Preliminary Investigations of Polylactic Acid (PLA) Properties

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Abstract: Additive manufacturing is a technology capable to directly manufacture 3D physical model alongside with their inserted mathematical model in an additive nature, where the materials are fused together to form a product, unlike the traditional manufacturing method. The emergence of 3D printing has secured a shorter cycle time for designing and developing innovative products. One of the most commonly used additive manufacturing technology is Fused deposition modelling (FDM). 3D printing applications has seen an immense growth, where it has included more load bearing parts targeted to fit an intended application as per user's requirement. Certain level of mechanical property information is being demanded as a benchmark to assess the strength of printed part in whole. This research work aims to investigate the tensile properties of PLA and find the optimum printing parameter combination using low-cost fused filament printer. Two parameters chosen to be varied in this research are raster angle and infill density, with value of 20°, 40°, 60° and 20%, 50%, 80% respectively. Tensile specimens with combination of these two parameters were printed according to ASTM D638 type 1 standard, with having layer height of 0.1mm as a constant. Tensile tests were conducted on the 3D printed PLA specimens to determine the best suited parameter combination that will result in optimum mechanical properties. Three mechanical properties were analysed, namely ultimate tensile strength, elastic modulus and yield strength. From the 9 combinations of parameter, the optimum combination was determined, which are 0.1 mm layer height, 40° raster angle, and 80% infill density of 3rd combination. Its optimum mechanical property is 32.93754MPa for ultimate tensile strength, 807.48931 MPa for elastic modulus and 26.08234 MPa for yield strength.

Keywords: 3D Printing, FDM, PLA, Tensile Testing, Elastic Modulus

1. Introduction

Additive manufacturing (AM) or 3D printing (3DP) are known rapid prototyping techniques due to their ability to manufacture parts directly from the CAD data resources, unlike conventional manufacturing technique which has to go through several stages of tooling before forming the final product(1). Consequently, it makes additive manufacturing superior in terms of the significantly shorter cycle time compared to the traditional approach(2). However, this is only true for small production scale, because additive manufacturing is meant for customization. Being labelled as a massive leap in manufacturing, additive manufacturing possesses plenty of advantages that surpasses the limitations of traditional manufacturing. Few of them are ability to directly manufacture products without molds, able to fabricate products with complex geometry, constant update on design changes, economic usage of material with minimal waste and being environmental friendly(3). Additive manufacturing can be classified into seven groups of approach; namely vat polymerization, material jetting, binder jetting, direct energy deposition, sheet lamination, powder bed fusion and material extrusion(4). The most commonly utilized technology is fused deposition modelling which falls into material extrusion. Fused deposition printers require the material to be processed into a filament form and the common type of material utilized are thermoplastics such as ABS and PLA. Generally, the thermoplastic filament is fed into the extruder head and melted using heat to be extruded through a nozzle with the help of pinch feed mechanism and finally deposited on the printing platform until the formation of full 3d structure. In recent years, this technology has become more accessible to small companies and even individual, also allowing hobbyists and do-it-yourselves to get exposed(5). In order to validate the strength and functionality of a printed part, it is necessary for the material properties to be studied in conjunction with the printing parameters. It is crucial to understand the relationship between mechanical properties and printing parameter combination so that a bridge to optimized information on mechanical properties can be formulated. There are two significant approaches can be applied in order to attain parts with certain level of mechanical property, which is by development of reinforced material or by suitably adjusting printing parameters during fabrication stage itself. Strength of FDM processed component primarily dependent on few printing parameters such as layer height, raster angle and infill density(6). They are defined as follows.

1) Layer height: It refers to the height of Z-axis motion of the extruder during the printing process and directly reflects the thickness of the deposited layer. The layer height cannot be more than the nozzle diameter.
2) Raster angle: This refers to the angle or direction of the beads of material about the loading of the part. Typically building apart using different modes and directions will affect the part strength and mechanical properties.
3) Infill density: Refers to the amount of deposited material in overall on each surface layer and directly proportional to the strength of printed component and inversely proportional to the printing time and amount of material used.

