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Effects of process parameters on print quality and mechanical properties of FDM printed polyoxymethylene samples

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Abstract
POM (Polyoxymethylene) is a widely used engineering thermoplastic. It is relatively easy to be recycled in many industrial applications and one such way could be through 3D printing. FDM printing of polyoxymethylene comes with numerous challenges such as: poor bed adhesion, warping, delamination, and loss of mechanical properties. This research aims to develop reliable printing parameters to improve print quality and investigate the corelation between print quality and mechanical properties of printed samples. Multiple repetitions of varying print parameters have resulted in parts ranging from small prints failing on the first few layers, to large beams and dog-bone samples printed with relatively high quality and just under 60% of bulk material strength.

Additive manufacturing, POM, Polyoxymethylene, FDM, 3D printing

1. Introduction

Polyoxymethylene (POM) is an engineering thermoplastic, preferred for its relatively high stiffness and hardness, low friction, dimensional stability and excellent chemical resistance to fuels and solvents. Many parts with engineering purpose utilize this material's advantageous material properties, such as bearing surfaces, pulley wheels, housing parts and gears. It is therefore not surprising that POM production has been rising steadily from the 1980's with a rate of about 5-7% annually. [1] This polymer is widely used in injection moulding and extrusion processes, as well as being applicable for machining operations. Because of its application in machining operations there is some waste generated in machine shops and factories, creating incentive to find ways to recycle this waste. One such way could be to process the discarded material into filament to use in FDM 3D-Printing. However, additive manufacturing of POM parts using FDM technology is restricted by a number of challenges arising mainly from the level of shrinkage occurring in solidification and by the low coefficient of friction of the material resulting in low adhesion to the build plate, delamination, and warping. FDM printing of POM filament has only recently become accessible through the availability of POM filament and therefore little research can be found about these problems. As an example, Yi-Ta Wang et al. documented effects of print angle on the mechanical properties of FDM manufactured POM structured. However, the article failed to document the printing parameters, show printed samples, or address the challenges involved in the FDM printing of POM material. [2]

The following work focuses on the experimental development of printing parameters, the qualitative assessment of their influence on print quality and destructive testing to evaluate mechanical properties of parts printed from POM material.

2. Material and methodology

Tensile bars and beam samples were produced using FDM technology to perform print quality evaluation by visually inspecting the parts and identifying faults and failures, as well as investigating the tensile strength of the samples by mechanical testing. The beam samples were visually inspected, and the tensile bars were tested.

2.1. Polyoxymethylene

The material used in the work was a polyoxymethylene copolymer supplied as pellets for injection moulding and extrusion production. The material was supplied in pellet form, however, needed to be extruded into rolls of filament to be used in an FDM printer. The filament was produced in a twin screw extruder, at 205°C with a diameter of 1.75 ± 0.2mm.

2.2. FDM printing parameters

The machine used for the printing of the samples was a ***Creality Ender 3 Pro*** with a simple temporary enclosure built around it to try to reduce rapid cooling of the printed parts.

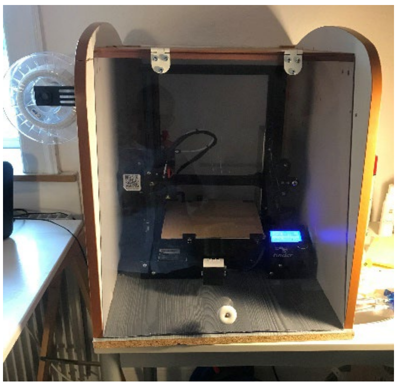

Figure 1. Printer with enclosure.

The Ender's build plate can reach 135°C without modification, limited by the slicer software to 130°C and was set to that maximum temperature throughout all successful prints. Successful printing also required using the backside of a sheet of ***Masonite*** hardboard as the build surface to increase bed adhesion. These factors would ensure that the print would not fail after only a few layers because of excessive warping or poor bed adhesion. Printing parameters that were adjusted included nozzle- temperature and diameter, material flow rate, layer hight and print angle. The tensile testing samples were printed in 5 different layer orientations: along the tension, perpendicular to the tension, alternating between the two by layer, printed standing with alternating print direction and printed standing with a uniform print direction. These are illustrated visually in figure 2 below and have been designated with abbreviations: **LO** for longitudinal, **LA** for lateral, **C** for cross layered, **ZU** for unidirectional z-print and **ZC** for cross directional z-print. The slicer software used to adjust parameters and generate the g-code of the printing process was the **Ultimaker Cura 4.6.1**.

