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MECHANICAL TESTING OF ADDITIVE MANUFACTURED POLYMER COMPONENTS USING MATERIAL EXTRUSION TECHNOLOGY.

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ABSTRACT

Additive Manufacture (AM), where 3D components are built up layer-by-layer, is growing within the manufacturing industry. Among other advantages, AM offers new processing routes for the manufacture of components with intricate geometries that are impossible to make by conventional means. However, the current generation of AM techniques have limitations that need to be overcome, particular concerns arise around reliability and consistency in material properties of AM produced parts. This work investigates the mechanical properties of parts produced by material extrusion using a Makerbot Replicator 2 with Polylatic Acid (PLA) filament. A designed experiment was generated to establish process parameter settings for tensile test specimens. Orientation, resolution, infill density and number of shells were the process parameters investigated during the experiment. Tensile test specimens were printed to a recommended ISO test standard for polymers. Tensile testing was carried out. Data was collected for each test specimen, showing main effects and interactions between parameters. The results showed that altering the settings for number of shells, orientation and infill density had an effect on the tensile modulus. However, resolution had minimal effect on the tensile modulus, when altered between 270 and 100 microns. Specific mechanical standards for additive manufacturing in polymers currently do not exist. This work highlights the issues that need to be addressed by any new standardised test methods for AM and proposes changes in current methodology to overcome these challenges.

KEYWORDS: FDM, PLA, Mechanical Properties

1. INTRODUCTION

When considering the mechanical properties of components processed using Additive Manufacture, questions arise regarding the integrity and safety of the material and part. Additive Manufacture technologies, such as Material Extrusion; known commercially as Fused Deposition Modelling or FDM (®Stratasys Inc), currently have no standards for mechanical testing. Another issue is that not all materials for this process are certified for industry use. When presented with Technical Data sheets for Polylatic Acid (PLA) feedstock, widely used in Material Extrusion processes, mechanical properties and testing methods vary. One manufacturer states test method, ASTM D882, which suggests testing has been carried out on the virgin material. Whereas the second used ISO 527 and outlines the processing parameters. This may leave a user confused and unwilling to adopt the process.

1.1 Aims and Objectives

This manuscript outlines results from an experimental study on a PLA Additive Manufacture process. The aim of this experimental study was to investigate process parameters that affect the mechanical properties of components processed via Material Extrusion.

Four objectives of the study were:

- Design and process polymer test specimens using Material Extrusion
- Conduct tensile testing on specimens to find mechanical properties.
- Determine how manufacturing processes parameters influence these mechanical properties
- Extract data from mechanical testing and input into a designed experiment to observe responses.

2. MATERIALS AND METHODS

2.1 Equipment and Material

Formfurtura EasyFil™ PLA, with diameter 1.75mm, was used. The technical data sheet gives the following mechanical properties and test method given in Table 1 below:

Properties	Typical Value	Test Method
Tensile strength	110MPa	ASTM D882
Tensile modulus	3310MPa (MD)	ASTM D882
Elongation at break	160% (MD)	ASTM D882

Table 1 Table showing Mechanical Properties of Formfutura EasyFil™ Filament

When using PLA, there are a number of known factors that may affect the process and mechanical properties of the test specimens. As PLA is hygroscopic, incorrect storage may affect tensile strength, part accuracy and surface finish. To reduce the likelihood of moisture absorption, a new spool in protective stored in protective wrapping was used each time and test specimens were stored with desiccant between processing and testing. The surrounding atmospheric temperatures and humidity were maintained at standard testing conditions of (23 +/- 2) °C and (50 +/- 10) % RH respectively.

In this experiment, a MakerBot Replicator 2® was used to process the test specimens. The machine has a build volume of 285x153x155mm, which is a design constraint to note when modelling parts. Resolution is defined, by the user, in the slicing software settings. Further adjustments were made to ensure the build platform was level. A build platform that is not level would cause issues with the build process and final part. During the experiment, a calibration disc was printed to minimise printing errors. Nozzle diameter and extrusion flow rate determine the extrusion width. The layer height is the distance between the nozzle and build platform. Figure 1 demonstrates this.