While significant work of this nature has been performed with ABS, very less research works has been performed using PLA due to its exclusive mechanical properties which limits its application range. However, its biodegradable nature, biocompatibility and high mechanical strength has brought a tremendous growth in biomedical and food industries. Since 3D printing quality solely depends on the controllable aspects of the FDM process, its resultant effect on PLA parts has been under critical observation. In overall, this paper aims to study the tensile property of PLA processed using fused deposition modelling technique while implementing a relationship between mechanical property and printing parameter combination for optimization purpose.

2. Materials and Methods

Rainstorm Desktop 2D Multicolor Printing Printer Reprap Prusa i3 with 0.4mm nozzle diameter was used to fabricate the tensile test specimen using 1.75 mm PLA filament. Arduino Mega 2560 was used as the microcontroller together with RAMPS 1.4 attached to it for extra pin input placements. Repetier Host slicing software was used to generate G-code files to be inserted as command and control language of 3D printer to carry out printing process. The firmware used is open-source Marlin firmware. Few parameters are kept constant throughout this entire experimental work to avoid mislead of result obtained.

Table 1. Printing parameters that were kept constant and their values.

No	Parameters	Values (Kept Constant)
1	First layer height	0.3mm
2	Horizontal Shell: a solid layer	Top and Bottom 3 layers
3	Fill pattern	Line
4	Printing speed	30mm/s
5	Nozzle diameter	0.3mm
6	Filament diameter	1.75mm
7	Extruder temperature	195°C
8	Print bed temperature	110°C

2.1 *Design of experiment*

The design of experiment includes the parameter and its value selected to be investigated. Two chosen parameters are raster angle and infill density, with value of 40°, 60°, 80° and 20%, 50%, 80% respectively. Layer height is kept constant at 0.1mm throughout this whole experiment. The total number of parameter combinations are 9. 5 specimens were printed for each parameter combination, making the total number of specimens to be printed are 45 specimens.

Table 2. Parameter combination list.

Combination	Layer height (mm)	Raster angle (°)	Infill density (%)
1	0.1	40	20
2	0.1	40	50
3	0.1	40	80
4	0.1	60	20
5	0.1	60	50
6	0.1	60	80
7	0.1	80	20
8	0.1	80	50
9	0.1	80	80

2.2 *Fabrication of PLA tensile specimen*

SOLIDWORK 2014 edition was used in designing the 3D model of the tensile geometries. The dimensions of the tensile specimen were based on ASTM D638 type 1 standard. Right after the designing process, the file is saved as. stl file format so that it can be further processed using slicing software. The slicing software used in this project is Repetier Host. Slicing software is used to customize the print setting, filament setting and specific printing parameter values of the specimen based on the design of experiment. After slicing, the G-code will be generated using built in G-code generator. Later on, it will be transferred into the SD card and detected in LCD screen of 3D printer upon insertion. In the physical fabrication process, PLA filament is lead into the extruder, whereby it holds a heat block which has a heating element in it. The filament is pulled inward with the help of a gear and roller inside the extruder, and melts when it passes through the heat block. From the heat block, the molten bead enters the nozzle installed underneath the block and comes out to be deposited on the printing platform. The moveable FDM head deposits the extruded material layer by layer onto a substrate in x and y axis. After completion, the extruder head levels up accordingly and repeats the layer deposition cycle until the full physical representation of the original CAD file is formed(7)

(a) (b)

Figure 1. (a) Fabricated PLA tensile specimen, (b) working mechanism of FDM(8).

2.3 *Tensile Testing*

Tensile test was done using INSTRON 3367 machine. The maximum load which can be applied on this machine is 50kN. According to ASTM D638 standard, the speed of testing that must be applied is 5mm/min. Below, the specimen geometry and the dimension of Type 1 specimen is shown. The thickness of specimen is 3.2mm.

