Effect of changing printing parameters on mechanical properties of printed PLA and Nylon 645

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Abstract
Nowadays, 3 Dimensional (3D) Printing is an effective and fast way to fabricate prototypes. It can fabricate desired shape by layering multiple thin layers using various types of plastics. Making objects with 3D printing are faster and less expensive than the existed ways like machining, molding and etc. But 3D printed objects are not considered as high robustness because of making method of Fused Deposition Modeling (FDM) such as 3D printing. Following experiments are planned to compare the strength of 3D printed objects. In this research, Nylon 645 and blue, green, brown, blue colored Polylactic Acid (PLA) filaments are used to fabricate tensile and compression test specimens. First, specimens are tested to investigate a relationship between filament colors, extrude temperature and strength. Second, tensile test is conducted to investigate a relationship between the rate of infill and strength using PLA and Nylon 645 specimens. Third, compression test is conducted to investigate a relationship between the rate of infill and strength using PLA and Nylon 645 specimens. This research shows that extrude temperature does not affect strength and each colored PLA filaments have their own strengths. Brown colored PLA is strongest of the PLA filament in this experiment. Rate of infill affects strength significantly. As infill rate become higher, Ultimate Tensile Strength (UTS), Ultimate Compressive Strength (UCS), and Young’s modulus also become higher. The results of this research will help designing objects which be made with 3D print to be loaded.

Keywords: 3D printing, Polylactic Acid (PLA), Nylon 645, Extrusion temperature, Infill

1. Introduction

The Additive Manufacturing technique is a remarkable method of fabricating 3D objects. It has the ability to build parts for designing and it can be manufactured with various plastics. Moreover, it offers a cheaper and faster solution with properties that are similar to injection molded product. There are three methods in Additive Manufacturing processes for common use. The first method is called Stereolithography (SLA) (Ferry Melchels et al., 2010) which uses light to change material from liquid into solids of desired shape. The second method is called Selective Laser Sintering (SLS) (Kruth et al., 2005) that fuses layers of powder into the desired shape by using high power energy laser or hot air. The third method is most commonly available method, FDM (Too et al., 2002). FDM is developed by S. Scott Crump in the late 1980s (Kruth et al., 1998). Thus, a 3D printer technique is able to create an object by ejecting out a filament of molten polymer, adding it up layer-by-layer, rather than cutting it away, until you have completed an object.

3D printing method is rapidly growing and developing by commercial companies and academics. 3D printers are becoming more common because of their reduced price which makes them attractive to researchers, labs, schools, families, and small businesses (Torrado Perez et al., 2014). They can be used to create prototypes, engineering models or replacement component to fix things. 3D printer creates objects by using filament form of material that comes on a large
spool. There are two regions, which control the feed of filament. These two regions are cold end and hot end, usually produced in a single unit called extruder. The filament is loaded into cold end that pulls off the filament of the spool and push it to hot end, then the hot end heats the filament to filament’s melting temperature (Lifton et al., 2014).

3D printers utilize three main software. First, Computer Aided Design (CAD), software that is required for forming the object as a format of STL file, defines a 3D object in various 3D views. Second, Computer Aided Manufacturing (CAM), software that takes the 3D object definitions as STL file and converts it into G-code file that contains instructions for the printer to control the parameters. Finally, Firmware, a software which loads into the memory of the printer and activates when it is turned on with no further modifications. In addition to these three main softwares, there is a printer control application that leads to completion of the operator. This software enables operator to connect printer with computer via USB and allows controlling many operations such as axes movement, hot end, and axes alignment.

