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Mechanical characterization of polylactic acid polymer 3D printed materials: the effects of infill geometry

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ABSTRACT: Today, technological advances have led to the discovery of newly developed manufacturing methods. Additive Manufacturing technology with three-dimensional (3D) printer is one of these new methods. In this method, parts with complex geometry that cannot be produced by conventional methods can be manufactured. The most popular and low-priced method among additive manufacturing technologies is FDM (Fused Deposition Modeling). In this study, 3D printer design and manufacturing using FDM technology has been realized. Five different infill geometries such as hourglass (HG), gyroid (GY), octahedral (OC), triangle (TR) and grid (GR) have been determined, then the tensile and 3-point bending tests were applied to the manufactured Polylactic Acid polymer (PLA) samples and mechanical properties were compared with each other. The most important aspect of the study is the comparison of grid infill geometry, which has been studied extensively in the literature, and the rarely studied geometries such as hourglass, gyroid, octahedral and triangle in terms of mechanical properties. It was concluded that the different cross-section type has a significant effect, especially on tensile strength. The highest strength values were determined in the samples with triangular infill geometry.

KEYWORDS: Additive manufacturing; Infill geometry; Mechanical properties; Polylactic acid; 3D printing

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RESUMEN: *Caracterización mecánica de materiales impresos en 3D de polímero de ácido poliláctico: los efectos de la geometría del relleno.* Hoy, los avances tecnológicos han llevado al descubrimiento de métodos de fabricación desarrollados recientemente. La tecnología de fabricación aditiva con impresora tridimensional (3D) es uno de estos nuevos métodos. En este método, se pueden fabricar piezas con geometría compleja que no se pueden producir mediante métodos convencionales. El método más popular y de bajo precio entre las tecnologías de fabricación aditiva es FDM (Fused Deposition Modeling). En este estudio, se ha realizado el diseño y la fabricación de impresoras 3D utilizando tecnología FDM. Se han determinado cinco geometrías de relleno diferentes, como reloj de arena (HG), giroide (GY), octaédrico (OC), triángulo (TR) y cuadrícula (GR), luego se aplicaron las pruebas de tracción y flexión de 3 puntos a las muestras fabricadas de polímero de ácido poliláctico (PLA) y las propiedades mecánicas se compararon entre sí. El aspecto más importante del estudio es la comparación de la geometría del relleno de la rejilla, que se ha estudiado ampliamente en la literatura, y las geometrías raramente estudiadas como el reloj de arena, el giroide, el octaédrico y el triángulo en términos de propiedades mecánicas. Se concluyó que el tipo de sección transversal diferente tiene un efecto significativo, especialmente en la resistencia a la tracción. Los valores de resistencia más altos se determinaron en las muestras con geometría de relleno triangular.

PALABRAS CLAVE: Fabricación aditiva; Geometría de relleno; Propiedades mecánicas; Acido poliláctico; Impresión 3D.

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1. INTRODUCTION

Three-dimensional printer (3DP) technology is one of the important products that technology creates and its area of usage is increasing day by day. Because the first examples of products and prototypes can be manufactured by 3DP technology at low cost and it is advantage in production. Today, production with 3DP technology is called additive manufacturing (AM). AM is developing very fast with Fused Deposition Modeling (FDM) within the additive manufacturing technologies. Although AM technologies are expected to replace traditional manufacturing methods or have a supportive technology, this technology is open to development and continues to mature.

In AM technology, mainly plastics and metals are used. Polylactic acid (PLA) polymer is preferred as a filament in 3D printers due to its organic and easy process. In our study, one of the thermoplastic materials (PLA) was also used.

There are several studies in the literature about 3DP. Fernandez-Vicente *et al.* (2016) investigated the effects of 3 infill geometries/density of internal infill and the tensile stress values were compared. It was reported that the change in the density of the internal infill caused a change in the tensile strength between 20% and 50%. The effect of printing position, printing speed and layer thickness on mechanical properties was examined in the study of Chacón *et al.* (2017). As the layer thickness decreases, higher tensile stress and lower bending stress were obtained. It was also concluded that increasing the printing speed caused a decrease in tensile and bending stresses. Rajpurohit and Dave (2016) worked on the tensile strength values of different layer thicknesses and infill geometry angles using PLA material. It was concluded that the highest tensile stress was achieved by changing the angle of the infill geometry parallel to the tensile force, but in this case the discontinuity in the fibers makes the 3d printed part more brittle. Durgun and Ertan (2014) investigated the different positions of the samples in the printing area and the tensile/ 3-point bending tests and measurement of surface roughness were performed. It was found that the horizontally produced sample exhibited optimum mechanical properties with optimum production time and cost and bonding between the layers in the vertically printed samples is weaker. The layer thickness, printing speed and the print position of the sample were studied by Jaya Christiyan *et al.* (2018). The 3-point bending tests were carried out and the highest bending strength was obtained in the printing process with a layer thickness of 0.2 mm.