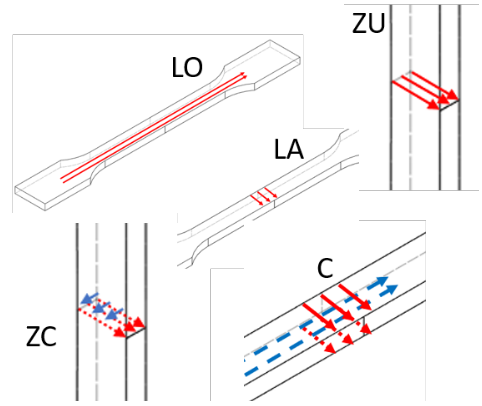

Figure 2. The figure shows how print direction is varied in the samples. **LO**: longitudinal, **LA**: lateral, **C**: cross layered, **ZU**: unidirectional z-print and **ZC**: cross directional z-print.

3. Experimental procedure and qualitative evaluation

The printed samples were beam samples for quality assessment and dog-bone specimen for tensile testing. Using the beam specimen to evaluate the quality of the prints, the print parameters could be tuned to ensure the best outcome for the printed test specimen.

3.1. Quality assessment

Print quality is assessed with two main characteristics in mind: warping and delamination. These are rated on a scale from 1-5, 1 being the worst and 5 being best. Table 1 shows the ranking of beam specimen from figure 3 and their respective print parameters. These print samples were used to progressively tune the parameters of the printing to ensure the highest quality of the tensile specimen. The parameters that were investigated as factors in the print quality were: diameter of the nozzle, nozzle temperature, material flow and layer height.

3.2. Mechanical testing

Tensile tests were conducted on dog-bone specimen after preliminary screening of print quality. The specimen were printed at 250°C with a 0.8mm nozzle diameter, 0.32mm layer height and 100% flow rate. The tensile tests were done in accordance with ***ASTM D638 – 14*** and the specimen were modelled after the type 1 specimen from the standard. As per the standard, the specimen were measured before tests were conducted and the area of the neck was recorded for future stress calculations. The tests were conducted at 5mm/min using the **Mecmesin Emperor™ Force** tensile testing machine.

4. Results

4.1. Print quality

Figure 3 clearly shows that a vast difference in print quality is experienced if certain print parameters are varied. The process of continuously improving print quality through trial and error began with figuring out the nozzle- and bed temperature range, followed by experimenting with various textured build surfaces for increased bed adhesion. Finally, the beam samples from figure 3 were produced to assess build quality and screen for the optimal printing parameters moving forward.

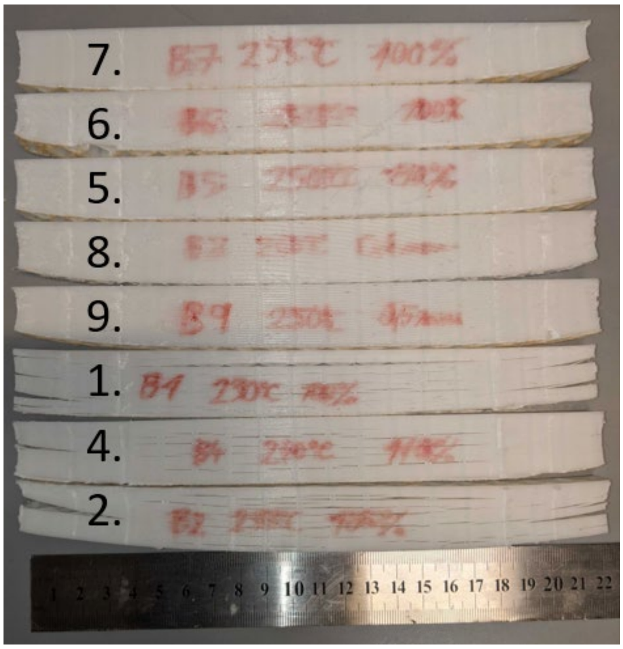

Figure 3. The figure shows beam samples printed at different temperatures and flowrates.

Inspecting the beams visually there are clear signs of both warping and delamination of the layers, as well as other visual defects that will not be evaluated in this report.

Table 1 shows the specific print parameters for each beam as well as the resulting grade each beam is given with respect to print quality. Higher nozzle temperature and flow-rate seem to result in the highest quality samples.

