Journal of Physics: Conference Series

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To cite this article: T J Suteja and A Soesanti 2020 *J. Phys.: Conf. Ser.* **1569** 042010

Mechanical Properties of 3D Printed Polylactic Acid Product for Various Infill Design Parameters: A Review

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Abstract. 3D printing is widely used for various applications as it offers many benefits. The mechanical property of the part manufactured by using 3D printing is very critical. For that reason, it is important to understand how different values of 3D printing process parameters impact the mechanical properties of the part. As Polylactic Acid (PLA) is most widely used as 3D printing material, it is chosen as the material discussed in this research. The purpose of this research is to provide information related to the influence of various parameters of 3D printing to the mechanical properties of the PLA part. A literature review was performed based on the current research that investigates the 3D printing process of PLA. Based on the literature review, the infill design parameters are considered as important parameters and discussed in this research. The infill design parameters referred in this research are layer thickness, infill pattern, infill density, infill width, and infill deposition speed. The mechanical properties discussed in this research are tensile strength and yield strength, ductility, elasticity or young modulus, compression strength, flexural strength, and stiffness.

1. Introduction

3D printing, also known as Fused Filament Fabrication (FFF), is an additive manufacturing process in which a material is extruded through a nozzle layer by layer to form the shape of the printed part. 3D printing is widely used for various applications such as for a product prototype because it is able to create complex shape in a faster time than other processes. For prototyping purpose, the mechanical property of the part printed by using 3D printing is very critical. For that reason, it is important to understand how different values of 3D printing process parameters impact the mechanical properties of the part.

Polymer is widely used as a material for a prototype as it has lower density and higher strains at failure. In addition, polymer also has higher strength per unit weight than metals. Polylactic Acid (PLA) is a polymer that is most widely used as 3D printing material because it required low melting point and therefore less energy to print. PLA is also a biodegradable polymer and does not spread a smell or toxic vapours. Finally, it adheres well to the platform and does not require a heated base. Therefore, PLA is chosen as the material discussed in this research.

The purpose of this research is to provide information related to the influence of various parameters to the mechanical properties of the PLA part. To achieve the purpose, first, this research summarizes important research in 3D printing process of PLA. Then, this research identifies important process parameters and their influences to the mechanical properties of 3D printed part.

2. Literature review

A literature review was performed based on the current research that investigates the 3D printing process of PLA. Chacon, et. al., have studied the effect of build orientation, layer thickness, and feed rate on the mechanical properties of PLA samples manufactured with a low cost desktop 3D printer. The result shows that the use of on-edge exhibit higher mechanical properties compared to flat and upright build orientation in terms of strength, stiffness and ductility. As layer thickness increased, tensile and flexural strengths are increased for the use of upright build orientation. Meanwhile, in case of on-edge and flat orientations, the maximum tensile and flexural strengths are varied according to the layer thickness. In the use of upright build orientation, tensile and flexural strengths decreased as the feed rate increased. In the case of on-edge and flat orientations, the effect of feed rate on the tensile and flexural strengths is varied according to the feed rate [1].

For rectangular pattern, 3D printed parts built with deposition angle of 90° have the increase of mechanical strengths as the infill density increased. The infill density has a significant effect on the effective printing time because the increased of infill density will reduce the size of the infill pattern. As a result, the nozzle has to travel a longer distance to print the same element [2].

The research by Luzanin concluded that minimal layer thickness radically affects maximum flexural force. In addition, the level of infill significantly influences the effect of deposition angle on the flexural force [3].

Modulus elasticity, tensile strength and the yield strength are lower using upright building orientation than using on edge or flat building orientation. The maximum values are achieved using the flat building orientation. In addition, the mechanical properties improved by increasing the infill density percentage. However, the mechanical properties are not highly affected by the feed rate or infill patterns. As the temperature increased the mechanical properties increased. However, there is no improvement in increasing the extrusion temperature after a certain limit. Last, the mechanical properties are shown to improve by increasing layer height [4].

The increase in the extrusion temperature leads to an increase in specimen's stiffness due to higher fusion between the layers until a certain temperature. A further increasing the temperature may not have any additional effect on the part's stiffness. In addition, the mechanical properties increased as the extruding temperature increased. The infill pattern processing parameter has minimal effect on the stiffness, with the rectilinear pattern having slightly larger Young's modulus value. The density percentage parameter shows the highest influence on the specimen's stiffness. As the layer thickness increases the ductility of the FDM parts increases. The results indicate processing parameters influence the yield and tensile strengths in a similar way as Young's modulus. However, the infill pattern has more influence on the tensile and yield strength than on Young's modulus. The maximum strength (yield and tensile) is obtained by triangular infill pattern. The maximum Young's modulus is maximized by rectilinear infill pattern [5].

The influence of the different printing patterns causes a variation of less than 5% in maximum tensile strength, although the behavior is similar. The change in infill density determines mainly the tensile strength [6].

The tensile yield strength of the samples was directly affected by infill density percentage. The modulus of elasticity is also dependent on infill density percentage. All infill density percentages of the PLA samples failed in a brittle manner, with no visible necking or deformation prior to failure [7].