In the study of the 3D printing of glass, kevlar and carbon fibers (Caminero *et al.*, 2018), the printing area layouts and impact strengths of the composite structures were investigated. It was concluded that glass fiber composites showed the best impact strength and the carbon fiber reinforced composites are more brittle. Sezer *et al.* (2019) produced composite materials using carbon fiber and ABS material and studied the effects of print head temperature on the mechanical properties of the sample during the 3D printing process. In the study by Rajpurohit and Dave (2018), the bending strength for different layer thickness and infill geometry angles were examined. They explained that the bending stress was inversely proportional to the layer thickness.

When these studies are evaluated, it is thought that the effect of additive manufacturing technology will increase progress further.

The concept of cross-section is an important subject to consider in the design of structural parts. Because the different section geometries could have different mechanical properties. On the other hand, the structural elements used in automobiles and machines have different strength values depending on their location and the load acting on them. The aim of this study is to examine the effect of section geometry, especially when plastic structural parts used in automobiles are subjected to different loads. In the current study, the 3D printer using FDM technology, with print dimensions of 200x200x210 mm, was designed and manufactured. Tensile and 3-point bending samples with using 5 different infill geometries were 3D printed and then tested by using PLA polymer filament. The most important difference is the new information about the comparison of tensile and bending strengths of hourglass, gyroid, octahedral, triangle filling geometries, which are rarely studied.

2. EQUIPMENT AND MATERIALS

The designed and manufactured plastic parts of the 3D printer were produced using 'Tronxy P802E 3D printer' and PLA (polylactic acid) material was used. The print dimensions of the designed printer are 200x200x210 mm. The printing head moves along the X and Z axes, and the print area moves along the Y axis. One and two NEMA 17 stepper motors are used for X-Y and Z axis movements, respectively. All stepper motors are controlled by A4988 stepper motor driver and Ardunio mega 2560 and Ramps 1.4 combination are used as control card. A 12 volt 360 Watt power supply is used in the printer. The print head reaches a maximum temperature of 300 °C and the print area to a maximum of 150 °C. The manufactured 3D printer is shown in Fig. 1.

In this study, 3D printed samples were produced using five different infill geometries and all the infill

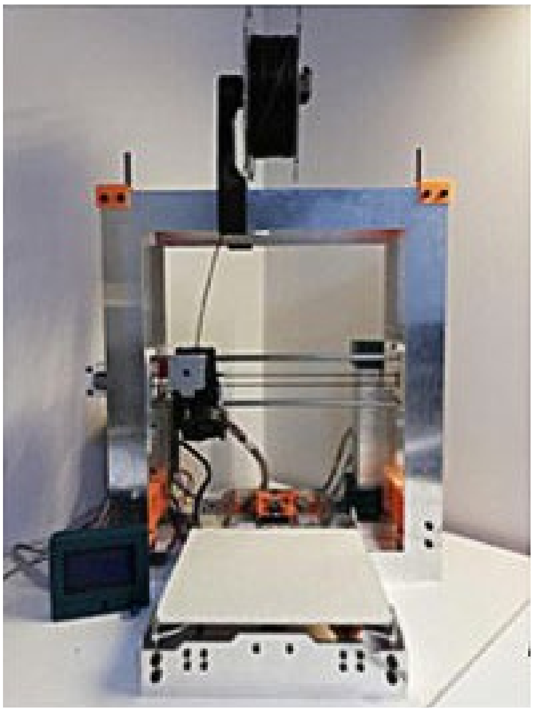

Figure 1. The designed and manufactured 3D printer.

geometries are shown in Fig. 2. The printing parameters of the samples are given in Table 1. All samples were produced one by one, using the same parameters, in the same position and printing area. The thickness of all samples is 4 mm and the material used in the production of all samples is PLA. Polylactic Acid (PLA) polymer filament of 1.75 mm in diameter.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Tensile properties

The tensile test samples were prepared according to ISO 527-2 type 1B. Sample sizes are shown in Fig. 3. The tensile tests were carried out on the Shimadzu AG-X plus tester at cross head speed of 5 mm/min. The strength values obtained from the tensile test are given in Fig. 4. According to the results, no excessive difference was observed between the maximum and minimum tensile and yield strength values. There is a difference of approximately 17% between the maximum and minimum values in the tensile stress, while the increment in yield stress is determined as approximately 14%. It was also determined that the yield and tensile strengths were close to each other (Rodríguez-Panes *et al.*, 2018). The maximum tensile strength was obtained with triangular infill geometry. This result is in accordance with the study by Chadha *et al.* (2019).

