Study on effects of additive manufacturing process conditions on part properties for engineering applications

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Abstract. The present research study focused on examining the impact of post-processing, i.e. annealing on Polylactic acid (PLA) parts processed through additive manufacturing for engineering application. The parts are fabricated corresponding to two variable parameters: layer thickness and infill density. The Makerbot replicator2 system is used for sample fabrication. The comparative analysis is performed for mechanical properties corresponding to annealed and non-annealed conditions of specimens. The results show that the post-processing positively affects the mechanical properties of PLA products for engineering applications. The specimens with 60% infill density, provided 6.015%, 11.748%, and -1.834% improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, and 0.4 mm respectively. In similar manner, the specimens with 90% infill density, provided 6.761 %, 7.184 %, 5.427% improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, and 0.4 mm respectively. Post-processing improved the mechanical properties. The significance of the annealing for engineering applications is also discussed in the study.

1 Introduction

The modern manufacturing technologies such as additive manufacturing (AM) fabricate the products directly from digital design data. Different AM systems have been developed to fabricate the parts using polymeric and non- polymeric materials for engineering and non-engineering applications [1, 2]. Fused deposition modeling (FDM) also called fused filament fabrication (FFF) is the most frequently preferred AM process for polymeric and non-polymeric materials [3, 4]. Earlier it was introduced by Stratasys Inc., USA [5, 6]. FDM is an extrusion-based AM method that constructs the parts by extruding the semi-molten material through a specific opening for layers [7]. This process has widely adopted for different polymers mainly due to its low cost and ease of use. FDM is evolving as one of the promising methods in part production. The mechanical properties and part qualities largely depend upon the selection of parameters used in the process. Each process parameter plays a different and significant role in deciding the materials property. Therefore, investigating parameters for desired properties important from the application perspective, such as gears, hooks, hangers, etc., is important [8].

The models of some application parts such as knuckle joint, gear and nut are also fabricated as shown in Figure 1. Thevisual effects of CAD models and additively manufactured models

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are clearly different. It declares that the actual properties of additively manufactured components will be other than ideal. The strength of parts was measured with and without annealing post-processing. Therefore, the present study analyzed the effect of annealing on the PLA parts fabricated by FDM technology. The significance of the annealing for engineering applications is also discussed in the study.

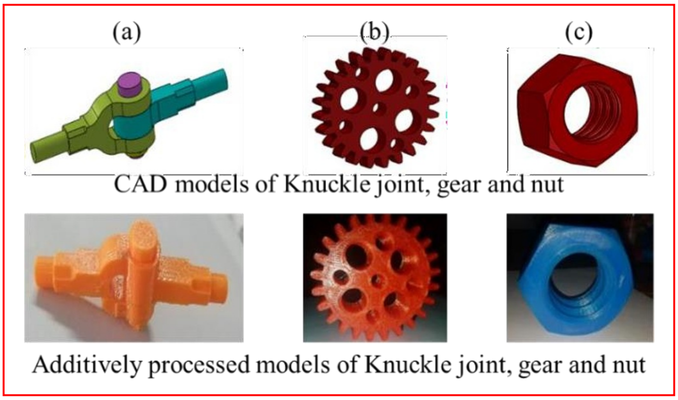

Fig.1. Engineering applications components, CAD model and AM processed parts (a) Knuckle joint (b) Gear (c)Nut

Through many former experimental studies it is clear that the quality and performance of AM processed parts are affected by numerous process parameters. There are several process parameters like infill pattern, infill density, layer thickness, raster angle, feed rate, build orientation, layer size, raster orientation & width, air gap, infill pattern and density, feed rate, etc. have a considerable influence on the properties of FDM fabricated products [9–17]. The characteristics of additively manufactured parts, like surface quality, product dimensions, etc., depend on different process parameters [18–23]. There has been a lot of research work that has been done in optimizing the process parameters. Earlier, there was a lot of focus on improving the surface roughness, and dimensional accuracy for ABS parts. An et al [24] investigated properties like surface roughness experimentally by varying FDM parameters on the ABS components' tensile strength and compressive strength. Several parameters like air gap, raster size, model temperature, and build orientation are considered as variables. The authors concluded that the tensile strength can be improved with an optimized selection of process variables.

