UDK 7.021.5:539.382
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 57(5)495(2023)

INFLUENCE OF THE BUILD AXIS AND ANGLE ON THE PROPERTIES OF 3D PRINTED PLA

VPLIV OSI IN KOTA GRADNJE NA LASTNOSTI 3D TISKANEGA MODELA IZ POLILAKTIČNE KISLINE

B. Anand Ronald*, K. N. Mohammed Riaz Khan, G. Kishore, V. Lokesh, R. K. Mullaivananathan

Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, India

Prejem rokopisa – received: 2023-06-02; sprejem za objavo – accepted for publication: 2023-07-28

doi:10.17222/mit.2023.900

Additive manufacturing is one of the sought-after methods for on-demand printing of customized parts. Although it has several advantages, namely design complexity, topologically optimized parts, tool-less and inventory-less manufacturing, etc., it also has challenges in terms of print parameter-dependent mechanical properties. The present paper studies the influence of the build orientation and angle on the tensile and flexural properties of fused-deposition-modelling (FDM) printed polylactic acid (PLA) samples. The samples are printed in different orientations including 0°, 15°, 30°, 45°, 60°, 75° and 90° with respect to the X- and Y-axis. From the tensile and flexural studies, we can infer that the orientation of the print plays a significant role, influencing the tensile and flexural properties. The X-axis build orientation and 75° build angle are preferred owing to better tensile and flexural properties compared to the other angles and Y-orientation.

Keywords: fused deposition modelling, polylactic acid, build orientation, tensile and flexural properties

Dodajna tehnologija je nova zelo iskana metoda za izdelavo delov po naročilu ali prototipov. Čeprav ima mnogo prednosti, kot so oblikovanje zahtevnih oblik in topološko optimiziranih izdelkov, manjše število orodij in manjše stroške, predstavlja za uporabnike tudi velike izzive vezane na parametre tiskanja in s tem povezane mehanske lastnosti izdelkov. V pričujočem članku avtorji opisujejo študijo vpliva orientacije in kota gradnje (plasti za plastjo) na mehanske in natezne lastnosti vzorcev iz polilaktične kisline (PLA, angl.: Poly Lactic Acid) izdelanih z metodo oblikovanja z nalivanjem oziroma nanašanjem taline (FDM; angl.: Fused Deposition Modeling). Vzorce (natezne in upogibne preizkušance) so tiskali pri orientacijah 0°, 15°, 30°, 45°, 60°, 75° in 90° z referenčno X ali Y osjo. Na osnovi rezultatov meritev natezne in upogibne trdnosti izdelanih vzorcev avtorji ugotavljajo, da ima orientacija na mehanske lastnosti pomemben vpliv. Ugotavljajo tudi, da imajo vzorci izdelani z orientacijo glede na X-os in gradnjo pod kotom 75° boljše natezne in upogibne lastnosti v primerjavi z uporabo drugih kotov in Y-orientacije.

Ključne besede: metoda modeliranja z nanašanjem taline, polilaktična kislina (PLA), orientacija gradnje modela, natezne in upogibne lastnosti.

1 INTRODUCTION

Fused deposition modelling (FDM) is one of the widely used methods for polymer additive manufacturing, wherein a thermoplastic material in the form of filament is extruded layer by layer to get the desired product.[1] For the current work, the thermoplastic chosen is polylactic acid (PLA). Apart from consumer goods like disposable tableware and cutlery, it finds application in biodegradable medical devices like rods, pins, screws and plates, especially for the components that need to degrade in a few months to a year.[2] Apart from customization and design complexity possibility in additively manufactured parts, it also permits tool-less, inventory-less (on-demand printing is possible) manufacturing. In spite of the above advantages, it also has certain limitations in terms of the accuracy of the parts produced, print parameter-dependent mechanical properties, removal of the support material, raw material limitations, etc. Some researchers examined the accuracies of dentistry models printed using stereolithography apparatus (SLA) and digital light processing (DLP) 3D printing processes at various thicknesses. They created dental pieces with a layer thickness of 20–100 µm. DLP-printed dental models with a layer thickness of 100 µm showed higher print accuracy. But in the case of SLA models, they observed that as the thickness of layers decreased, the printing accuracy was good.[3] Few researchers experimented with a two-layer thickness and two different densities of an ABS material. With 100-% infill densities and layer thickness of 0.254 mm, they got better dimensional accuracy behaviour.