Table 1 Beam samples and their print quality score. Parameters are nozzle temperature and flow-rate. (Nozzle diameter: 0.8mm, layer height: 0.32mm except beam nr 8 and 9)

Beam nr	Print parameters	Warping	Delamination
1	230°C & 100%	3	1
2	235°C & 105%	1	1
4	240°C & 110%	3	3
5	250°C & 110%	3	5
6	250°C & 100%	1	4
7	255°C & 100%	2	5
8	260°C & 100% 0.4mm layer height	2	5
9	250°C & 100% 0.5mm layer height	1	5

4.2. Mechanical properties

Mechanical properties were evaluated by subjecting the dog-bone specimen to tensile tests and measuring their ultimate tensile strength (UTS). Figures 5 show the results from the tensile tests of the specimen. Unsurprisingly, the samples printed in Z-direction exhibited the lowest tensile strength as experienced in previous experiments. [4, 5] It is also noteworthy that the samples did not all break within the gage length of the specimen as is clear by the accompanying pictures of samples after testing besides each graph. This must be considered when evaluating the strength of the samples.

In figure 4 the results from samples that broke outside the gage length have been discarded and the UTS of the remaining samples has been averaged and compared to the UTS from the datasheet of the bulk material. The disregarded samples were: C1, C6, La2, Lo2, ZC1, ZC2, ZC3, ZC5, ZU4 and Zu5. It should be considered that this leaves only one sample from the ZC type.

Table 2 Mean UTS values of tested samples and bulk material as shown in figure 4 [3].

Samples	*Strength [MPa]*	*% of bulk strength*
Cross	30.47	45.5
Lateral	25.59	38.2
Longitudinal	38.22	57.1
Z-Cross	24.15	36.0
Z-Unidirectional	26.03	38.9
Bulk material	67	100

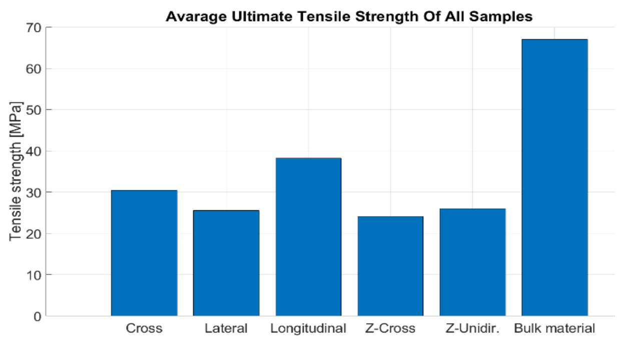

Figure 4. Mean UTS for each of the five sample types tested, as well as UTS of stock shape bulk material taken from the datasheet [3].

5. Analysis

The process of manufacturing parts from POM using FDM technology requires optimized printing parameters and the environment at which the printing is done must be kept under control to provide the best conditions to achieve consistent and high print quality as well as maintain mechanical properties at an acceptable level. The following sections will detail the results of this work with regards to print quality and mechanical properties.

5.1. Print quality

Warping and delamination are both a result of the shrinkage that the extruded material endures when it begins to cool down. Rapid cooling and insufficient bond strength cause the parts to warp and layers to separate. To counteract this, it is important to let the part cool slowly and, improve the bond strength by increasing the thermal energy and pressure of the extruded material to ensure a better fusion of the bead to the previous layer.

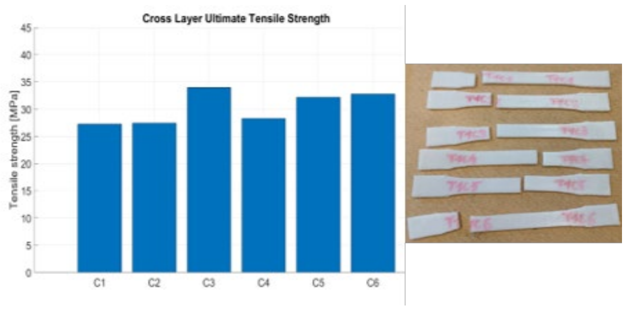

Figure 5a. Cross layered tensile test specimen UTS results (left) and broken samples (right).

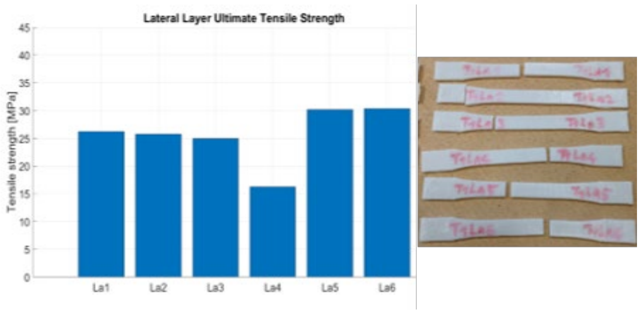

Figure 5b. Laterally printed tensile test specimen UTS results (left) and broken samples (right).

