MATERIAL INVESTIGATION AND EFFECT OF PRINTING ORIENTATION, TENSILE SPEED, AND DENSITY ON THE MECHANICAL BEHAVIOUR OF 3D PRINTED PARTS

K. Ben Amor[1], S. Chatti[2*], B. Louhichi[3]

[1]Laboratory of Mechanical Engineering (LGM), National Engineering School of Sousse (ENISO), University of Sousse, 4000 Sousse, Tunisia
[2]Laboratory of Mechanical Engineering (LGM), National Engineering School of Monastir (ENIM), University of Monastir, Rue Ibn El Jazzar, 5000 Monastir, Tunisia
[3]Department of Mechanical Engineering, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), 11432 Riyadh, Saudi Arabia
*Corresponding author's e-mail address: sami.chatti@udo.edu

ABSTRACT

Additive manufacturing (AM), also known as 3D printing, is becoming one of the main manufacturing sources in most fields, due to its easy manipulation and time, and cost savings. It is the most favourable manufacturing technology for prototyping, unit or limited production size, and personalized objects. However, the AM's most common problem found is the lack of material information due to the different printing parameters and different materials. The fused deposition modelling (FDM) is the mostly used AM technology since it is the cheapest and easiest manufacturing technique. This technology has various materials and printing parameters that affect the mechanical properties. Multiple types of research were made on the effect of the different printing parameters, other on the material properties, and few worked on the effect of different materials. In the scope of our work, the effect of the printing orientation on different materials and the effect of varying the density on the mechanical behaviour are investigated. Moreover, the FDM part's mechanical behaviour is still on investigation. We investigated the effect of tensile tests with different speeds on the specimens to analyse this behaviour. For this purpose, we printed different tensile specimens with different materials, printing directions, and densities. Then, we studied the effect of each parameter on the mechanical behaviour using tensile tests. It was found out that the printing parameters have a significant impact on the mechanical properties, but the tensile speed doesn't affect the behaviour if the test is made at an environmental temperature.

KEYWORDS: 3D printing, fused deposition modelling, printing parameters, tensile test, mechanical behaviour

1. INTRODUCTION

Additive manufacturing (AM), also referred to as 3D printing, was recently used to manufacture rapid prototyping components. This technology has been mostly used for object development, the development of prototypes, testing products, and the development of customized products [1]. The AM has the potential to manufacture parts for various fields including medicine, automotive, aerospace, education, prototyping, architecture, and construction industries [4]. It can produce parts using a big variety of materials with high quality. AM was initially used to demonstrate surgical planning and research in the medical field, and step by step, this technology has been implemented for the fabrication of various biomedical applications such as implants for medical, dental and tissue engineering, as well as scaffolds and organ transplantation [5]. Various materials ranging from plastics to metals are utilized in different 3D printing processes, which include binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), also known as Fused Deposition Modelling (FDM), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), and vat photopolymerization (VPP) [29]. Each of these technologies has its unique set of printing parameters [2,3]. Among these 3D printing types, the MEX technology is the best known and mostly used due to its ability to manufacture complex objects with high

Date of submission/acceptance: 31.05.2024/15.12.2024
http://doi.org/10.35219/awet.2024.10

precision, low cost, easiness, accessibility of the printing machine, a wide range of material availability and cost, and low power consumption [1]. This process begins with the transformation of a CAD model into a tessellated file format, enabling the model to be divided into discrete layers.

A specialized Computer-Aided Manufacturing (CAM) software is then employed to segment the model into a tool path. This toolpath (G-code) guides the extrusion of the molten thermoplastic material in which material is selectively dispensed through a nozzle or orifice deposited layer by layer, typically in filament form, onto the printing bed following the imported G-code to create the desired part. The MEX process can make parts exhibit varying mechanical behaviour, even when using isotropic materials for the filament [6,29]. This anisotropy depends on factors from the process parameters like part orientation and raster orientation. Several printing parameters, including printing orientation, layer thickness, raster width, raster printing strategy, angle, density, and printing speed, play a crucial role in determining the mechanical properties and quality of a 3D printed part, in addition to influencing the part printing orientation [7]. Also, the choice of material affects the mechanical properties. The most common materials used in the MEX process are PLA, ABS, PETG, nylon, and reinforced polymers. Choosing the optimal process parameters in this technology is a need to attain the desired part response [8].