Tensile properties, including yield strength and modulus elasticity decreased until a certain infill density percentage then increased regardless of the number of shells or layer thickness involved. At lower percent infill values, a higher number of shells results in greater strength and stiffness [8].

According to Sukindar, the shell thickness gives highest significant impact on the tensile strength. The different in shell thickness contributes to the variation on the tensile strength. On the contrary, feed rate and layer thickness have slightly lower influence compare the other two parameters. The highest feed rate will lead to ductile fracture. Meanwhile the increased layer thickness reduced the tensile strength [9].

The tensile strength value of PLA prints showed greater variability between layer heights. Differences between tensile strength values based on deposition angle were much smaller. On average, the mechanical property values of RepRap prints are higher than what has been found in similar studies of printed parts from commercial printers. While PLA RepRaps printed parts generally have similar strengths to PLA injection molded parts [10].

The research reveals that increasing the infill density improves the mechanical strength as this makes the part more solid and reduces the number of cavities. The increase of layer height causes the maximum tensile strength to fall. Upright and on edge build orientation reduces the mechanical tensile strength [11].

The results of the research show that the process of 3D printing can provide good and reproducible results regarding the mechanical strength of the printed parts. This applies both to the inexpensive as well as to the higher-priced printers. In the comparison of materials, the PLA parts can reach a higher mechanical strength than those printed with ABS [12]. In addition, the line infill pattern provides higher mechanical strength compare to honeycomb infill pattern.

It has been found that the mechanical properties of the printed parts strongly depend on the deposition angle, extruder temperature, and feed rate. The tensile strength model resulted based on the experimental data exhibits that deposition angle has a negative influence on the tensile strength, higher extruder temperature causes higher tensile strength, and faster feed rate decrease the tensile strength. Meanwhile, the interaction between deposition angle and other parameters has a positive influence on the tensile strength. The effect of other parameter interactions can be observed but difficult to be interpreted [13].

The research by Farbman, et. al. concludes that the specific ultimate tensile strength decreases as the infill density percentage decreases. In addition, the printed parts with hexagonal pattern infill geometry had significantly higher ultimate tensile strengths and were stiffer than rectilinear infill parts. The strength of parts with hexagonal infill was more consistent as a function of orientation [14].

The increase of infill density improves modulus of elasticity, deflection at the breakpoint, and maximum stress values. Full infill density produces printed part with the highest value of modulus elasticity, deflection, and stress. Deposition angle does have an impact on strength of the part. Part with 45° deposition angle has higher strength value than 90° deposition angle. The infill pattern also influences the strength of the part. Part with 25% honeycomb infill has similar modulus of elasticity and maximum stress values as part with 50% grid infill pattern [15].

3D printed part with different type of infill pattern at the same infill density percentage and the same number of perimeter shells will creates different stiffness and strength. Part, that uses higher number of perimeter shells for the same infill pattern, improves the stiffness and the strength at the same density [16].

The research by Moradi, et. al. investigates the influence of layer thickness, infill density percentage, and extruder temperature with honeycomb infill percentage to mechanical loads [17]. It identifies that layer thickness is the major influenced variable for maximum failure load and elongation at break. It also shows that interaction of infill density percentage and extruder temperature has a significant influence on elongation at break.

Wittbrodt, et. al. characterizes 3-D printed PLA in various colors from a single supplier. The result shows that there is a strong relationship between tensile strength and crystallinity percentage of a 3-D printed part. The results also show a strong relationship between percent crystallinity and the extruder temperature. Therefore, it concludes that coloring agents altered the percentage of crystallinity and impacts the strength [18].

From the research conducted by Tao Y., et. al., it is found that different infill patterns exhibit different compression performance [19]. In-layer cavities caused by layer thickness will impact their compression performance. In addition, greater line width creates higher cavity porosity and decrease the compression performance.

Based on the literature review, several 3D printing parameters and their influence to mechanical properties of the printed part has been identified. The parameters and the influenced properties are shown in Table 1. The parameters are build orientation, layer thickness or layer height, feed rate or infill deposition rate, infill density, deposition angle or raster angle or infill angle, extrusion temperature, infill pattern, number of outer shell layers, shell thickness, material type, printer type, strain rate, colouring agent, and nozzle diameter or infill width. Most of the reviewed articles investigate the influence of infill design parameters of the 3D printing to the mechanical properties of the printed part. The infill design parameters consist of layer thickness, infill deposition speed, infill density, infill pattern, and infill width. They are considered as important parameters and discussed in this research.

Table 1. 3D Printing Parameters and Influenced Mechanical Properties.