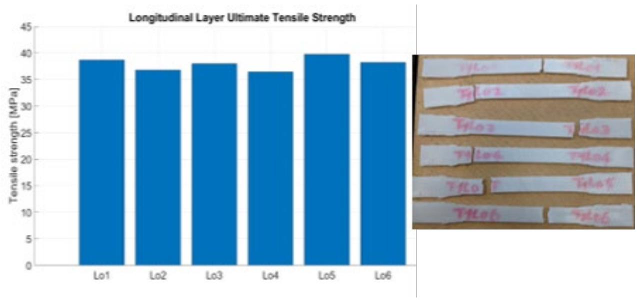

Figure 5c. Longitudinally printed tensile test specimen UTS results (left) and broken samples (right).

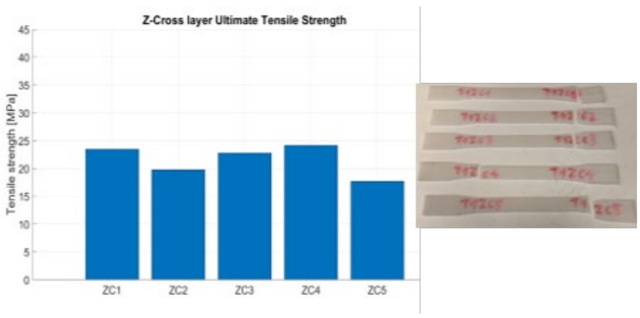

Figure 5d. Cross-layered, vertically printed, tensile test specimen UTS results (left) and broken samples (right).

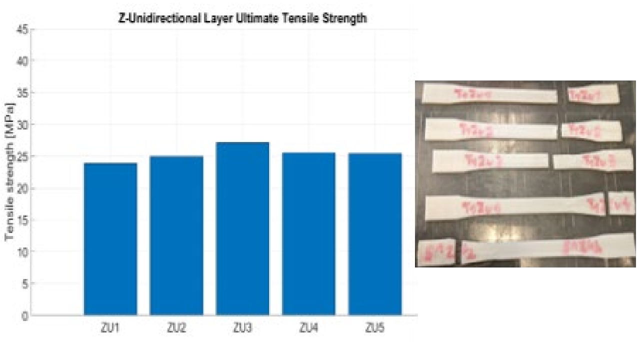

Figure 5e. Unidirectionally-layered, vertically printed, tensile test specimen UTS results (left) and broken samples (right).

5.2. Mechanical properties

It is clear from figures 4 and 5 that the strongest orientation of the printed samples is the longitudinally oriented print direction. The average strength of the longitudinally printed samples was about 57.1% of the bulk strength of 67MPa [5], according to the datasheet. These results suggest a more loss in UTS of the material after printing than some previous work. [6, 7] Unsurprisingly the lowest strength was exhibited by the samples printed vertically (in the z-direction), with the Z-Cross sample reaching only about 36% of the bulk strength. These results intuitively make sense since the FDM process is based on layer-by-layer replication and the tension carried by the pieces printed standing is only as much as the strength of bonding between layers. It is surprising, however, to see that the ZU samples display marginally higher strength on average than La samples, and the difference between strongest and weakest orientation is only about 14MPa or 36.8% of the Lo sample average strength compared to about 50% in the findings of Rybachuk et al [4]. This could be explained by the difference in materials being tested, however, another explanation could be that since POM has a relatively high heat capacity, it requires more energy to bond layers and fuse subsequent print-bead passes. Therefore, the concentrated heat, as a result of continuously depositing material on the small cross-sectional area of the sample, favourably effects the bond strength between the layers.

6. Conclusion and future work

To achieve relatively high print quality of larger parts, the results suggest using a nozzle temperature of 250°C and 110% flow rate and a layer height of 0.32mm and a nozzle of 0.8mm diameter. Furthermore, to achieve up to 57.1% of the tensile strength of bulk material orientating the print direction along the tension applied will have the most influence on UTS, as well as having the same printing parameters as for quality, however, the effects of flow rate on UTS were not investigated.

The ability to produce parts from POM using FDM technology could be a real benefit for professionals and enthusiasts alike. The ability to use additive manufacturing to produce parts with such favourable properties could reduce lead time of parts and product, inspire new design and stimulate innovation. What is even more promising is the relative ease at which POM can be recycled into printable filament. Thus, the use of FDM technology for the production of POM parts could reduce the waste even more since it utilizes additive manufacturing as opposed to subtractive manufacturing, thereby generating exponentially less waste.

For future work, experiments with recycled material, increased build volume temperature and more thermally conductive build surfaces would be suggested, as well as investigating the effects of printing and print parameters on other material properties such as stiffness and hardness.

Acknowledgement

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