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INVESTIGATION OF MECHANICAL BEHAVIOURS OF PLA PARTS MANUFACTURED BY FUSED DEPOSITION MODELING

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Abstract: *Experiments were conducted to characterize the mechanical properties of specimens that were manufactured with fused deposition modelling. Polylactic Acid (PLA) is used as material. One of the tests was tensile test to get informations about the strength value of the material. The other conducted test was cycling loading to learn about material's deformation mechanism.*

Keywords: *Additive Manufacturing, 3D Printing, Fused Deposition Modeling, Effectiveness, Mechanical Behaviour*

INTRODUCTION

Additive manufacturing is a technology that produce parts from three-dimensional model without any process planning. Nowadays, this technology is mostly called 3D printing. The other term is rapid prototyping. This technology makes manufacturing of three-dimensional parts a lot easier.

There are many applications in additive manufacturing and the method and materials classify these applications. Basic methods could be classified as laser melting/laser sintering, stereolithography, material jetting, binder jetting, electron beam melting and fused deposition modelling (FDM). In recent years, FDM technology has gained a public interest. Because, it is easy to use and its machinery is simple. In the coming years, CAD models that would be homeprinted for cost reductions and personalization will replace many of our daily-use plastic products, especially spare parts that are produced by Injection Moulding. However, the problem is mechanical properties of these FDM parts. These properties are not as good as that of the injected materials. In Fused Deposition Modelling, the material that is used in the process is in the form of filament. This filament goes through a nozzle that is heated. Then the material melted and extruded from this nozzle. This process is done layer by layer. The bonding between neighbouring fibres takes place via thermally driven diffusion welding [1]. The choice of material depends on the type of application and desired properties. Nowadays, commonly applied materials include Polylactic Acid (PLA) as a stiff and environmentally-friendly material, Nylon for soft applications (e.g.bracelets), high density polyethylene (HDPE) for the production offood-compatible parts and Acrylonitrile Butadiene Styrene (ABS) as a general solution for tough parts with acceptable strength. Strength of these parts show an alteration according to the manufacturing process, type of material, etc. Process parameters have great influence on the quality and properties of FDM parts.

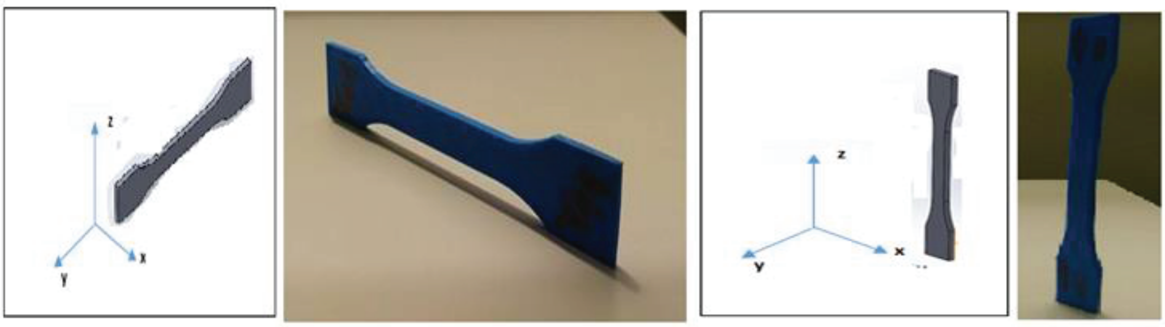
There are studies about effects of characterization and process parameters on mechanical behaviours of polymer based parts produced by FDM. Ahn et al. [2] investigates the mechanical properties of ABS parts manufactured by FDM. Process parameters like raster orientation, air gap, model temperature, color, bead width are studied by using design of experiment approach. Some mechanical properties of FDM parts like tensile strength and compressive strength are compared with the injection-molded parts. The results show that tensile strengths of the parts built by FDM is ranged between 65 and 72 percent of injection molded parts and the compressive strength is about 80-90 percent of the injection molded parts. These ecperimental results are used to formulate build rules in designing FDM parts. O.S. Es-Said et al. [3] performed several tests like tensile, impact and three point bending tests to investigate infleunce of layer orientation on the mechanical properties of ABS samples that built by FDM. During the manufacturing five different orientations are used and these are 0° orientation, 45/-45° orientation, 90° orientation, 0/45° orientation, 45/0° orientation. B.M Tymrak et al. [4] measured the tensile strength and elastic modulus of FDM parts. Distinctly, during the manufacturing process, environmental conditions are choosed realistically and an open source 3D printer for standard users is used. As a result, average tensile strengths of ABS and PLA parts are 28.5 and 56.6 MPa and average elastic modulus are 1807 MPa and 3368 MPa respectively. These research shows that low cost 3D printers could be functional as the ones that used in industry. Rui Zou et al. [5] examined the elasticity and yield strength of specimens of acrylonitrile butadiene styrene (ABS) built by using FDM and investigated the infleunce of different orientation on mechanical properties.There are works in the literature on mechanical behaviours like tensile strength, compressive strength, fatique strength and buckling strength of FDM parts. However, there is no such work about viscoelasticity of these parts. In this work, tensile tests are performed to characterize mechanical properties of material. Viscoelasticity of FDM parts are investigated by conducting cyclic loading tests.