From the studies on the effect of processing parameters on the mechanical characteristics of PLA produced with fused filament fabrication, researchers concluded that as the infill density increased the tensile and Young's modulus values increased as well. However, the infill patterns used, namely i) a gyroid ii) concentric iii) square grid and iv) triangle, did not have any significant impact on the properties.[4] Among the different process parameters tried, namely the raster orientation, build orientation, infill density, nozzle diameter, shell number,

*Corresponding author's e-mail:
anandronaldb@ssn.edu.in (B. Anand Ronald)

extrusion temperature, and extruding speed, the authors found that build orientation, infill density and nozzle diameter significantly influenced the part strength.[5,6] From the fracture studies on FDM-printed PLA, the authors concluded that the 0° raster direction gave a higher fracture strength compared to the 45° and 90° orientation.[7] In the study on the influence of different printing parameters, namely the number of layers, layer height and interfilament distance, on the tensile properties of 3D printed, continuous flax/PLA biocomposites, the results showed that by changing the layer height from 0.6 mm to 0.2 mm, the porosity was reduced and tensile properties were improved. And when the number of layers was increased owing to the compaction effect of the current layer on the previous layer, better tensile properties were observed. When the layer height was increased from 0.2 mm to 0.6 mm, there was a significant increase in the porosity levels. When the interfilament distance was low, there was a possibility of overlapping, leading to porosity.[8]

According to the study on the influence of the degree of hollowness (0–30 % with a 10 % increment) on the tensile and flexural properties of PLA, irrespective of the type of material or internal porous structure, the properties decreased with increasing the hollowness level.[9] The influence of the infill density and layer thickness on the mechanical properties (tensile, fracture) was studied and good tensile properties were found for the 0.3 mm layer thickness and 80 % infill density.[10] Some researchers also made a PLA–Cu composite filament wire with a 1.75 mm diameter that was FDM printed, followed by shear and impact testing.[11]

The studied literature mostly talks about understanding the influences of the infill densities, infill pattern, a few print angles (0°,45°,90°) and layer parameters (layer height, interfilament distance) on the mechanical properties and dimensional accuracies using different printing methods. However, the influences of intermediate angles and build orientation axis on the mechanical properties were not studied much according to the literature. Hence, in the present work, the influence of the build orientation axis and angle on the tensile and flexural properties of FDM-printed PLA samples are studied.

2 EXPERIMENTAL PART

A Sharebot Viper fused deposition modeling machine (**Figure 1**) was used for printing the PLA, having specifications as follows: Nozzle Diameter: 0.4 mm, Filament Diameter: 1.75 mm, Printing Speed: 60 mm/s, Layer Thickness: 180 microns, Extrusion Temperature: 210 °C, Bed Temperature: 35 °C, Infill Density: 100 %, Tool Path Contour: Rectilinear. First, a CAD model of a sample was prepared using *Autodesk Fusion 360* and slicing was done using the *Simplify 3D* software. For this study, dog bone tensile samples based on ASTM D638 Type 1 were printed. The samples were printed (**Figure 2**) for 0°, 15°, 30°, 45°, 60°, 75° and 90° in both orientations (with respect to X & Y) and the influence of the build orientation axis and angle on the tensile and flexural properties were studied.