A Tinius Olsen Model 25ST was used to carry out tensile testing. The machine has a maximum test force of 25kN and ran at a test speed of 100mm/min.

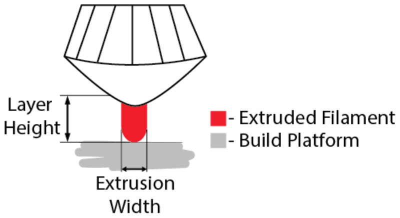

Figure 1 Image showing layer height and extrusion width (amended from source [1]**)**

2.3 Tensile Testing Standards

There are no standards available for tensile testing of polymer parts, processed via material extrusion methods. ISO 17296-3 2014 [2] recommends ISO 527 [3] as a suitable testing method to determine the tensile properties of plastics. ISO 527 [3] references ISO 20753 [4] for test specimen design and dimensions.

Following guidelines, the test specimen in Figure 2 was produced. Test specimens were printed at a reduced size, so they could be processed in z orientation. Test specimens had a designation, A12; where A is the specimen type; 1 is the method of preparation, that is injection moulding and 2 is the scale factor.

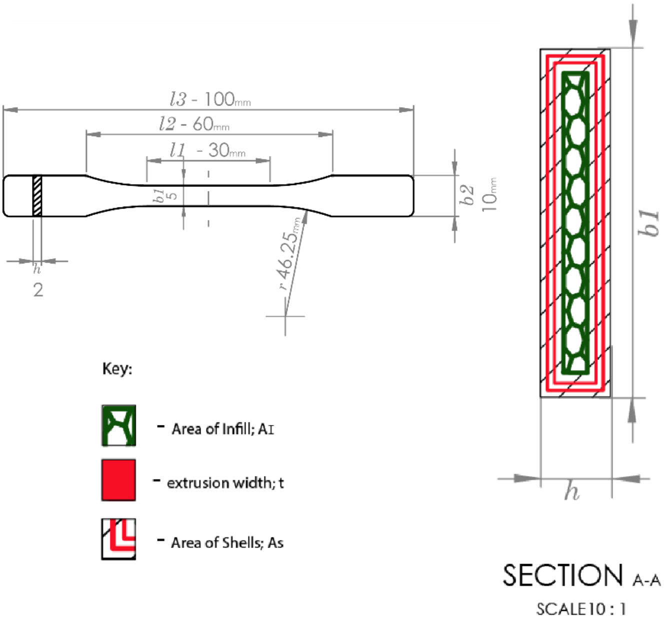

Figure 2 Cross Section Area of a Material Extruded Test Specimen

Figure 2 also shows the internal features of the cross section of a test specimen. Eq. 1 is the calculation used and defined in ISO 527 [3].

$$\boldsymbol{A = bh} \tag{1}$$

Where *b* is the width (mm) and *h* is height (mm).

Calculating cross-sectional area in this way was deemed unsuitable for all test specimens as some had varying infill density and number of shells (that is, they were not always solid). Cross-sectional area was calculated using Eq. (2):

$$\boldsymbol{A_0} = \boldsymbol{A_s} + \boldsymbol{A_I} \tag{2}$$

Where A_0 is the total cross sectional area (mm²), A_s is the area of the shells (mm²), and A_I is the area of Infill (mm²).

Area for Number of Shells and Infill Density were calculated using Eq. (3) and Eq. (4) respectively:

$$\boldsymbol{A_s} = \boldsymbol{bh} - [(\boldsymbol{h} - \boldsymbol{xt})(\boldsymbol{b} - \boldsymbol{xt})] \tag{3}$$

$$\boldsymbol{A_I} = [(\boldsymbol{h} - \boldsymbol{xt})(\boldsymbol{b} - \boldsymbol{xt})]\boldsymbol{I} \tag{4}$$

Where I is the Infill Ratio (e.g., I equals 0.1 when infill density is set to 10%); x is the number of shells, and t is the extrusion width.

Note that if I is equal to 1 (where infill density is 100%) Eq. 1 may be used. If t is greater than b/2, then Eq. 1 may be used.