2. STATE OF THE ART

Various research activities have been made to find the optimal printing parameters for an optimum output needed for 3D printed objects. Using Taguchi's design of experiments (DOE) Galantucci et al. [9] worked on the build direction for the nylon filaments and it was concluded that this parameter has a low effect on the printed parts.

Baier et al. [10] investigated the impact of the printing temperature, layer height, and cooling rate of PLA material. According to the experiments conducted, it was demonstrated that a low layer height, high printing temperature, and high cooling rate have a notable impact in reducing the tensile strength. For the same material, an investigation was conducted to examine how layer thickness, shell thickness, and printing speed affect the tensile strength.

According to the findings presented in the reference [11], it was observed that the maximum tensile strength was attained by increasing the thickness of the shell, decreasing the printing speed, and reducing the layer thickness. Meanwhile, Tontowi et al. [12] conducted a study using Taguchi's orthogonal array and the response surface method to predict the effects of varying raster angles (-45°, 0°, and 60°), extrusion temperature (195 °C, 200 °C, and 205 °C), and layer thickness (0.05, 0.1, and 0.15 mm) on the tensile strength. The results showed that the primary layer thickness had the greatest impact on tensile strength. Furthermore, the response surface method demonstrated a better tensile strength than the Taguchi orthogonal array. In another study conducted by Maloch et al. [13], the influence of extrusion temperature and primary layer thickness on mechanical properties was investigated. The results indicated that rising the temperature and increasing the layer thickness can improve mechanical properties.

A study was carried out by Chadha et. al. [14] to investigate how mechanical properties are affected by the bed temperature and primary layer thickness. Their research revealed that, initially, the tensile and flexural strength of the printed part increased as the bed temperature was raised. However, beyond a certain point, further increases in temperature led to a decline in mechanical strength. Fernandez et al. [15] analysed the impact of infill density, raster angle, extrusion temperature, and layer thickness on the mechanical properties of 3D printed parts with PLA material. Using the analysis of variance (ANOVA) method, it was shown that the layer thickness has the biggest impact on the tensile strength. In this work, the best tensile strength was obtained by 60% infill, 220 °C printing temperature, 0°/90° raster angle, and 0.1 mm layer thickness.

Giri et al. [16] worked on the effect of layer thickness, printing orientation, and cooling rate on the tensile strength and printing time of PLA material. The study revealed that the cooling rate did not impact the mechanical properties for the horizontal orientation. However, increasing the layer thickness from 0.05 mm to 0.1 mm resulted in a higher tensile strength, whereas a decrease in tensile strength was observed above 0.2 mm layer thickness. For the vertical orientation, tensile strength decreases significantly with a higher cooling rate. For the layer thickness, the highest tensile strength was obtained with 0.2 mm and the tensile strength starts decreasing the higher the layer thickness is. The relationship between printing time and layer thickness was established to be inversely proportional, as supported by evidence. This implies that as layer thickness increases, the strength of the printed part decreases. This conclusion was also corroborated by the reference [17].

According to Rankouhi et al. [18], the mechanical properties of ABS material are significantly affected by both layer thickness and raster orientation. Chacon et al. [19], using PLA material, evaluated the effect of the build orientation, feed rate, and layer thickness on the tensile and bending properties. Results showed that these parameters have a big impact on the output. Using ANOVA, Liu et al. [20] showed that layer height, infill pattern, raster width, raster angle, and air gap affect the mechanical properties of the PLA material. The effect of various infill patterns on the compressive strength of ABS material was examined by Iyibilgin et al. [21]. Their research found that the honeycomb infill pattern resulted in the highest modulus. Gebisa et al. [22] conducted a study on the use of high-performance ULTEM 9085 polymeric material and analyzed the impact of various process parameters, including air gap, raster orientation, number of contours, contour width, and raster width, on the tensile properties of the material. It was proved that raster orientation has the highest impact on tensile strength. To have the highest mechanical properties, build time, and surface quality, a study conducted by Sheoran et al. [23] found out that to achieve maximum tensile strength, the build orientation and raster angle should be 0°, with high raster width and lower layer thickness. Additionally, higher infill density, number of contours, and extrusion temperature were shown to result in higher tensile strength. The study also revealed that infill density, layer height, and build orientation had the greatest impact on build time. To have the least build time, it was shown that the part should be built with the least infill density, higher layer thickness, and 0° build orientation. And to have the best part quality, it was recommended to have a low layer thickness which aims to reduce the staircase effect of MEX technology. Some researchers worked on different materials and other parameters. Tymrak et al. [24] investigated PLA and ABS materials and varied layer thickness and raster orientation. They proved that the PLA material had better mechanical properties than ABS. Jiang et al. [25] demonstrated that by adding carbon fiber to MEX polymers, the mechanical properties will be enhanced. Kumar et al. [26] worked on the effect of adding carbon fiber to PETG material and annealing post-process on different infill densities on the mechanical properties. It was found out that the annealing process is more effective on the specimens with 100% infill density and that the CR-PETG specimen at 100% density has higher mechanical properties compared to the PETG specimen at 100% density by 23% gain. These investigations are resumed in the table 1.