According to Fig. 5, there is an increase of approximately 30% between the minimum and maximum elastic modulus. This shows that the infill geometry has a significant effect on the elastic modulus. While the maximum value is obtained as 1852 MPa with the triangle infill geometry, the minimum value is obtained with gyroid infill geometry as 1420 MPa. The highest value followed by octahedral (OC), hourglass (HG) and grid (GR) infill geometries. It shows that bonding between the PLA polymer materials and the

Table 1. Printing parameters

Internal infill rate	20%
Layer height	0.2 mm
Wall thickness	1.2 mm
Lower and upper surface thickness	0.6 mm
Printing speed	50 mm·s^{-1}
First layer printing temperature	200 °C
Printing area temperature	40 °C

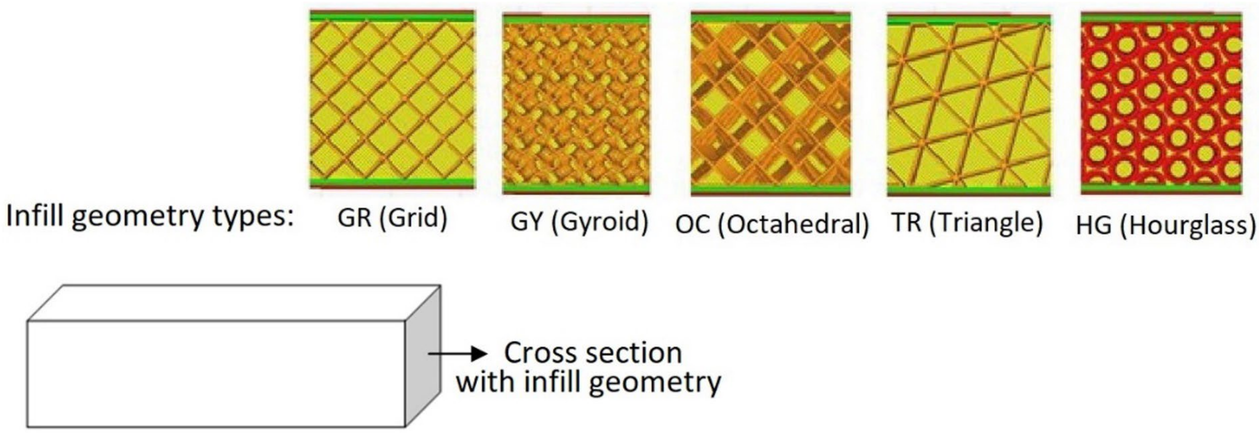

Figure 2. All of the infill geometries used in the study.

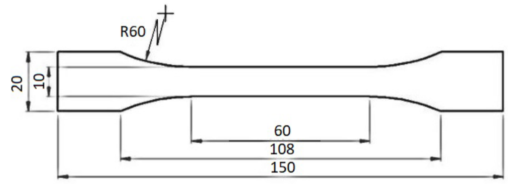

Figure 3. The dimensions of the tensile specimen (mm).

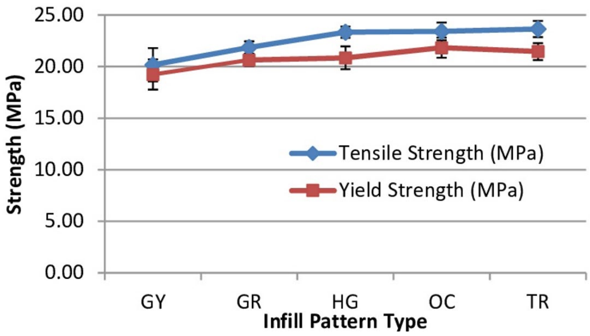

Figure 4. The strength values of 3D printed materials.

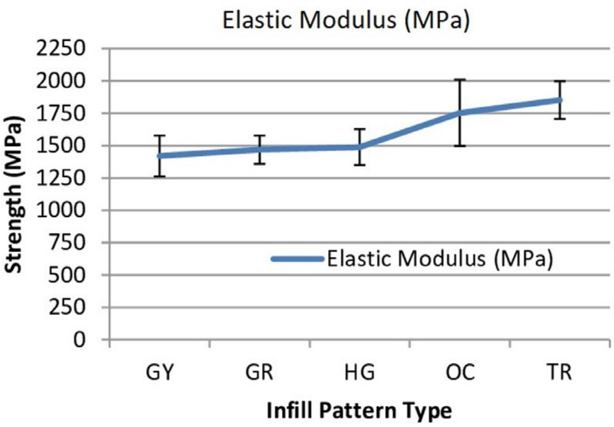

Figure 5. Elastic modulus values of 3D printed materials.