References	3D Printing Parameters	Mechanical Properties
[1]	• Build Orientation • Layer Thickness • Infill Deposition Speed	• Tensile Strength • Flexural Strength • Ductility
[2]	• Infill Density	• Compression Strength • Time
[3]	• Layer Thickness • Infill Angle • Infill Density	• Flexural Force
[4]	• Build Orientation • Infill Density • Infill Deposition Speed • Extrusion Temperature • Layer Thickness • Infill Pattern	• Accuracy and Repeatability • Young Modulus • Tensile Strength • Yield Strength
[5]	• Infill Density • Infill Pattern	• Tensile Strength
[6]	• Extrusion Temperature • Layer Thickness • Infill Pattern • Infill Density	• Dimensional Accuracy • Tensile Strength • Young Modulus • Ductility
[7]	• Infill Density	• Tensile Strength • Young Modulus • Failure Mode
[8]	• Layer Thickness • Infill Density • Number of Outer Shell Layers	• Strength • Stiffness • Ductility
[9]	• Shell Thickness • Infill Deposition Speed • Layer Thickness	• Tensile Strength
[10]	• Infill Angle • Layer Thickness	• Tensile Strength • Young Modulus
[11]	• Layer Thickness • Infill Density • Build Orientation	• Mechanical Strength
[12]	• Material Type • Infill Density • Infill Pattern • Printer Type	• Tensile Strength • Young Modulus • Yield Strength • Specific Strength
[13]	• Infill Angle • Extruder Temperature • Feed Rate	• Tensile Strength • Young Modulus
[14]	• Material Type • Infill Density • Infill Pattern • Load Orientation • Strain Rate	• Tensile Strength • Stiffness
[15]	• Infill Density • Infill Pattern	• Young Modulus • Maximum Bending Stress • Deflection
[16]	• Infill Density • Infill Pattern	• Stiffness • Strength
[17]	• Layer Thickness • Infill Density • Extruder Temperature	• Maximum Failure Load • Elongation • Part Weight • Build Time
[18]	• Coloring Agent	• Strength
[19]	• Infill Pattern • Infill Width	• Compression Load

The influenced mechanical properties are tensile strength and yield strength, compression strength, flexural strength, ductility, elasticity or young modulus, and stiffness. In addition, the parameters also have influences on the failure mode, accuracy and repeatability, specific strength, part weight, and build time of the printed part.

3. Results and discussion

Tensile strength and yield strength of a 3D printed part are affected by various infill design parameters to the mechanical properties, which are layer thickness, infill density, and infill deposition speed. The increase of layer thickness increases the tensile strength and yield strength for a small value of layer thickness. Smaller layer thickness results in smaller cavity among the infill and increases the strength. However, larger layer thickness also strengthens the 3D printed part. Therefore, a small cavity in a certain layer thickness increases the tensile strength and yield strength. On the contrary, the tensile strength and yield strength decrease by the increase of high value of layer thickness when the cavity among the infill reaches a certain size.

Infill density also influences the tensile and yield strength. The increase of infill density increases the density of a 3D printed part. A higher density part has higher tensile and yield strength compared to lower density part. Therefore, the higher the infill density increases the tensile and yield strength.

Tensile and yield strength of a 3D printed part increase with the decrease of infill deposition speed. The lower speed decreases the cavity among the infill. The smaller the cavity increases the tensile and yield strength of the part.

Compression strength of 3D printed part is affected by infill density and infill width. Both infill density and infill width influence the porosity of the part. The lower the infill density and the higher infill width increase the porosity of the part. The compression strength decreases when the porosity increases. For that reason, the lower the infill density and the higher the infill width decrease the compression strength of the part.

Layer thickness and infill width have an impact to flexural strength. The lower value of layer thickness and infill width increases the flexural strength. Flexural strength is influenced by the moment of resistance. The lower the value of layer thickness and infill width, the smaller the cavity resulted by 3D printing process. The smaller the cavity increases the moment of resistance. A higher moment resistance requires higher bending moment to break. Therefore, it has higher flexural strength.

Infill density affects the stiffness of a 3D printed part. The higher value of infill density increases the density of the part. A part with higher density has more resistance to shape change. Therefore, a higher infill density of a part increases the stiffness of the part. As a stiffer material will have a higher elastic modulus, then modulus of elasticity will increase if the infill density increases. The elastic modulus of a 3D printed part is also influenced by layer thickness. A higher value of layer thickness causes a larger the cavity size. A larger cavity size creates a low porosity part. Low porosity part has a high modulus of elasticity.

The ductility of a 3D part is influenced by the layer thickness. The increase of the layer thickness increases the ability for dislocations to move and for undergoing significant plastic deformation. Therefore, the ductility of a 3D part increases when the layer thickness increases.

4. Conclusions

The infill design parameters which are layer thickness, infill deposition speed, infill density, infill pattern, and infill width have impact to mechanical properties of a 3D printed part. The increase of layer thickness increases the tensile and yield strength for a small value of layer thickness. On the contrary, the tensile and yield strength will be decreased by the increase of high value of layer thickness when the cavity among the infill reaches a certain size. The higher the infill density increases the tensile and yield strength. However, the higher the infill deposition speed decreases the tensile and yield strength of the part. In addition, the lower the infill density and the higher the layer width decrease the compression strength of the part. Further, the lower value of layer thickness and layer width increases the flexural strength. A higher infill density of a part increases the stiffness and modulus elasticity of the part. The modulus elasticity of a part also increases in accordance with the increase in the layer thickness. The ductility of a 3D part increases when the layer thickness increases.

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