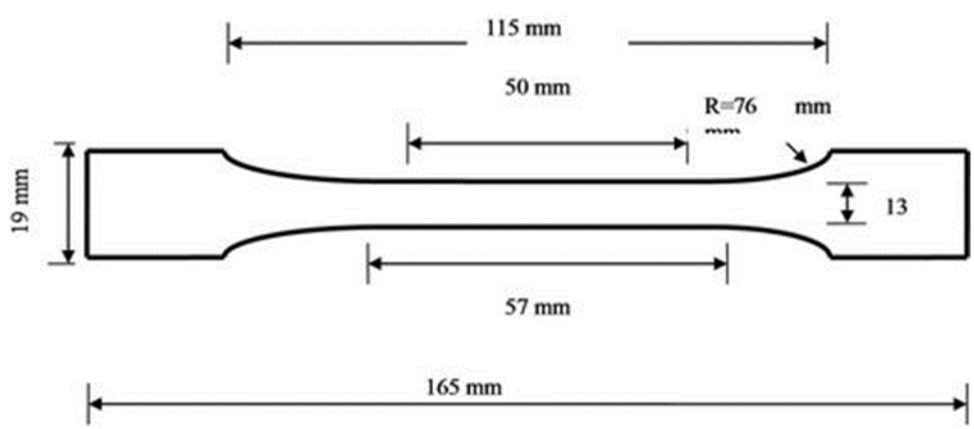


Figure 2. Type 1 specimen geometry according to ASTM D638 standard(9).

3. Result and discussion

From the tensile testing result data, mechanical property information was extracted by plotting the stress strain curves. The overall stress-strain curve of all the parameter combination is shown in Figure 3. From the graphs, the ultimate tensile strength, elastic modulus and yield strength were obtained.

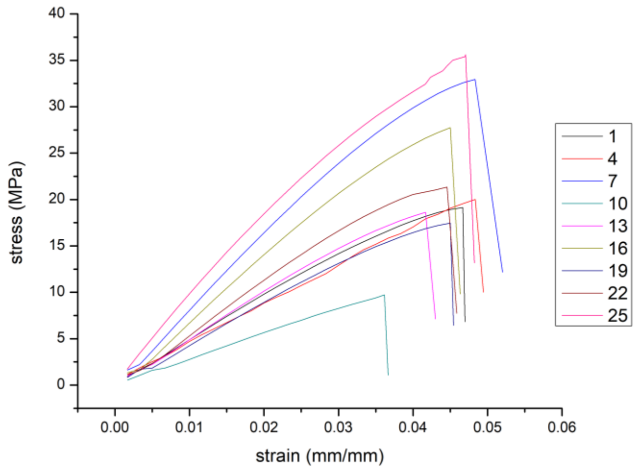
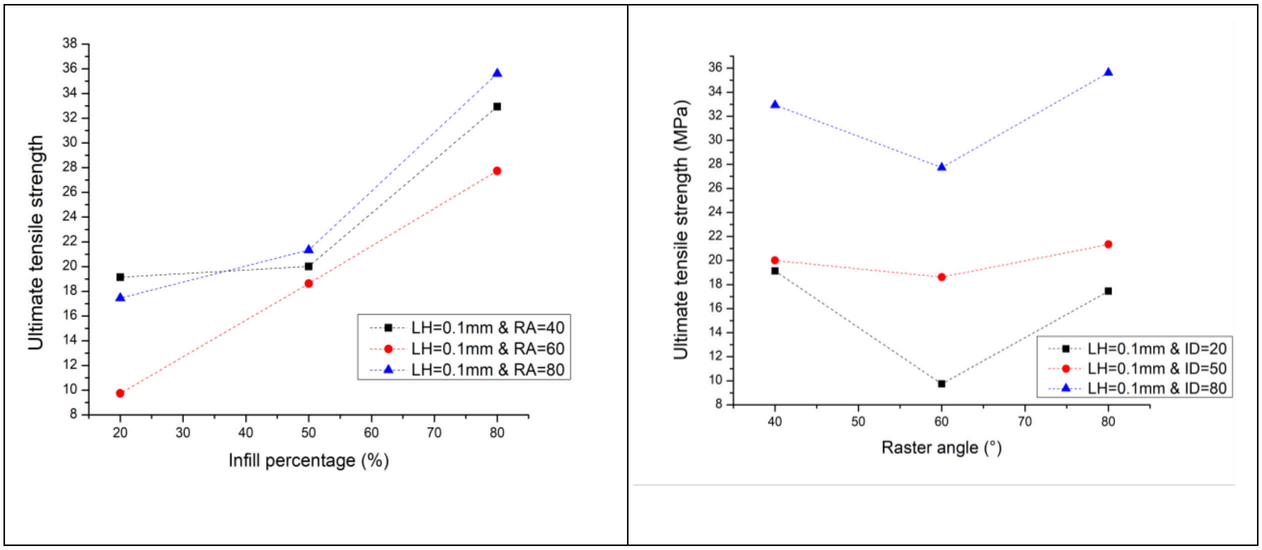


Figure 3. Average stress strain curve for all 9 parameter combinations.