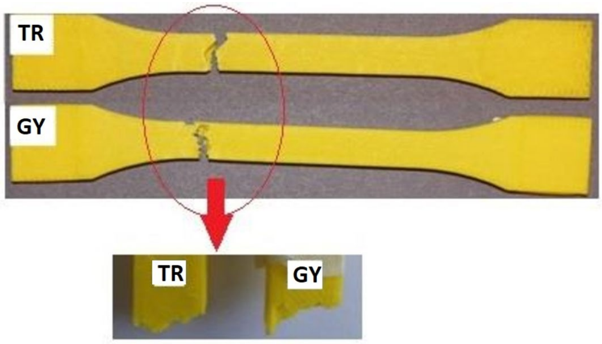

Figure 6. The fracture regions of the triangular and gyroid infill geometries.

different infill patterns are very important to the Elastic Modulus in the 3D printing process (Fernandez-Vicente *et al.*, 2016; Khan *et al.*, 2018).

In tensile test, the fracture region of the samples gives information about strength of the specimens. According to the literature, there are two types of failure, tensile and delamination. Since the tensile failure creates higher strength and therefore it is a desired type of failure but the delamination failure causes low strength (Schmitt *et al.*, 2020). Figure 6 shows the photographs of the fracture regions of the infill geometries with the highest and lowest strength. Accordingly, the tensile and delamination fractures were observed in triangular and gyroid infill geometries, respectively. In the tensile failure type, the fracture is along infill rasters while the delamination failure is between rasters (Schmitt *et al.*, 2020).

As it is known from the literature, while displacement is a measure of ductility, toughness is a measure of the energy absorbed by the material (Galeja *et al.*, 2020). For this reason, the variation of toughness and maximum displacement depending on the geometry was investigated in this study. The modulus of toughness was calculated from the area under stress-strain curve (Wan Muhamad *et al.*, 2020). Toughness vs. maximum displacement values are seen in Fig. 7. Accordingly, the ductility increased in infill geometries where the toughness also increased. The ductility of the samples decreased as the displacement was also decreased.

Toughness is a function depending on the tensile strength and elongation (ductility) of the material. If a material has a higher toughness value, it means that this material has higher strength and/or higher elongation (Ning *et al.*, 2017). The effective parameter in obtaining high toughness value was the ductility of the sample in this study. Because low strength was obtained at high elongation values (ductilities).

3.2. Bending properties

The 3-point testing is important for automotive applications and used before manufacturing

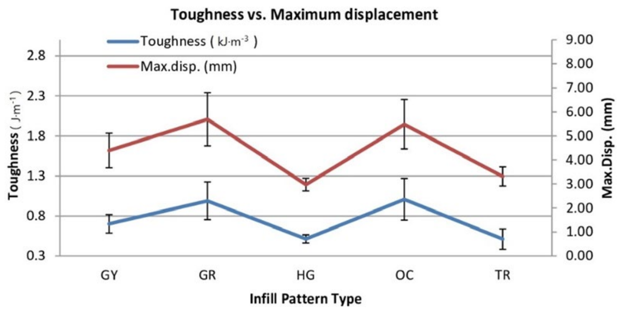

Figure 7. Toughness vs. maximum displacement values of 3D printed materials.

of automobile parts (Yadav *et al.*, 2020). In this study, the 3-point bending test samples shown in Fig. 8 were prepared according to ASTM D790. The tests were carried out on the Shimadzu AG-X tester at a cross speed of 2 mm/min. and terminated when a break occurred.

Figure 9 (a-b) presents the strength results of the tests. According to this, the maximum flexural modulus and maximum stress values are obtained with the triangular infill geometry, while the lowest values are achieved with the grid infill geometry. The difference between the maximum and minimum stress value is approximately 12%. These results are in accordance with the study Chadha *et al.* (2019). The highest bending strength followed by octahedral (OC), hourglass (HG) and gyrodi (GY) infill geometries.

The maximum flexural modulus is 1922 MPa, and the minimum is 1664 MPa, with a decrease of approximately 16%. On the other hand, the strength values obtained by the bending test are higher than the tensile tests. This increase is particularly prominent in HG, GR and GY infill geometries and the increase values vary between 13% and 24%. The bending test results showed that the infill geometry plays an important role for the bending strength of 3D printed PLA materials. Because of the interaction between layers, different infill geometries effect the bending strength as in the tensile strength (Wicaksono *et al.*, 2018). In order to evaluate the ductility, the elongation values of the bending process obtained until fracture were examined. According to Fig. 10, while the similar displacement values are observed in TR, HG, GY and GR fill geometries, the OC infill geometry has the highest value with a significant increase.