EXPOSITION

Rapid prototyping processes generally include lasers, powders and resins. Fused deposition modelling process by Stratasys Inc. is based on extrusion of semi molten thermoplastic filaments from a nozzle. These semi molten filaments that lay on the manufacturing platform solidates at room temperature. Essentially, five important parameters have great influence on the strength of the FDM part. These are orientation, layer thickness, raster angle, raster width and air gap. Orientation is considered in this study and other parameters are selected constant.

Tensile Tests

In this work, relationship between manufacturing orientation and tensile strength, orientation and strain at ultimate strength, orientation and elastic modulus are investigated. Two manufacturing orientation are used as seen in Figure 1. Orientation is the position of the part on the built platform. Generally, X and Y-axis are considered paralell to this platform and Z-axis is the built direction.



(a) (b)

Fig. 1. Manufacturing Orientation a) Horizontal b) Vertical

For each orientation, three specimens were printed with Maker Robot Replicator 2. Tensile test specimens made from PLA were manufactured by fused deposition modeling with using ISO 527-2 201 standards. Table 1 shows the parameters for the 3D printing.

Table 1. Basic 3D Printing Parameters

Layer Height(mm)	0.2
Raster Angle(^{o})	+45/-45
Infill (%)	100

All specimens were printed in the x-y plane layer by layer and built direction were in the z axis. Tensile test were performed with Testometric Universal Testing Equipment with 3kN load cell and 5mm/min cross head rate. Test results showed that specimens printed with vertical orientation had greater strength and strain values. However, elastic modulus for this orientation were very close to that of the specimens, which had horizontal orientation. Results are shown in Table2.

Table 2. Tensile Test results

Orieantation	**Average Tensile Strength (MPa)**	**Average Yield Strength (MPa)**	**Average Elastic Modulus (MPa)**
Horizontal	47	17,91	1156,12
Vertical	53	21,84	1149,13

Cyclic Loading Tests

Cyclic loading tests are conducted for providing informations about material's deformation mechanism and strength values. It contains loading and unloading of tensile test specimens in certain crosshead speeds. There are four cases about the material's behaviour. These are elastic behaviour, plastic behaviour, viscoelastic behaviour and viscoplastic behaviour. These behaviours could be observed from stress strain graphs for the cyclic loading. In the stress strain graph, if loading and unloading curves overlap and after the unloading, curve gets back to the starting position, it means that material shows elastic behaviour. If loading and unloading tests curves do not overlap and no elastic recovery is observed, we have a plastic behaviour. If the loading and unloading curves do not overlap but merge in the starting point, we have a viscoelastic behaviour. If there is no overlapping but partially elastic recovery is observed, we have viscoplastic behaviour [7].