Table 3. The list of average ultimate tensile strength, elastic modulus and yield strength for each parameter combination.

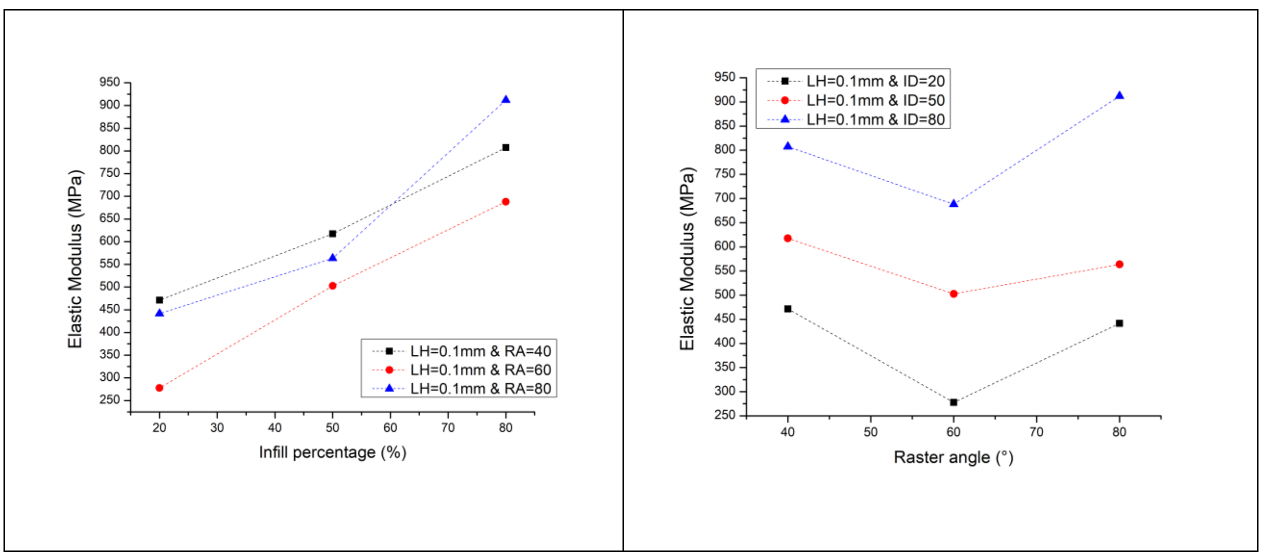
Combination	Layer height (mm)	Raster angle (°)	Infill density (%)	Ultimate tensile strength (MPa)	Elastic Modulus (MPa)	Yield strength (MPa)
1	0.1	40	20	19.13284	471.36800	14.80733
2	0.1	40	50	20.01269	617.45320	18.20973
3	0.1	40	80	32.93754	807.48931	26.08234
4	0.1	60	20	9.737220	277.74950	9.02682
5	0.1	60	50	18.62290	502.59040	15.39083
6	0.1	60	80	27.74211	688.12960	22.57436
7	0.1	80	20	17.45173	441.46120	15.45240
8	0.1	80	50	21.33669	563.48140	17.40802
9	0.1	80	80	35.61776	912.16466	19.77362

For all the obtained independent mechanical property data, its relationship with the parameter combination were studied by plotting graphs to observe the trends. The effect of raster angle and infill density on ultimate tensile strength, elastic modulus and yield strength is to be investigated. Below are the plotted graphs.