Control programs for 3D printers can control many variables. For example, feedrate, nozzle and bed temperature settings, and infill rate. Manufacturers extensively recommend setting variables based on materials or 3D printers, providing a material equivalent. However, when it comes to making tools that are sensitive to physical properties, there are many cases where the supplied physical values are not known or incorrect. Because the properties can vary with the difference in small variables. Therefore, when using a 3D printer to make an experimental tool, researchers need to understand the variables that affect the results, so researchers need to study the following. i) The type of filament affects the printouts because the color and size of the filament are different. Typical sizes are 1.75mm or 3.0mm. ii) One of the benefits of 3D printers is that they can control the strength of objects created at charging speeds. In general, injection speed increases with intensity. However, it is difficult to ensure that the charging speed and strength are increased linearly at the same time. It's essential for design that wants the best strength with less weight and less filament. iii) Mechanical properties using Poly Lactic Acid (PLA) have been studied but have not been studied how strength varies with the color and height of the PLA filament. This explains the color, extrusion temperature, and charging effects through the mechanical properties of the PLA and Nylon 645.

2. Materials and method

2.1 Specimen preparation

There are many parameters affect quality of 3D printed objects, but we assume that the important parameters to build up high quality 3D objects are the temperature and filament material. Also, we predict that if infill is increased, stiffness like UTS, UCS, and Young’s modulus of PLA will also increase.

To verify that this hypothesis is correct or not, we designed and fabricated specimens with PLA which have variety condition on ‘Extruding temperature’, ‘Color of PLA filaments’ and ‘Infill rate’. After fabricating specimens, we conducted tensile test to find optimal range of temperature to print PLA.

We conducted experiment to investigate relationship between infill and strength by stress-strain curve. Specimens of PLA were fabricated with different infill. After fabricating specimen, we conducted an experiment of tensile test and compression test with fabricated PLA specimen to find optimal range of infill to print PLA.

2.1.1 Fabricating specimens

All specimens were made by ‘Infinity 3D single extruder printer’ of Manufacturer, Revolution 3D printers. Specimens used in tensile test to investigate the effect of extruding temperature, color of filaments, were designed by SolidWorks according to ASTM 638, type V (Torrado Perez et al., 2014) as in Fig.1. Specimens were printed with different colors of PLA and were printed at 10°C intervals of extruder temperature from 180°C to 230°C. Specimens used in tensile test to investigate about relationship between material properties and infills, were designed by SolidWorks according to ISO 527: 1993 (ISO 527 (1993) Plastic - Determination of tensile properties) (Pilipović et al., 2009) as in Fig.2. Specimens were printed at 10% intervals of infills from 20% to 100%. While fabricating specimens, some parameters were fixed as shown in Table 1. We fabricated specimens with PLA and Nylon 645 to be used in tensile test with this condition.

Specimens were designed by SolidWorks according to standard ASTM D695 (Ahn et al.,2002) and were printed at bed temperature 45°C for PLA and 30°C for Nylon, while the extruder temperature was 200°C for PLA and 245°C for Nylon with different infill at 10% intervals from 30%, to 100%. The dimensions of specimens are 25.4 mm in length and 12.7 mm in diameter. Fabricated ASTM D695 specimens with PLA and Nylon 645 were used in compression test.
2.2 Experimental preparation

2.2.1 Tensile test preparation

We used ‘Adelaide testing machine’ as shown in Fig.3 for tensile test. Tensile speed of machine for the specimens was 1.0mm/min. Applied forces and displacements of tensile specimens were measured by the data collected from ‘Adelaide testing machine’ to draw out the properties of the different infill of PLA Filaments. Young’s modulus and stress-strain curve were drawn out after tensile test.
2.2.2 Compression test preparation

We used ‘MTI.10K universal testing machine’ as shown in Fig.4 for compression test with specimens. Compress speed was 1 mm/min, and the deflection was specified to 10.5 mm. Applied forces and displacements of compression test specimens were measured by the data collected from ‘MTI.10K universal testing machine’ to draw out the properties of the different value of infill for PLA and Nylon. Ultimate Compressive Strength (UCS), young’s modulus and stress-strain curve were drawn out after Compression test.