Engineering Stress (σ) is defined in ISO 527 [3] and considers the actual cross section of the test specimen. Engineering Stress is defined in Eq. (5):

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A_o}} \tag{5}$$

Where *F* is Force in Newtons (N); and *A_o* is the cross-sectional area, mm².

Engineering Strain was calculated using Method A as defined in section 10.2.2.3 of ISO 527 [3]. Eq. 6 was used to calculate Engineering Strain:

$$\boldsymbol{\varepsilon_t} = \frac{\boldsymbol{L_t}}{\boldsymbol{L}} \tag{6}$$

Where $\boldsymbol{\varepsilon_t}$ is the strain, L is the distance measured between the grips (mm); and L_t is the increase in distance between the grips, from the start of the test (mm).

ISO 527 [3] determines the modulus as the slope of the stress/strain curve, within a strain interval of ε_1 (0.0005) and ε_2 (0.0025). The chord slope was found using Eq. (7).

$$\boldsymbol{E_t} = \frac{\boldsymbol{\sigma_2 - \sigma_1}}{\boldsymbol{\varepsilon_2 - \varepsilon_1}} \tag{7}$$

Where E_t is the Tensile Modulus; σ_1 is stress measured at strain value $\varepsilon_1 = 0.0005$; And σ_2 is stress measured at strain value $\varepsilon_2 = 0.0025$.

2.4 Design of Experiments

A General Factorial Design was set up using Minitab 17. Four factors tested in the General Factorial Design, were Orientation (O), Resolution (R), Infill Density (I) and Number of Shells (S). Table 2 shows each factor and the level they were tested at.

Factors	**Orientation**		**Resolution (microns)**		**Infill (%)**		**Shells**		
Levels	xy	z	270	100	10	100	2	4	6
Numeric Levels	-1	1	-1	1	-1	1	-1	0	1

Table 2 Factors and levels used in General Factorial Design

Table 3 shows the Design matrix generated by Minitab. It includes 24 combinations. ISO 527 [3] recommends 5 replicates, which totalled to 120 runs in the experiment.

Test No.	O	R	I	S	Test No.	O	R	I	S
1	-1	-1	-1	-1	**13**	-1	1	-1	1
2	-1	-1	-1	-1	**14**	1	1	-1	0
3	1	-1	-1	1	**15**	1	1	1	-1
4	-1	1	-1	1	**16**	1	-1	1	-1
5	-1	-1	1	0	**17**	1	-1	-1	0
6	1	1	1	1	**18**	-1	-1	-1	1
7	-1	-1	-1	0	**19**	-1	-1	1	1
8	1	1	1	0	**20**	-1	1	-1	0
9	1	1	-1	-1	**21**	-1	-1	1	-1
10	-1	1	1	1	**22**	-1	1	-1	-1
11	1	-1	1	0	**23**	-1	1	1	-1
12	1	-1	-1	-1	**24**	-1	1	1	0

Table 3 Design Matrix for General Factorial Design

3. RESULTS

Table 4 shows the average Tensile Modulus for the four factors at each level.

Response	O	Mean (MPa)	R	Mean (MPa)	I	Mean (MPa)	S	Mean (MPa)
Tensile Modulus (MPa)	-1	1898.90	-1	2148.20	-1	2394.00	-1	2743.00
							0	1954.50
	1	2426.70	1	2182.10	1	1939.70	1	1812.40

Table 4 Average Responses for each factor and level

An analysis was carried out on Minitab and Tensile Modulus was plotted against factors. The Main Effects Plot (Figure 3) and Interaction Plot (Figure 4) show how each factor effected the response. Figure 3 shows that the Number of Shells, from low factor setting (-1) to high factor setting (1), has the greatest effect on the mean Tensile Modulus. Where 2 shells resulted in a higher Tensile Modulus. Resolution exhibit minimal change along the x axis. This meant that changing resolution from 270 microns (standard resolution) to 100 microns (high resolution) had minimal effect on the mean Tensile Modulus. Figure 4 shows how Infill Density and the Number of Shells affected the mean Tensile Modulus with some interaction observed between Orientation and Infill Density. Other factors showed minimal interactions on the outputs.