Based on the literature review, the MEX printing parameters have a significant impact on the final properties of the 3D printed part. The various parameters, such as layer thickness, raster orientation, infill patterns, infill density, number of contours, extrusion temperature, and build time all affect the mechanical properties of the printed part, such as tensile strength, compressive strength, and modulus. Therefore, selecting optimal printing parameters is crucial to ensure the desired properties of the final product. As per Mohamed et al. [27], the mechanical properties of a 3D printed part are mainly affected by five significant parameters, which include layer thickness, infill density, build orientation, air gap, and raster width. These parameters play a crucial role in determining the final properties of the printed part, including tensile strength, modulus, and compressive strength. Therefore, selecting the optimal values for these parameters is important to ensure the desired mechanical properties of the 3D printed part. Choosing the right material should be considered as a high influence parameter for the part mechanical properties. However, PLA is the most attractive material for researchers because of its high influence on the process parameters compared to ABS [28]. Also, it is easy to print, easy to melt at low temperature, and biodegradable [1].

Various studies were made on the effect of printing parameters and different materials on the mechanical behaviour, which leads us to make an investigation and a comparative study on varying the printing material and its printing orientation and density which are the major parameters affecting the material behaviour. We worked on the different materials PLA, ABS and PETG reinforced with carbon fibers. We printed the needed tensile specimens for this study and made the tensile tests to extract our results. Also, there is a high lack of mechanical characterization of the MEX printed part material in the literature survey. To have a precise modelling of the mechanical behaviour of the material after printing, we made different tensile tests with different tensile speeds (5 mm/min; 50 mm/min; 100 mm/min, and 150 mm/min) at standard environment temperature.

3. MATERIAL AND METHODS

3.1. Material and Machines

3.1.1. Filament

The present study employed Raise3D Premium PLA, FormFutura Premium ABS, and FormFutura Carbonfil PETG as the materials for printing the samples. The diameter of the filaments used was 1.75 mm. The recommended printing parameters for each material are given in table 2.

3.1.2. 3D printer

The specimens in this study were printed using the Raise3D Pro2 printer, as shown in figure 1. This printer is compatible with a wide range of MEX materials and can print at high temperatures of up to 300 °C. The printer is also capable of producing high quality parts with a layer resolution that goes up to 0.01 mm and a precise positioning resolution of 0.0123 mm.

3.1.3 Tensile testing machine

The tensile test was performed on an MTS Insight® Electromechanical Testing System with 200 kN shown in figure 2. It is a universal and flexible computer-driven machine. The PC and the corresponding software process the measured values and control the test sequence. The test speed was set as 5 mm/min (according to the ASTM standard) at an ambient temperature of 23 °C. The results obtained are the engineering stress and strain values. An extensometer was used to measure the strain during the test to ensure accuracy. To convert these values into true stress and strain values, we used the equations (1) and (2):