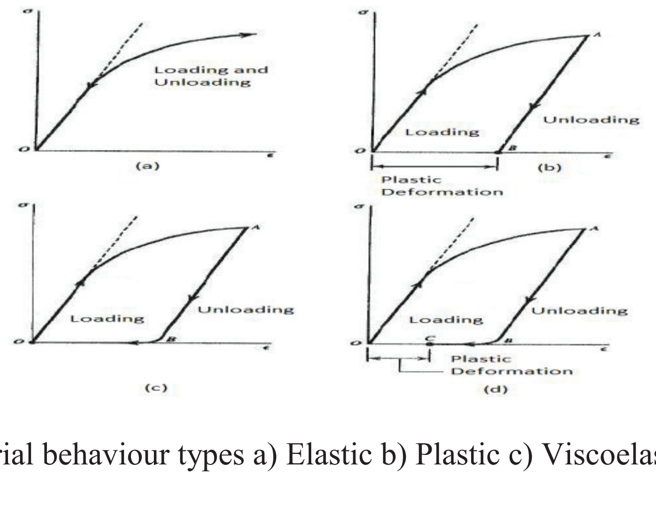
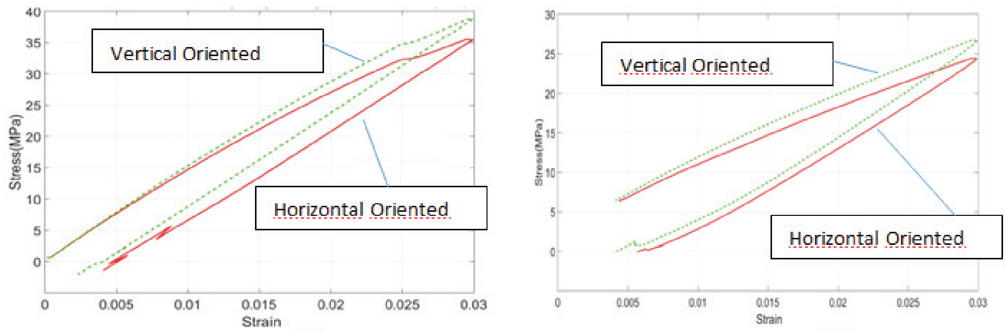


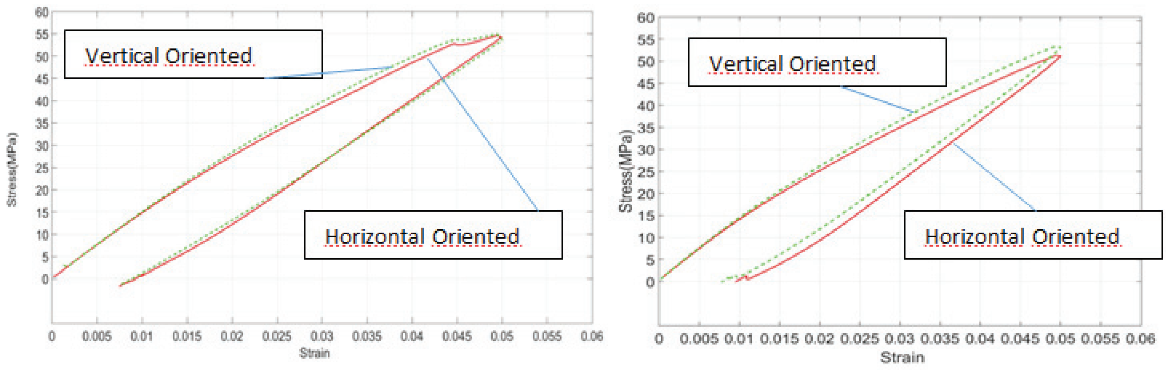
Fig. 2. Nonlinear material behaviour types a) Elastic b) Plastic c) Viscoelastic d) Viscoplastic [8]

3D printed specimens were tested with different speeds that provide quasi-static conditions at different strains. These tests were repeated three times for each speed and strain values then average stress strain curves were plotted. Average stress strain curves for different oriented specimens are shown in Figure 3 and Figure 4. In these plots, experiments were done for 3% strain and 5% strain values at 10^{-2} s^{-1} strain rate and 10^{-3} s^{-1} strain rate.