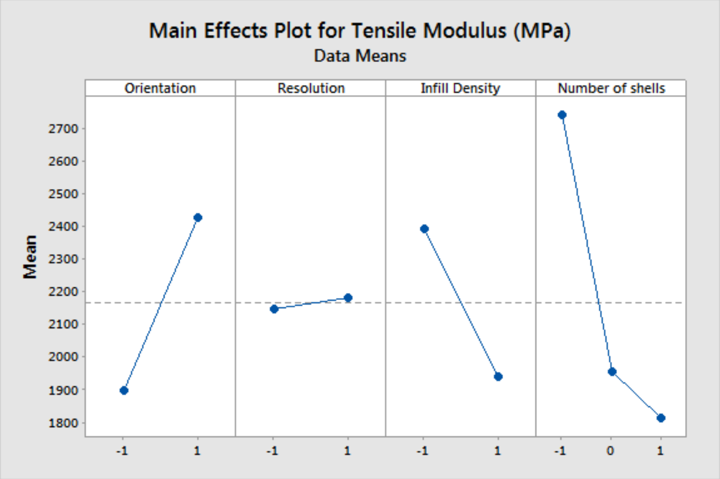

Figure 3 Main Effects Plot for Tensile Modulus (MPa)

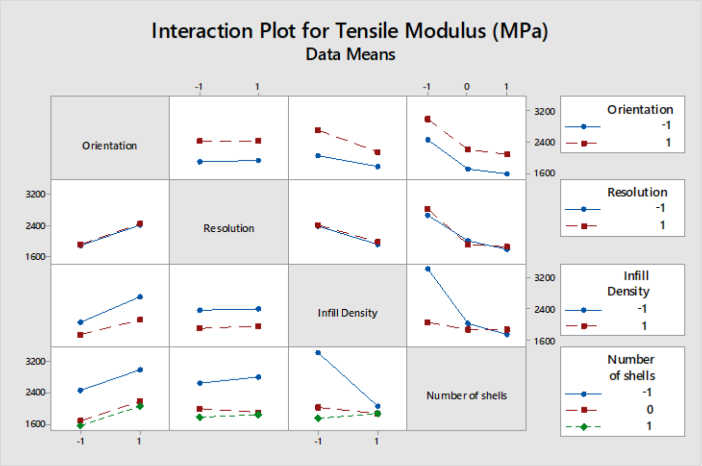

Figure 4 Interaction Plot for Tensile Modulus

A further analysis was carried out to generate a Pareto Chart. A 2k design, which analysis all factors at two levels, was created by removing Number of Shells with a factor setting of 0 (i.e., 4 shells). A total of 80 specimens were evaluated giving the Pareto Chart in Figure 5. The chart shows that factor D (Number of Shells) had the largest effect on Tensile Modulus. Factor B (Resolution) did not have a significant effect on Tensile Modulus.

4. DISCUSSION

During the designed experiment four factors and their levels were altered simultaneoulsy, so their effect on mechanical properties of the additively manufactured test specimens could be analysed.

Results were compared to the properties values given in the Formfutra data sheet. These values can be seen in Figure 1 where it states a Tensile Modulus of 3310 MPa. Within the experiment the minimum and maximum values for Tensile Modulus were 1160 MPa and 4277 MPa respectively:

1160 MPa was the Tensile Modulus of a test specimen printed in the z orientation with resolution of 100 microns, infill density of 100% and 6 Shells.

4277 MPa was the Tensile Modulus of a test specimen printed in the xy orientation with resolution of 100microns, infill density of 10 %, and 2 Shells.