Table 1. Recapitulation of the state of art

Reference	Material	Printing parameters	Output of the investigation
Galantucci et al. [9]	Nylon	Build direction	Low effect on the printed parts
Baier et al. [10]	PLA	Printing temperature, layer height, cooling rate	Low layer height, high printing temperature and high cooling rate lower the tensile strength of the specimen
Sukindar et al. [11]	PLA	Layer thickness, shell thickness and printing speed	High shell thickness, lower printing speed and low layer thickness increase the tensile strength
Tontowi et al. [12]	PLA	Raster angles, extrusion temperature and layer thickness	Layer thickness has the highest impact on the tensile strength
Maloch et al. [13]	PLA	Extrusion temperature, primary layer thickness	Increasing the extrusion temperature and the layer thickness increases the mechanical properties
Chadha et. al. [14]	PLA	Bed temperature primary layer thickness	Bed temperature affects the mechanical properties
Fernandez et al. [15]	PLA	Infill density, raster angle, extrusion temperature and layer thickness	Layer thickness has the highest impact on tensile strength, the optimum results were obtained with 60% infill, 220 °C extrusion temperature, 0°/90° raster angle and 0.1 mm layer thickness
Giri et al. [16]	PLA	Layer thickness, printing orientation and cooling rate	Cooling rate doesn't affect the mechanical properties on horizontal orientation. Tensile strength increases when increasing the layer thickness from 0.05 to 0.2 mm and it decreases with a layer thickness above 0.2 mm. High cooling rate decreases the tensile strength at vertical orientation.
Ziemian et al. [17]	PLA	Printing time and layer thickness	Low layer thickness increases printing time and increasing the layer thickness causes a decrease in tensile strength.
Rankouhi et al. [18]	ABS	Layer thickness and raster orientation	Layer thickness and raster orientation have a big impact on the mechanical properties
Chacon et al. [19]	PLA	Build orientation, feed rate and layer thickness	Big impact on the bending properties
Liu et al. [20]	PLA	Layer height, infill pattern, raster width, raster angle	Impact on the mechanical properties
Iyibilgin et al. [21]	ABS	Infill patterns	Honeycomb infill patterns have the highest modulus
Gebisa et al. [22]	ULTEM 9085 polymeric	Air gap, raster orientation, number of contours, contour and raster widths	Raster orientation has the highest impact on the mechanical properties, build time and the surface quality
Sheoran et al. [23]	PLA	Build orientation, raster angle, raster width and thickness, infill density, number of contours, extrusion temperature	Infill density, number of contours and extrusion temperature have the highest impact on tensile strength. Infill density, layer height and build orientation have the highest impact on build time and to have the maximum tensile strength, build orientation and raster angle should be 0°, high raster width, low layer thickness.
Tymrak et al. [24]	PLA and ABS	Layer thickness and raster orientation	PLA material has better mechanical properties
Jiang et al. [25]	carbon fiber filled (CFF)	Raster orientation	By adding the CFF, the tensile modulus gets higher in all orientations. The 0° orientation performed the best tensile

	PLA, ABS, PETG, and amphora		strength. PLA material performed better than ABS, PETG and amphora in terms of mechanical properties.
Kumar et al. [26]	CR-PETG and PETG	Infill density and annealing post-process	Annealing process works better on specimens with 100% infill and by adding the carbon fiber to the PETG, the specimen gains 23% of its mechanical properties

Table 2. Recommended printing parameters for different materials (according to material providers)

Material	Printing temperature	Bed temperature	Printing speed	Flow rate
PLA	180 °C-240 °C	0 °C-60 °C	40 mm/s-120 mm/s	100%
ABS	220 °C-270 °C	90 °C-110 °C	40 mm/s-90 mm/s	104%
PETG-CR	230 °C-265 °C	0 °C-100 °C	40 mm/s-120 mm/s	100%

Fig. 1. Raise3D Pro 2 MEX printer

Fig. 2. Tensile test machine

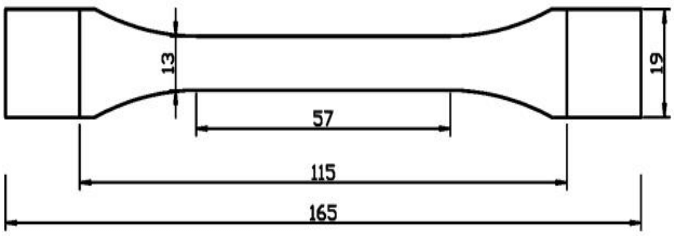

Fig. 3. ASTM D638-02a standard dimensions

True stress : $\delta = R(1+e)$ (1)

True strain : $\varepsilon = \ln(1+e)$ (2)

with R: engineering stress and e: engineering strain.

3.2. Methods

3.2.1. Tensile specimen

To carry out a study on the different specimens printed by the FDM technology, the ASTM D638-02a (type I specimen) standard was chosen to accomplish the tensile tests with the dimensions indicated in figure 3 with a thickness of 4 mm. The design of the tensile test specimens was performed using SolidWorks software and this file was saved as STL. Then we imported the STL file into the slicing software.

3.2.2. Printing parameters

To set our printing parameters, we used the slicing software IdeaMaker. It is easy to manipulate, and it gives the user the freedom to manipulate the advanced printing parameters. Each material we used has its own printing parameters and conditions. We fixed the following common parameters given in table 3.