(a) (b)

Fig. 3 Average Stress Strain Graph (loading-unloading) a) 10^{-2} s^{-1} strain rate, 3% strain b) 10^{-3} s^{-1} strain rate, 3% strain



(a) (b)

Fig. 4 Average Stress Strain Graph (loading-unloading) a) 10^{-2} s^{-1} strain rate, 5% strain b) 10^{-3} s^{-1} strain rate, 5% strain

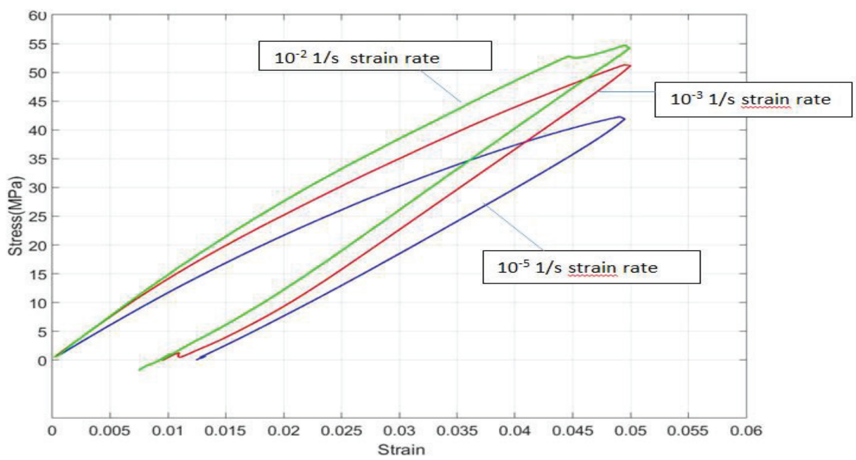


Fig. 5 Uniaxial tensile tests (loading - unloading) at different strain rates and 5% strain. (**Average** stress-strain graph for **horizontal oriented** specimens)

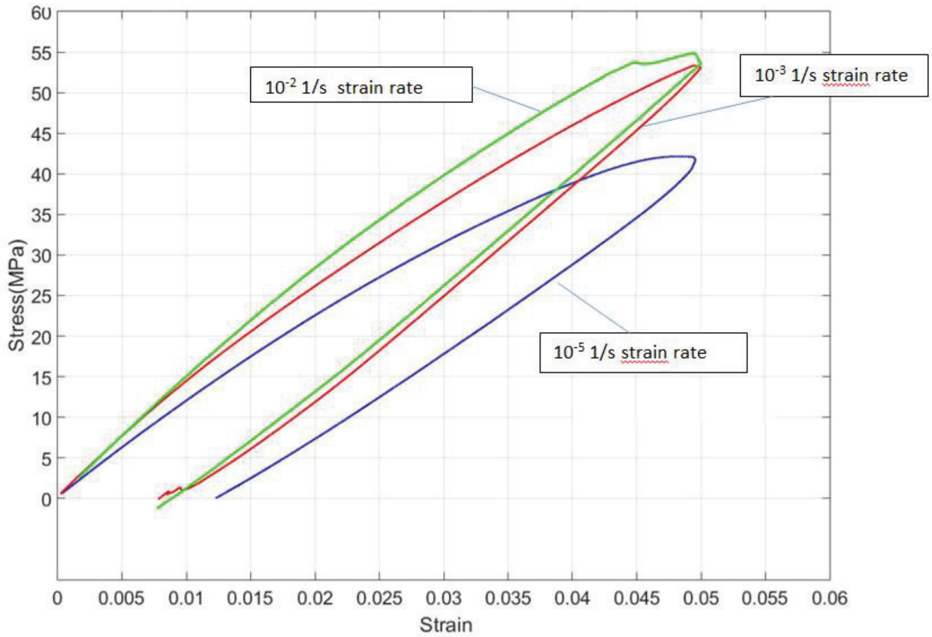


Fig. 6 Uniaxial tensile tests (loading - unloading) at different strain rates and 5% strain. (**Average** stress-strain graph for **vertical oriented** specimens)