3. Results

3.1 Effect of the extruding temperature and specimen’s color for tensile test specimens

We had conducted experiments about the effect of extruding temperature and the color of PLA material with the tensile test. The UTS and Young’s modulus were measured to draw out mechanical properties to investigate which colors of PLA and temperature had positive effect on properties. Fig.5 shows that there was no peculiarity effect on strength and young’s modulus by the temperature for each color. The specimen, which was printed with brown colored PLA filaments, had the highest UTS and Young’s modulus but there were not any significant differences about extrude temperature. We were able to figure out the overall tendency. Brown colored PLA had the strongest mechanical properties between all colored PLA used in this research. Black, green, blue filaments had similar distribution of strength, including UTS and Young’s modulus by temperature.

Fig. 3  Tensile test machine, ‘Adelaide testing machine’

Fig. 4  MTI.10K universal testing machine during compression test
3.2 Effect of the infill on the mechanical properties of PLA specimens for tensile test specimens

We conducted experiments about the effect of infill of green colored PLA with tensile test. Stress-strain curve were drawn out as shown in Fig.6. We found conspicuous differences and tendency between each infill. In addition, Fig.7 (a) showed the average tensile strength of PLA with different infill from 20% up to 100%. UTS was emerging to almost 47Mpa at 100% of infill and gradually lowered following a decrease in infill, recording about 27Mpa in 30% of infill. 20% and 30% of infills, 90% and 100% of infills had same average UTS. Even though same strength between 20% and 30% of infill and 90% and 100% of infill. However, we found a tendency of stress in different infills. As infill increased, UTS was slightly increased. Average UTS was increased from 27Mpa at 20% of infill to 46Mpa at 100% of infill. As shown in Fig.7 (b), Young’s modulus increased gradually with increase of infill. Average Young’s modulus was almost 640Mpa at 20% of infill and average Young’s modulus increased almost to 1140Mpa at 100% of infill.

Fig. 5  UTS and Young’s modulus of various colored specimens were printed at various extrude temperature. (a): Young’s modulus of specimens (b): UTS of specimens

Fig. 6  Stress-Strain Curve from tensile test with different infill of green PLA specimens were printed at 200 °C
3.3 Effect of the infill on the mechanical properties of Nylon 645 specimens for tensile test specimens

Nylon 645 showed a similar pattern to the results of PLA. Similar to PLA, Nylon 645 also showed an increasing tendency in strength as infill increased. As shown in Fig. 8 and Fig. 9 (a), except 100% of infill, UTS of specimens increased from 19Mpa at 30% of infill to 31Mpa at 90% and 80% of infills. Young’s modulus of specimens also increased as infills increased. As shown in Fig. 9 (b), Young’s modulus increased from 84Mpa at 30% of infill to 150Mpa at 90% of infill.

Fig. 7 UTS and Young’s modulus of Green PLA specimens were printed at 200 °C. (a): UTS of specimens (b): Young’s modulus of specimens

Fig. 8 Stress-Strain Curve from tensile test with different infill of Nylon 645 specimens were printed at 245 °C
3.4 Effect of the infill on the mechanical properties of PLA and Nylon 645 specimens for compression test specimens

The stress-strain curve on compression test with PLA specimens showed a distinct result as shown in Fig.10. As shown in Fig.11 (a), Ultimate Compressive Strength (UCS) gradually increased from 26Mpa of 30% of infill to 105Mpa of 100% of infill. As shown in Fig.11 (b), Young’s modulus gradually increased from 242Mpa of 30% at infill to 868Mpa at 100% of infill.

Fig. 9  UTS and Young's modulus of Nylon 645 specimens printed at 245 °C. (a): UTS of specimens (b): Young's modulus of specimens

Fig. 10 Stress-Strain Curve from compression test with different infill of brown PLA specimens were printed at 200 °C
The stress-strain curve on compression test with Nylon 645 specimens also showed a distinct result as shown in Fig.12. UCS gradually increased from 14Mpa of 30% of infill to 80Mpa of from 80% and 100% of infills as shown in Fig.13 (a). There were same UCS at 80%, 90% and 100% of infills; UCS had shown an increasing tendency when infills were lower than 80%. As shown in Fig.13 (b), Young’s modulus gradually increased from 47Mpa at 40% of infill to 232Mpa at 100% of infill.