The variable parameters are divided into two groups; those who are related to the materials given in table 4, and those non-related to the materials. We varied the latter depending on our research conditions. The printing orientations chosen are 00°, 45°/-45°, and 90°. The infill densities are 10%, 30%, 60%, 80%, and 100%. The mechanical behavior of the PLA material was studied to examine the impact of infill density, as it is the most utilized material in MEX technology, and its properties are significantly influenced by the process parameters. The objective of this research was to gain valuable insights into the optimization of printing parameters for this widely used material by investigating the effect of infill density on its mechanical properties.

Once the printing parameters were chosen, the necessary specimens were printed, and tensile tests were conducted to evaluate the mechanical properties. The results of these tests are discussed in the subsequent section of this study.

Table 3. Fixed printing parameters

Parameter	Value / type
Nozzle diameter	ø0.4 mm
Layer height	0.15 mm
Number of contours	2
Pattern	Grid
Overlap	15%
Infill printing speed	60 mm/s

4. RESULTS AND DISCUSSION

4.1. Effect of the Material and Printing Orientation

To validate our results, for each material and for each orientation (0°, 90°, 45°/-45°), 3 tensile specimens were printed. We took the average curve and compared the effect of printing orientations for each material and the effect of the material on the mechanical behavior as given in the figures 4, 5, 6, 7, 8, and 9.

In the following part, we calculated the percentages following the equation (3), which is used to evaluate the gain or loss between the results to better understand the influence of the parameters discussed.

$$Percentage = (V_{max} - V_{min})/V_{min} \qquad (3)$$

Figure 4 shows that the 00° PLA specimen possesses the most stress resistance by 50 MPa and a strain value at fracture of 8.4%. The 45°/-45° specimen has 34 MPa stress resistance and 13.4% strain at fracture, which is nearly double the 00° specimen. And the 90° specimen has the lowest stress resistance by 16 MPa and 4.8% strain at fracture.

For the ABS material, figure 5 shows that both 00° and 45°/-45° specimens have almost the same curve shape with a small difference; the 00° possesses a higher stress resistance with 38 MPa and the 45°/-45° 33 MPa maximum stress. And reversed for strain values, the 45°/-45° specimen is higher with 3.1% and 2.8% for 00°. The 90° specimen possesses the same elastic curve, but the failure occurs close to the 0.8% strain at a stress of 14 MPa.

Figure 6 gives the PETG-CR material curves. The 00° specimen possesses the highest stress resistance of 62 MPa with the lowest strain of 2.5%, followed by the 45°/-45° with 38 MPa stress resistance and 3.4% strain at fracture. The lowest stress resistance is for the 90° specimen at 3% strain. The table 5 resumes these results.

Figures 7, 8, and 9 give the different curves of the different materials for the same printing orientation. The 00° printing orientation curves (figure 7) showed that PETG-CR material has the highest stress resistance by 24% more than PLA and 63% higher than ABS, but it possesses nearly the same strain value as ABS which is a low strain value compared to PLA. Thus, PLA material has the highest strain value, nearly 236% higher than PETG-CR and 200% than ABS.

Figure 8 provides us with the different curves of 45°/-45° tensile specimens of different materials, the strain value is the same as the 00° specimens where PLA material has the highest value and both ABS and PETG-CR materials have nearly the same strain value. For stress resistance, the three materials have similar values.

Both ABS and PETG-CR materials have the same curve shape with a small difference that the ABS is a bit lower than PETG-CR in both stress and strain values. And PLA material is in between both for stress resistance, but it has a high ductility (13.4%) which makes it the best deformable material.

Table 4. Selected printing parameters for each material

Material	Printing temperature [°C]	Bed temperature [°C]	Printing speed [mm/s]	Flow rate [%]
PLA	210	60	60	100
ABS	260	100	60	104
PETG-CR	260	80	60	100