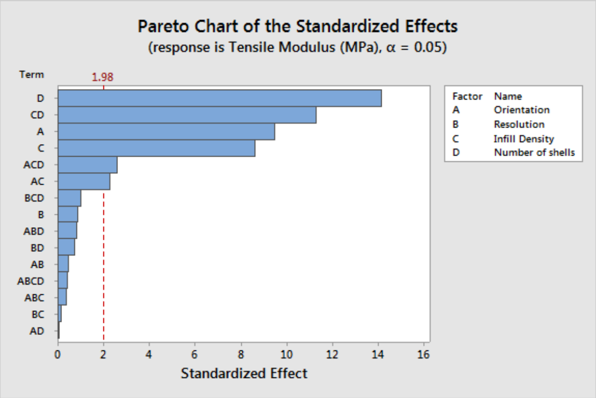

Figure 5 Pareto Chart of Standardised Effects of Response Tensile Modulus

The results show that resolution had minimal effect on Tensile Modulus as both the minimum and maximum values were processed using a high setting of 100 microns. This phenomenon was also confirmed by the main effects and interaction charts. This outcome was not expected as was assumed that the higher the resolution, the greater the tensile properties of the part. When printing at the higher resolution, build time increased considerably. When resolution was set at a high level of 100 microns, build time was increased by 20 minutes in xy orientation and an increase of 1 hour and 15 minute, in z orientation.

Tensile test specimens with 6 Shells, had lower values for Tensile Modulus. Figure 6 is a test specimen printed with 6 shells in xy orientation, producing a

low Tensile Modulus of 1698MPa. This may be the result of a void that occurred during processing with parts printed with 6 Shells, resulting in an area of increased stress.

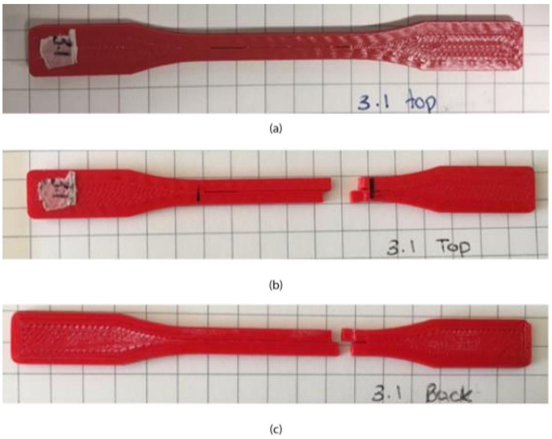

Figure 6 test specimen with 6 shells (a) top view, before testing (b) top view, after testing (c) bottom view, after testing

Minitab was used to generate a summary table of observations with large residuals. This analysis highlighted a number of outlier runs with higher values of Tensile Modulus. It was found that these outlier prints were processed with Scotch Blue 3M tape on the build platform (which assist with the removal of finished specimens). This tape was used for test specimens with 100 micron Resolution and xy Orienation. Issues arouse when printing these parts, so it was decided to add tape for ease of printing. Test specimens processed using tape had a smoother undersurface when compared to those printed without (where shells and infill were visible). The stress/strain curves for these test specimens exhibitted ductile behavious in the material rather than the brittle fracture generally exhibited by the material. A design experiment was set up to test if tape had an effect on Tensile modulus. 3 factors were set at two differnent levels; Tape, Infill and Shells. The results showed that higher Tensile Modulus was produced by parts processed with 2 shells, 10% infill ion a build platform with tape.

5. CONCLUSIONS

The aim of the research was to investigate process parameters that affect the mechanical properties of components processed via polymer material extrusion. It was found that Number of Shells, Infill Density, and Orientation all affected the tensile modulus of the test specimens; whereas, changing Resolution settings from 270 microns to 100 microns had little effect.

The optimal settings for maximum modulus were found to be:

- Orientation set to a high factor level, xy orientation;
- Resolution set to a low level of 270 microns;
- Infill Density set to a low level of 10%;
- Number of Shells set to a low level of 2 shells.

The experiment highlighted that the current approach to tensile testing standards, ISO 527 [3], is not fully suitable. It should be noted that the need for improved testing standards is clear and that efforts to develop the standards are underway, for example, by the America Makes and ANSI Additive Manufacturing Standardization Collaboration (AMSC) organisation. Modification to the current ISO standard test specimen is proposed in this manuscript with supporting results.

6. ACKNOWLEDGEMENTS

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