The print material used was PLA +, having its Tensile strength – 65 MPa; Elongation at break – 12 %; Density – 1.25 g/cm^3; Melt flow index (g/10 min) – 4 (190°C/2.16 kg); Heat distortion temperature (°C, 0.45 MPa) – 52; Flexural strength – 75 MPa; Flexural modulus – 2102 MPa; Izod impact – 8.5 KJ/m^3, based on the information provided by the supplier (eSUN Filaments). Tensile tests were performed using UTM WDW100 (Make: Jinan Testing Equipment IE Corpora-

Figure 1: SHAREBOT VIPER FDM machine

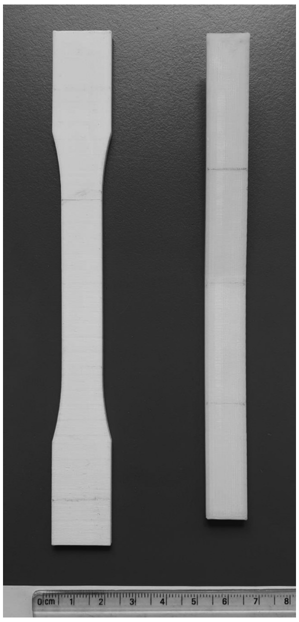

Figure 2: Tensile and flexural samples

tion, having a load capacity of 100 kN. Flexural tests were conducted on an MTS inside an EM 100 kN machine, following the ASTM D790 standard. Results for the flexural modulus and flexural strength are reported in the results and discussion section.

3 RESULTS AND DISCUSSION

3.1 Tensile properties for different print angles and orientations

While performing mechanical tests, internal stresses develop in the sample. A mechanical test is conducted up to the limit when these internal stresses exceed the material's maximum bearing stresses. Referring to the illustrations in **Figure 3** (stress-strain graph) and **Figure 5**, we can conclude that the X75 sample showed an ultimate tensile strength (UTS) value of around 44 MPa, and the X90 sample showed a comparable value.

However, the strain % is better for the X90 sample (13 %) compared to the X75 sample, which showed only a 7 % strain. The strain % of the X90 sample is even slightly higher than that of the initial raw wires (see experimental details), which shows that the bonding between layers was good, thereby providing good tensile properties. The X0 sample also showed a strain (ie., 11 %) comparable to that of X90, although its ultimate tensile strength was relatively low. The X15 and X60 samples showed relatively low UTS values.

On the illustration of the stress-strain characteristics for the samples printed at different angles with respect to the Y-orientation, shown in **Figure 4**, we can see an opposite trend. For higher print angles, the UTS was relatively low and the strain % was also low. The Y0 sample showed the highest ultimate tensile strength of around 36 MPa. The lowest UTS was observed for Y60 followed by Y45. The strain % was also relatively high for the Y0 sample compared to any other sample. When printing in the Y0 configuration, the number of layers needed for the desired geometry is lower compared to the other build angles; hence, only the bonding between a few layers is required, giving scope for relatively fewer defects. On the contrary, Y90, Y75, Y60 and Y45 showed relatively poor strain %, indicating a poor ductility compared to the Y0 sample. The UTSs of these samples were also relatively low compared to Y0. For higher build angles, more layers are required and so the bonding between many layers is required, leading to delamination of layers during the tensile testing.[12,13]

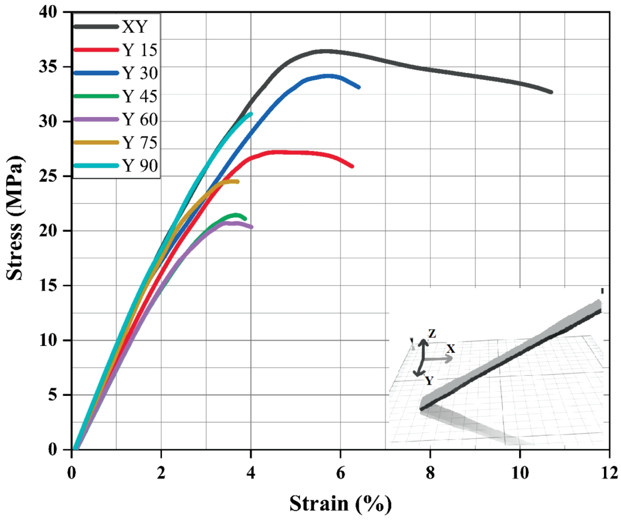

Figure 4: Stress-strain graphs for Y-oriented samples

From **Figures 3, 4** and **5**, it can be observed that the X-oriented samples show better ultimate tensile strength values, irrespective of the build angle, compared to the Y-samples. At the 0° build angle, the orientation of the build does not influence the UTS and % elongation values. However, at the 90° build angle, the orientation (X or Y) of the print has a significant influence on the UTS and % elongation values. As discussed earlier, when