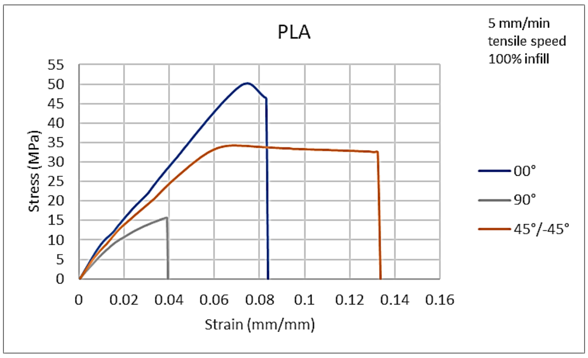

Fig. 4. PLA material curves for each orientation

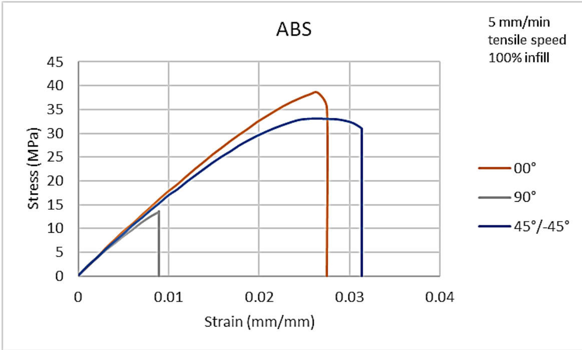

Fig. 5. ABS material curves for each orientation

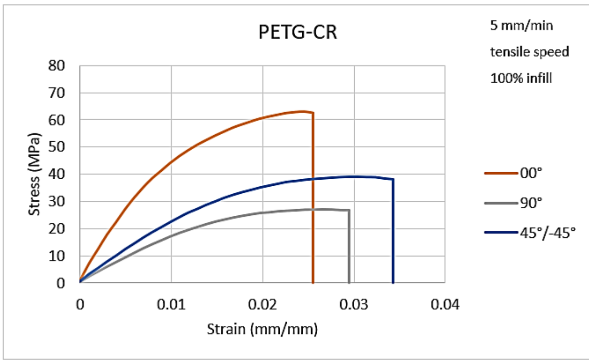

Fig. 6. PETG-CR material curves for each orientation

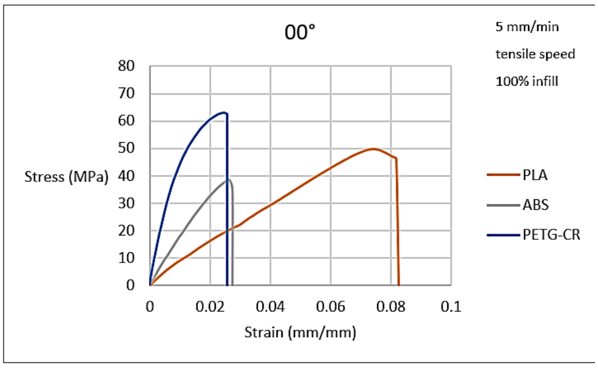

Fig. 7. Different material curves for 00° orientation

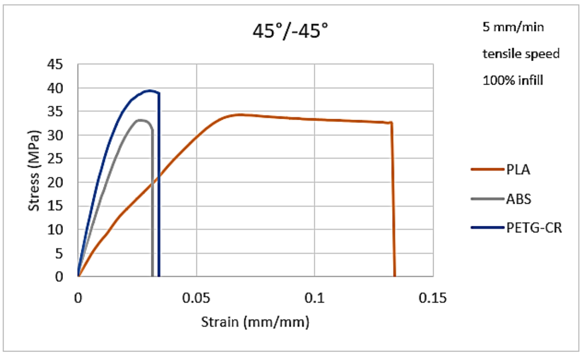

Fig. 8. Different material curves for 45°/-45° orientation

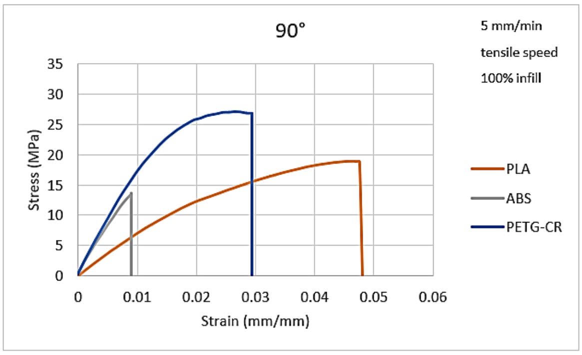

Fig. 9. Different material curves for 90° orientation

Table 5. Tensile tests maximum stress and strain values

Printing orientation	**Material**					
	PLA		**ABS**		**PETG-CR**	
	Max Stress [MPa]	Strain [mm/mm]	Max Stress [MPa]	Strain [mm/mm]	Max Stress [MPa]	Strain [mm/mm]
0°	50	8.4%	38	2.8%	62	2.5%
90°	16	4.8%	14	0.8%	27	3%
45°/-45°	34	13.4%	33	3.1%	38	3.4%

Moving to the 90° specimens, figure 9 shows that both ABS and PETG-CR specimens have the same curve shape in the beginning of the tensile test, but the failure occurs away faster for ABS material, nearly the third strain amount of PETG-CR. PLA material provides a different mechanical behavior, it has the highest strain value with 60% more than PETG-CR and a 500% higher strain than ABS.

