon nanotubes. It can be seen that proper amount of carbon nanotubes enhances the toughness of nylon-6, but excessive amount will lead to increased brittleness.

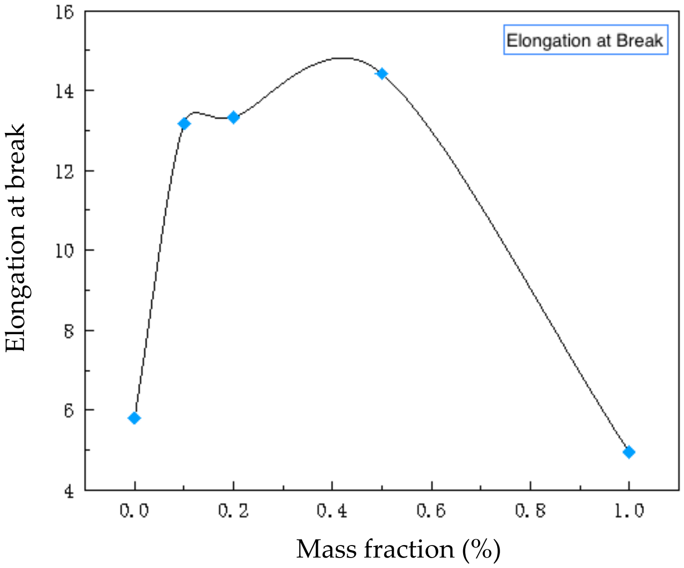


Figure 8. Elongation at break of PA-6/CNT composite with different mass fractions

3.3 Young's Modulus

As shown in Figure 9, reflecting the Young's modulus of 3D printed PA-6/CNT composite with different carbon nanotube mass fractions. Young's modulus of elasticity reflects the ability of materials to resist deformation. It can be seen from Figure 9 that with the increase of the proportion of carbon nanotubes, Young's modulus of composite increases significantly, which makes nylon materials have more impact resistance, thus being applied to the aerospace industry.

The different characteristics of the composite material for injection molding are depicted in Figure 10. Compared with the parts processed by 3D printing, injection molding has a closer combination of dissimilar materials. Therefore, the parameters are slightly better than fused deposition molding. It can be seen from the Figure 10 that with the addition of carbon nanotubes, the tensile strength of the composite increases correspondingly. The nylon-6/CNT composite injection molded parts with mass fraction of 0.2% has the highest tensile strength, similar to 3D printing.

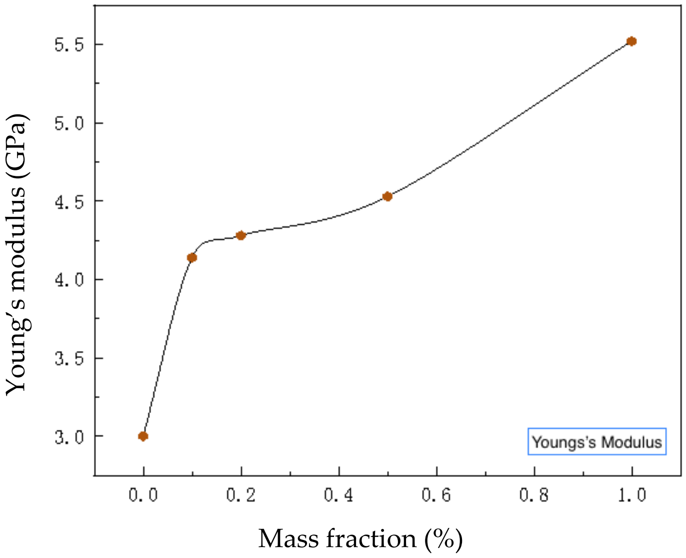


Figure 9. Young's modulus of 3D printed PA-6/CNT composite with different mass fractions

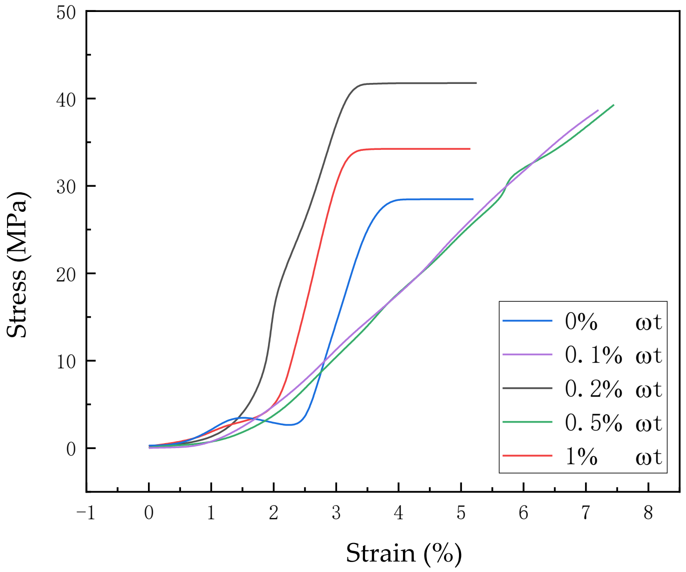


Figure 10. Stress-strain diagram of injection molded PA-6/CNT composite with different mass fractions

4. Conclusion

In this experiment, two methods were used to prepare tensile parts (1) 3D printing, (2) injection molding for the PA-6/CNT composite materials. The experimental results shows that carbon nanotubes effectively enhance the tensile strength and Young's modulus of nylon-6, and the composite materials have more excellent properties than single materials, and can give full play to the characteristics that raw materials don't have. With the increasing of the proportion of carbon nanotubes, Young's modulus of composite increases significantly, which makes nylon materials have more impact resistance, thus being applied to aerospace fields. Based on the findings, the following conclusions can be drawn:

1. The experimental comparison of several mass fractions shows that the tensile strength of composite is the highest when the mass fraction of carbon nanotubes is 0.2%. When the mass fraction exceeds 0.2%, the tensile strength shows a downward trend.
2. 3D printed PA-6/CNT composite with mass fraction of 0.2% has the highest tensile strength is about 41.762 MPa. Compared with pure nylon, the tensile strength of 3D printed nylon-6/CNT composite can be increased by up to 165%. Injection molding is denser than 3D printing parts, so it has better mechanical, at the same time it has higher brittleness. Compared with pure nylon, the tensile strength of injection molded nylon-6/CNT composite can be increased by 46.7%.

At the same time, after adding carbon nanotubes, the melting point of nylon increased slightly from 220°C to 250°C, an increase of 13.6%.

3. 3D printed and injection molded PA-6/CNT composite Young's modulus are quite similar, with mass fraction of 0.2% has the highest Young's modulus.
4. When PA-6/CNT composite mass fraction reaches about 0.5%, the elongation at break reaches the maximum, and then decreases with the increase of carbon nanotube. Therefore, proper amount of carbon nanotubes can enhance the toughness of nylon.

Author Contributions:
Haque Md Imdadul: Conceptualization, Methodology, Writing—Review and Editing.
Rana Ruhul Amin: Formal analysis, Software, Resources, Writing—Original Draft Preparation.
Sarkar Md Sajib: Investigation, Visualization, Data curation, Validation.
All authors have read and agreed to the published version of the manuscript.

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