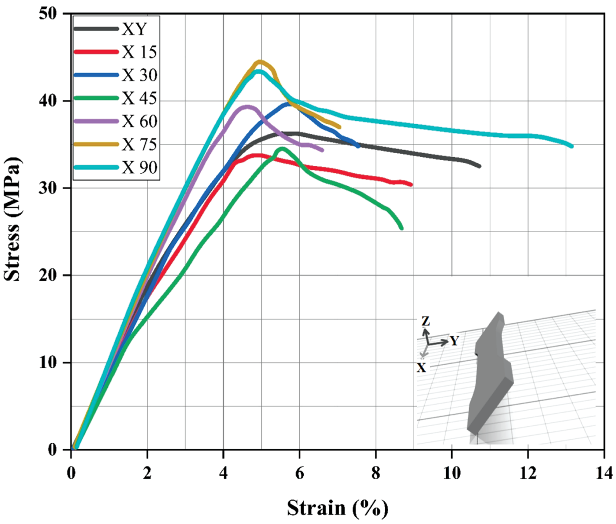

Figure 3: Stress-strain graphs for X-oriented samples

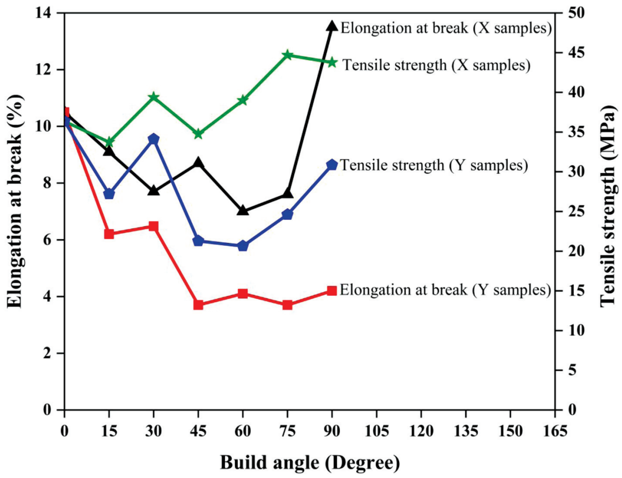

Figure 5: Comparison of the failure strain (elongation at break) and tensile strength of the samples printed at different angles to the X- and Y-orientations

samples are printed with their longer edge being the base in the X-orientation, the number of layers is lower than for the Y-orientation. The higher the number of layers for the Y-orientation, the higher are the chances of improper fusing. Also, the staircase effect in the case of curved and inclined surfaces, typical of additively manufactured parts, becomes more prominent for the Y-orientation since more layers (more steps) are printed to get the desired geometry.[14,15]

3.2 Flexural properties for different print angles and orientations

The capacity of a material to endure the bending forces applied perpendicularly to its longitudinal axis is known as the flexural strength. For biomedical applications like rods, pins, screws, plates, etc., the flexural properties are important. According to **Figure 6**, for most print angles the bending strength was in the 70 MPa (X15) to 90 MPa range (X75, X30). The flexural strength for most print angles was almost equivalent to that of the raw wire, i.e., 75 MPa. We can also infer that the 75° print angle and X-axis build orientation allow better flexural properties. For the Y-samples (**Figure 7**), the trend of the flexural strength was similar to that of the tensile samples with higher build angles showing a poorer flexural strength, and lower angles showing a better flexural strength. For most print angles there was an overlap of the stress–strain graphs and hence, only a few curves can be seen. Hence, we can observe that the orientation of the build has a significant effect on the tensile as well as flexural properties of the printed PLA material.