Fig. 11 UCS and Young’s modulus of Brown PLA specimens printed at 200 °C. (a): UCS of specimens (b): Young’s modulus of specimens

Fig. 12 Stress-Strain Curve from compression test with different infill of Nylon 645 specimens were printed at 245 °C
4. Conclusion

We fabricated specimens with a variety of material and studied their mechanical properties. In the first experiment, we investigated mechanical properties of the fabricated specimens in terms of colors of PLA and extruder temperatures. Brown colored PLA had the strongest properties like UTS and Young’s modulus; other colored PLAs had similar properties. We also confirmed that there was no conspicuous effect with extrude temperature. In the second experiment, tensile test with PLA specimens, we noticed changes in mechanical properties according to infill change. When specimens had a high rate of infill, it showed a tendency to have a high strength including UTS and Young’s modulus. Infill rate of 100% had the highest UTS of 45Mpa and the highest Young’s modulus of 1133Mpa. In the third experiment, tensile test with Nylon 645 specimens, there was a similar tendency result with PLA tensile test. Stress-Strain curve was less clear than graph of tensile test of PLA, but we found UTS and Young’s modulus of specimens of Nylon 645. The highest UTS was obtained at 80% of infill, 31Mpa and the highest Young’s modulus was obtained at 90% of infill, 150Mpa. In the fourth experiment, compression test with PLA and Nylon 645 specimens, both materials showed clear experimental results. We found out mechanical properties of PLA specimens with compression test. The highest UCS was obtained at 100% of infill, 105Mpa and the highest Young’s modulus was obtained at 100% of infill, 868Mpa.

In compression test with Nylon 645, the highest UCS was obtained at 100% of infill, 81Mpa and the highest Young’s modulus was also obtained at 100% of infill, 232Mpa. We decide to pay attention to change of specific strength that appear by changing the infill rate. Therefore, after normalizing each result into a range of 0 to 1, we will note which infill rate has the largest normalized value. Normalizing formula we used is Eq. (1). X in Eq. (1) is normalized value of Young’s modulus and UTS in each infill.

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X_{\text{normalized}} = \frac{(X - X_{\text{min}})}{(X_{\text{max}} - X_{\text{min}})}
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Fig. 13 UCS and Young’s modulus of Nylon 645 specimens printed at 245 °C. (a): UCS of specimens (b): Young’s modulus of specimens

Fig. 14 Gap of normalized value between each infill rate. (a): gap of normalized in tensile test of PLA. (b): gap of normalized in tensile test of Nylon 645.
Figure 14 (a) is result of gap of normalized value in tensile test of PLA. According to graph, maximum average increased normalized value is recorded 0.23 at from 60% to 70% and from 80% to 90%. This result means that high specific strength is appeared at 70% of infill and 90% of infill. Figure 14 (b) is result of gap of normalized value in tensile test of Nylon 645. According to graph, maximum average increased normalized value is recorded 0.31 at from 60% to 70%. This result means that high specific strength is appeared at 70% of infill.

![Graph showing the gap of normalized value in tensile test of PLA and Nylon 645.](image)

**Fig. 15** Gap of normalized value between each infill rate. (a): gap of normalized in compression test of PLA. (b): gap of normalized in compression test of Nylon 645.

Figure 15 (a) is result of gap of normalized value in compression test of PLA. According to graph, maximum average increased normalized value is recorded 0.23 at from 80% to 90%. This result means that high specific strength is appeared at 90% of infill. Figure 15 (b) is result of gap of normalized value in compression test of Nylon 645. According to graph, maximum average increased normalized value is recorded 0.30 at from 60% to 70%. This result means that high specific strength is appear at 70% of infill. As a result, PLA recorded maximum specific strength increasement at 90% of infill. And Nylon 645 recorded maximum specific strength increasement at 70% of infill.

In this research, we fabricated specimens and could draw out mechanical properties of PLA and Nylon 645, materials used in 3D printing. The results of this experiment would play an important role in selecting material for 3D printed products that need to be considered by mechanical properties.

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