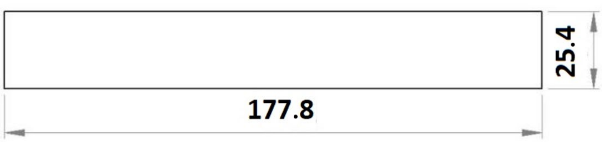

Figure 8. The dimensions of the 3-point bending specimen (mm).

4. CONCLUSIONS

In this study, the effect of cross-sectional change on mechanical properties was investigated. For this purpose, the tensile and bending properties of 3D printed specimens having different infill geometries were investigated experimentally. The selected infill geometries were hourglass, gyroid, octahedral, triangle and grid. The original part of the study is the comparison of the most investigated grid section and the less studied hourglass, gyroid, octahedral and triangle sections in terms of mechanical properties.

The results showed that; the maximum strength in bending and tensile samples was obtained with triangular infill geometry. The triangle infill geometry increased elastic modulus by 30% in the tensile test and 16% in the bending test. It also increased the tensile stress by 17% and the maximum bending stress by 12%. As it is seen in the study, the infill geometry change had a more pronounced effect on tensile tests. In addition, in the tensile test, the lowest strength values were obtained with gyroid infill geometry, whereas in the bending experiment, it

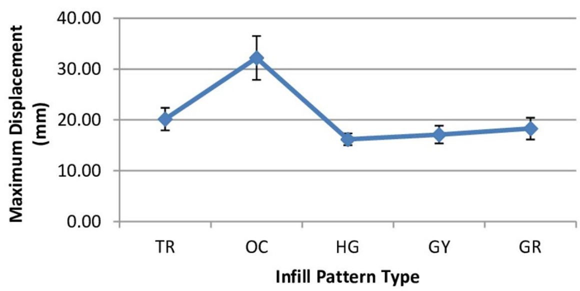

Figure 10. Maximum displacement at 3-point bending tests.

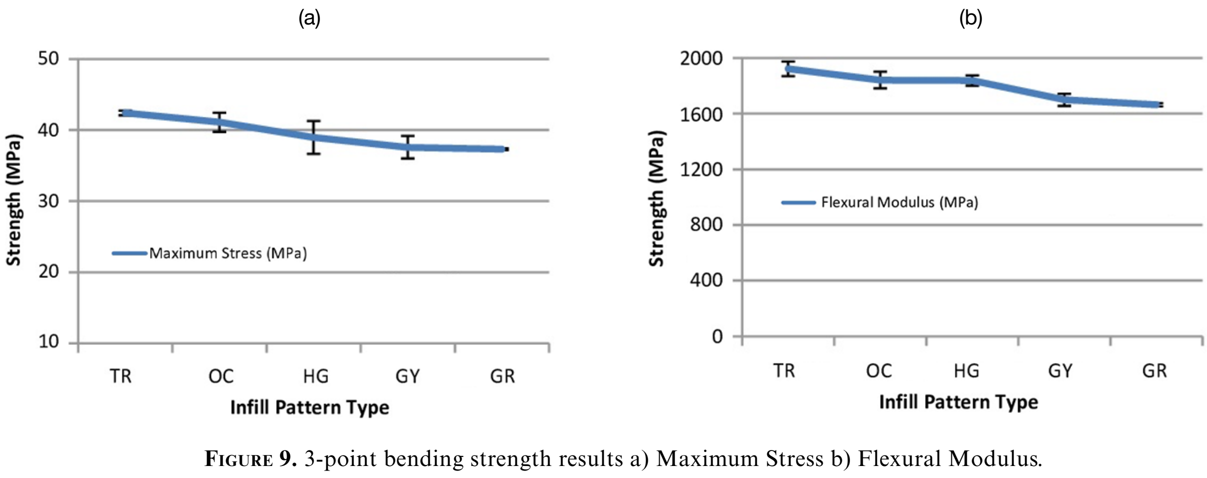

Figure 9. 3-point bending strength results a) Maximum Stress b) Flexural Modulus.

was obtained with grid. According to the toughness and ductility values obtained in the tensile test, the ductility of the samples was determined to be high while the toughness value was also high. The maximum ductility value obtained in the bending test was achieved with an approximate 99% increase by selecting octahedral infill geometry.

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