From **Figure 8**, it can be observed that an increase in the build angle increases the flexural modulus for both X- and Y-samples in most cases. For a given build angle, X-samples always exhibit a higher flexural strength than

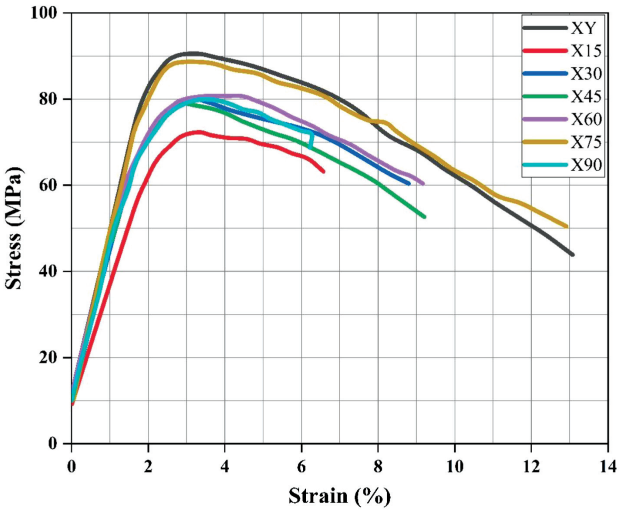

Figure 6: Flexural stress-strain graphs for X-samples

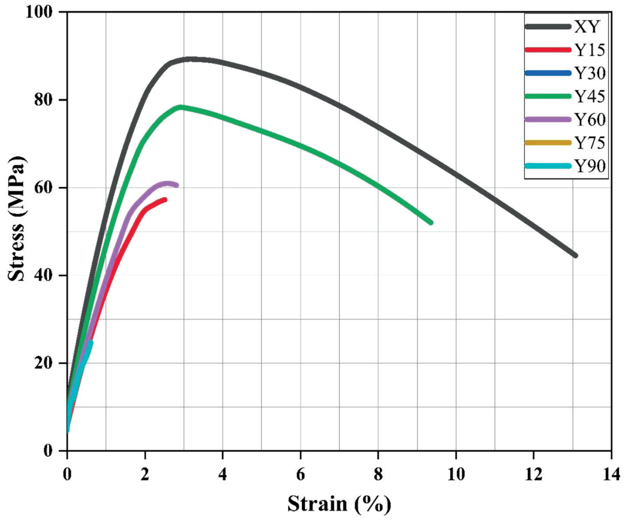

Figure 7: Flexural stress-strain graphs for Y-samples

Y-samples. Also, for a given angle, Y-samples show a higher flexural modulus than X-samples.

4 CONCLUSIONS

From the above study of the influence of the build orientation on the tensile and flexural properties of fused deposition modelling (FDM) printed polylactic acid (PLA), the following inferences can be made:

- From the study of the influences of the build orientation axis and build angle on the mechanical properties, we can infer that the X-oriented samples had better tensile and flexural properties and the trend reversed when the print orientation was changed to the Y configuration.
- The X75 orientation provided the highest tensile strength value of 44 MPa and flexural properties on par with the raw wire.
- Commercially used fused deposition modelling 3D printers could very well be considered as an econom-

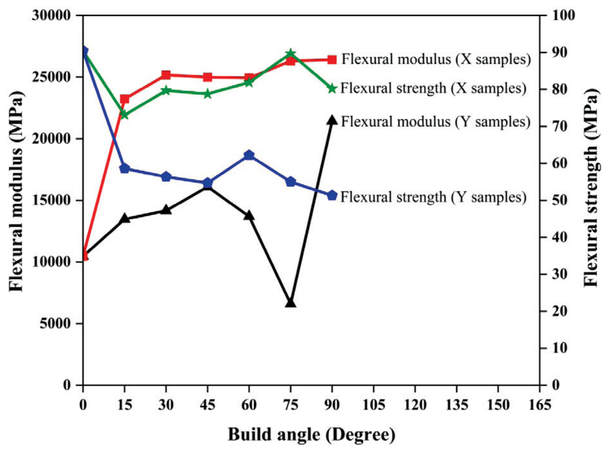

Figure 8: Comparisons of the flexural modulus and flexural strength values of the samples printed at different angles for X- and Y-orientations

ical optiona for making useful parts with good mechanical properties under the above-mentioned printing conditions.

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