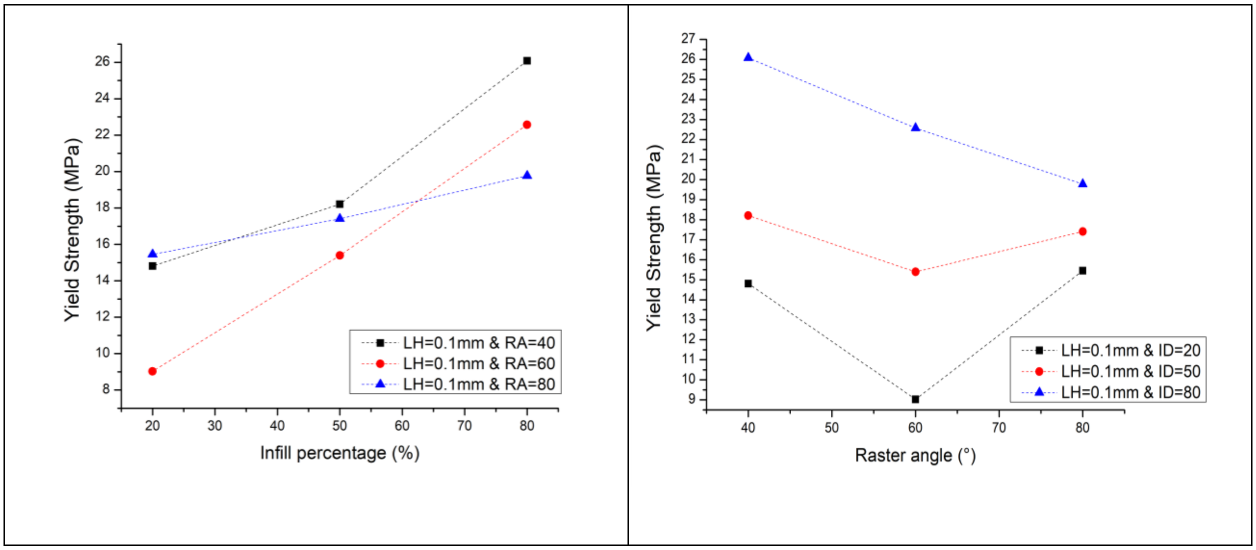
(a) (b)

Figure 4. (a) Ultimate tensile strength vs infill percentage chart, (b) Ultimate tensile strength vs raster angle chart.



(a) (b)

Figure 5. (a) Elastic modulus vs infill percentage chart, (b) Elastic modulus vs raster angle chart.



(a) (b)

Figure 6. (a) Yield strength vs infill percentage chart, (b) Yield strength vs raster angle chart.

From all the obtained data, the highest achieved mechanical property data has been highlighted. From the plotted graphs, it can be observed that all three mechanical property shows similar relationship with infill percentage. When the infill increases, all the property values increase as well with having 80% at the highest. Higher infill implies higher material availability with more resistance to overcome the applied stress internally(10, 11). However, depending on the requirement of a specific application, the right infill percentage can be chosen so that material can be used economically. As for the effect of raster angle, it can be deduced that low and high raster angle has resulted in considerably high mechanical property value. However, commonly high raster angle is preferred due inclination of the raster along the direction of loading which will offer more resistance thus strength will improve. At the same time, high raster angle will result in long raster formation which will increase the stress accumulation along the direction of deposition resulting in more distortion and hence weak bond(12, 13). Plenty of studies have been conducted to investigate the effect raster angle on the ultimate tensile strength and elastic modulus of PLA specimens. Some research results support that high raster angle result in maximum mechanical property while some supports the opposite(14-18). Upon analysis of all obtained data, the best suited parameter combination that results in optimum mechanical property have been identified, which is 3rd parameter combination of 40° raster angle and 80% infill density. It has resulted in high ultimate tensile strength, elastic modulus and as well as the yield strength, unlike 9th combination which resulted in low yield strength.

4. Conclusion

The objective of the research work to obtain best suited parameter combination was achieved. However, this research results are not adequate for 3D printer user to explore the options they have based on their specific need. Therefore, this scope of research must be extended by including more ranges of parameter values to be investigated. By this way, users can choose what is the best according to their need. Besides, research works should concentrate on legit parameter such as raster angle, layer thickness, build orientation and infill density because these parameters ultimately affects the strength, surface roughness, build time, material cost and energy used to print a product. Furthermore, it should be ensured that the humidity and temperature of printing environment are at ideal so that research results would be more accurate.

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