The PLA material has the highest deformations for all printing orientations. The PETG-CR material is the most resistant to stress, but it has a lower strain resistance than PLA, making it harder but more fragile. ABS material is the weakest material and the hardest for printing. This work can lead us to the following benefits:

- The 00° orientation provided the highest stress resistance and reasonable strain values. The 45°/-45° orientation showed increased ductility, which can be beneficial for certain applications requiring flexibility. Which shows that the raster orientation has a big impact over the mechanical properties, which was also proven by Rankouhi et al. [18].
- At 00° the PLA material performed the best tensile stress resistance (50 MPa) compared to ABS material (38 MPa), which was also proven by D. K. K. Cavalcanti et al. [30]. However, the strain results are different with his ABS material which performed a higher ductility than PLA. This can be due to the different material providers or other material properties.
- PLA material demonstrated good overall performance, higher ductility and better mechanical properties. This was proven by Tymark et al. [24] and Jiang et al. [25].
- PETG-CR material displayed high stress resistance, making it suitable for applications requiring strength. However, it had lower strain resistance compared to PLA, indicating that it may be less deformable.
- ABS material showed relatively good performance, with comparable stress resistance in different printing orientations. And this material is mostly suitable for applications with high temperature.

4.2 Effect of Infill Density on PLA Material

In the following study, the effect of different infill densities on the mechanical properties of 3D printed objects was investigated using PLA material. PLA was chosen for its superior ductility and overall performance compared to other materials. The infill densities examined were 10%, 30%, 60%, 80%, and 100%. By varying the infill density, the study aimed to understand how it influences the strength, flexibility, and other mechanical properties of PLA prints. The findings of this investigation will provide valuable insights for optimizing the infill density to achieve the desired balance between strength and deformability in PLA 3D printed objects.

Figure 10 shows the different stress-strain curves for different density values of the PLA specimens. We notice that the five curves have almost the same shape and the mechanical properties evolve in a proportional way to the density. These tests results are resumed in the table 6.

Table 6. Different infill tensile tests results

	Infill				
	10%	30%	60%	80%	100%
Stress [MPa]	19	21	24	27	34
Strain [mm/mm]	7.6%	10.1%	10.6%	11.4%	13.4%

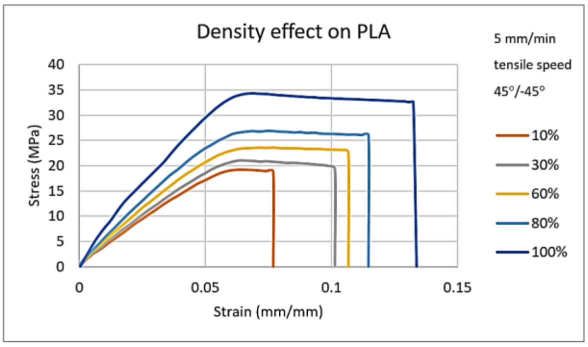

Fig. 10. Curves of different densities of PLA

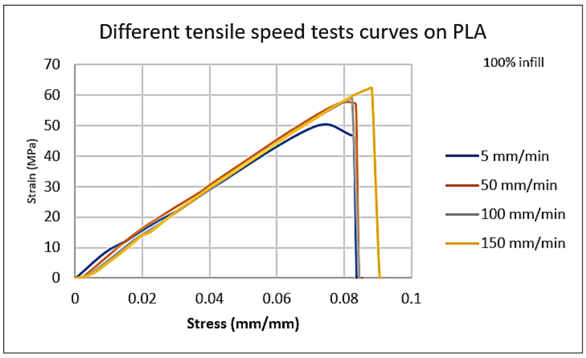

Fig. 11. Curves of different tensile speed on PLA

The stress values increased as the infill density increased. Similarly, the strain values also showed an increasing trend with higher infill densities.