CONCLUSION

It could be seen that vertical oriented specimens' strength values are distinguishably higher than horizontal oriented specimens's strength values at 3% strain. However, this distinguishability decreases at 5% strain and strength values are almost the same at this strain. On the other hand, speed dependence of the specimens can be seen in the graphs. Higher strain rate values provides better strength. This statement could be seen much better in Figure 5 and Figure 6. Material shows viscoplastic behaviour as seen in the graphs. Elastic recovery was examined for the tests that were conducted at 5% strain values because there are no distinct differences between different strain rates at 3% strain values. Recovery results are shown in Table 3. Results shows that elastic recovery amounts are not direction depended. Horizontal oriented specimens have almost same elastic recovery amount with the vertical oriented specimens at same strain rates. On the other hand, at lower strain rates elastic recovery amount decreases. It could be associated with the strain hardening. Higher strain rates causes strain hardening and material resists to deformation. This resistance increases the elastic reacovery.

Table 3. Elastic Recovery

Orientation	Strain	Strain Rate	Elastic Recovery
Horizontal	5%	10^{-5} s^{-1}	75%
Vertical	5%	10^{-5} s^{-1}	75%
Horizontal	5%	10^{-3} s^{-1}	81%
Vertical	5%	10^{-3} s^{-1}	84%
Horizontal	5%	10^{-2} s^{-1}	85%
Vertical	5%	10^{-2} s^{-1}	84,4%

REFERENCES

[1] Anoop K. Sood , Raj K. Ohdar , Siba S. Mahapatra (2012), *Experimental investigation and empirical modelling of FDM process for compressive strength improvement,* Journal of Advanced Research (2012) 3, 81–90.

[2] Anoop K. Sood , Raj K. Ohdar , Siba S. Mahapatra (2010), *Parametric appraisal of mechanical property of fused deposition modelling processed parts,* Materials and Design 31 (2010) 287–295.

[3] O. S. Es-Said , J. Foyos , R. Noorani , M. Mendelson , R. Marloth & B. A. Pregger (2000), *Effect of Layer Orientation on Mechanical Properties of Rapid Prototyped Samples,* Materials and Manufacturing Processes, 15:1, 107-122, DOI: 10.1080/10426910008912976.

[4] B.M. Tymrak , M. Kreiger , J.M. Pearce (2014), *Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions,* Materials and Design 58 (2014) 242–246.

[5] Rui Zou a, Yang Xia , Shiyi Liu , Ping Hu , Wenbin Hou a, Qingyuan Hu , Chunlai Shan (2016), *Isotropic and anisotropic elasticity and yielding of 3D printed material*, Composites Part B 99 (2016) 506-513.

[6] Jose´ F. Rodrı´guez, James P. Thomas, John E. Renaud (2003), *Mechanical behavior of acrylonitrile butadiene styrene fused deposition materials modelling,* Rapid Prototyping Journal, Vol. 9 Issue: 4, pp.219-230.

[7] Düşünceli, N. and Çolak, Ö. Ü. (2007), *High Density Polyethylene (HDPE): Experiments and Modeling,* Mechanics of Time-Dependent Materials, 10.1007/s11043-007-9026-5.

[8] Khan F., (2003), *The Deformation Behavior of Solid Polymers and Modeling with The Viscoplasticity Theory Bades on Overstress,* Rensselaer Polytechnic Institute, Troy.