The higher the density, the higher the stress resistance gain. Starting from 10.5% stress gain from 10% to 30% density, up to 14.2% stress rise for the passage from 30% to 60% density. From 60% to 80% density, the stress is raised by 12.5%. An increase of 25.9% in stress resistance is reached when increasing the density from 80% to 100%. The same goes for the strain ratio, by increasing the density, the strain increases. The highest gain is obtained by increasing density from 10% to 30% with a 32.8% strain value gain. And respectively 4.9%, 7.5%, and 17.5% gain moving from 30% to 60%, 60% to 80%, and 80% to 100% density.

The investigation focused on studying the effect of different infill densities on PLA prints. The results showed that increasing the infill density led to higher stress resistance and strain values before fracture.

By analysing these findings, several benefits can be derived:

- The infill density has high impact on the mechanical behaviour of the printed parts, which was also proven by Sheoran et al. [23].
- Optimum Infill Density depending on the load case.
- Lightweight Parts by choosing the optimum infill density.
- Cost Savings by choosing a lower infill density, which will decrease the manufacturing time, and the material needed.

Selecting the best infill density provides the user with lightweight parts, cost savings, enhanced printing efficiency, and the ability to customize mechanical properties and achieve a balance between strength and flexibility to meet specific application needs. By optimizing infill density, users can achieve high-performance PLA prints that are both lighter and capable of fulfilling their desired functionality.

4.3. Effect of Tensile Speed on PLA Material

PLA material is also an ideal candidate for investigating the effect of viscosity on printed parts due to several key factors. Firstly, PLA exhibits significant ductility, making it highly suitable for analysing viscosity-related behaviors. Additionally, PLA is known for its ease of printing, lower melting, and crystalline transition temperatures compared to other materials. Consequently, any material with lower ductility and higher crystalline transition temperatures would exhibit a similar dependency on viscosity. Although PLA is considered a visco-elastoplastic material prior to the printing process, limited studies have explored its mechanical behavior specifically after 3D printing.

This knowledge gap motivated our investigation, where we conducted tensile tests on PLA specimens printed in the 00° orientation using various tensile speeds. The results, as shown in figure 11, indicate that the mechanical behavior remains relatively consistent as the tensile speed increases at ambient temperature. Moderate speeds up to 100 mm/min seemingly have negligible effects on the mechanical behavior, while higher speeds (150 mm/min and above) start to exhibit viscosity-related influences. It's worth noting that such high speeds are not commonly encountered in typical applications. Therefore, this observation allows us to consider the behavior of PLA as elastic-plastic when parts are utilized at room temperature, presenting an opportunity for better understanding and utilization of PLA's mechanical properties in practical applications.

The study aimed to understand the material's behavior after 3D printing and how it is influenced by tensile speeds. Tensile tests were conducted on PLA specimens with different tensile speeds, and the results indicated that the mechanical behavior remained relatively consistent with increasing speeds at ambient temperature. Notably, at low and medium speeds, the viscosity effects could be neglected, allowing for simpler material modelling in numerical simulations. The most valuable benefit of this work is the realization that PLA exhibits elastic-plastic behavior in load-speed stress conditions. This finding simplifies material modelling in numerical simulations by enabling the neglect of viscosity effects at low and medium speeds, thus streamlining the modelling process.

5. CONCLUSION

This paper presented a comprehensive exploration of the influence of FDM printing parameters on the mechanical properties of 3D printed specimens. Tensile testing was employed to assess the effects of various printing materials, orientations, infill density, and viscosity on the printed parts.

The findings highlight the distinct characteristics of different materials, with PETG-CR demonstrating high stress resistance and low deformation, while PLA exhibits notable ductility. These insights enable the selection of suitable materials based on specific application requirements, considering factors such as stress levels and ductility needs.

The investigation on infill density emphasized the importance of optimizing density based on the load case to achieve a balance between strength and weight. It is worth noting that the impact of density should also be considered in relation to the size of the part, as larger parts may experience a lower density effect. Additionally, the study revealed that polymer 3D printing materials can be treated as elastic-plastic at low and medium speeds, allowing for the neglect of viscosity effects in material modelling for numerical simulations at room temperature.

As a future direction, further exploration of other printing parameters and a more in-depth analysis of viscosity properties (such as higher tensile speed tests, elevated testing temperatures, and additional materials) are recommended. These perspectives of work will contribute to advancing our understanding of 3D printing processes and enhancing the accuracy and efficiency of material modelling in various applications.

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