Ang et al [25] did research work on the mechanical properties and porosity of parts manufactured from ABS. They had taken the process parameters like air gap, raster width, build orientation a layer thickness. Raegan and Oubou [26] also conducted an experimental investigation to study the tensile test of the specimens. The most recent work carried out by Chicon et al [27] focused on analyzing the effect of part build angle, layer size and print speed on part properties. The results show that upright orientation reduces the mechanical strength of parts. The on-edge and flat orientation provides the highest strength and stiffness of the same material. It was also found that as feed rate increases, the ductility decreases and ductility also increase for the upright orientation.

Though, direct testing of components without any treatment has been investigated by many researchers. The mechanical strength, dimensional accuracy and surface quality of engineering components such as knuckle joints, gear and nut bolts are also very important from application perspectives. A very few studies investigated the effect of post processing i.e. annealing on strength of FDM processed parts. Post-processing is also one of the solutions to improve the performance of additively manufactured parts. The present study focused on investigating of strength for engineering components with and without post processing of end parts at different temperatures and infill densities corresponding layer thicknesses.

2 Experiment methodology and Setup

The SMARTFIL PLA with 1.75 mm diameter is considered as manufacturing material in present research that Smart Materials 3D supplies. The standard mechanical properties of this material are shown in Table 1.

Table 1. Typical values of PLA characteristics

Properties	TS (MPa)	TM (GPA)	EB (%)	FS (MPa)	FM (GPA)
Value	15-72.2	2.020-3.550	0.5-9.2	52-115.1	2.392-4.930

The parameters such as layer thickness, infill density and post-work are considered to study their effect on the tensile strength of PLA products for mechanical engineering applications. Table 2 shows considered process variables in this study to evaluate their effect on tensile mechanical strength of PLA parts. The layer size varies at three levels, whereas the infill density and annealing temperature are at two levels each.

Table 2. Considered process variables

Process variables		Assessing values
Layer size (mm)		0.2 (1), 0.3 (2) & 0.4 (3)
Infill Pattern (type)		Linear
Infill Density (%)		60 (1) and 90 (2)
Annealing (̊C)		80 (1) &120 (2)

2.1 Preparation of specimen & 3-D printer used

Standard specimen D 638 Type 1 is used for performing the tensile test. Figure 2 (a) and (b) show the dimensions and CAD model of the standard specimen.

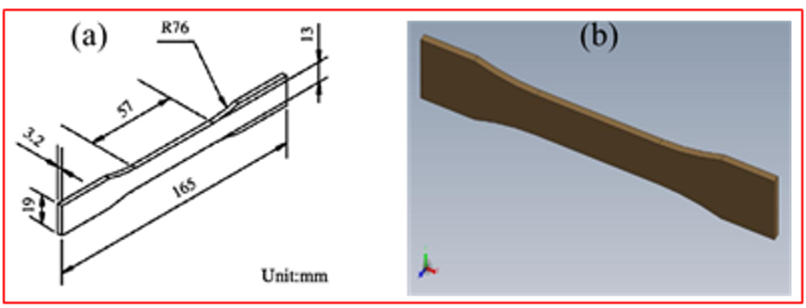

Fig.2. ASTM D638 Type 1 specimen (a) dimensions (b) solid works model

MakerBot Replicator -2 is used to fabricate the specimens as shown in Figure 3. The Makerware is used as slicingsoftware that creates the interface between the CAD model and AM system.

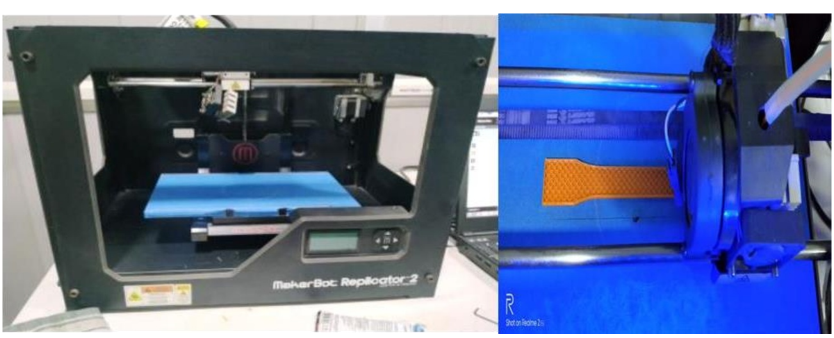

Fig.3. Preparation of specimen on MakerBot replicator 2 printer

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2.2 Post-processing

Two sets of specimens were fabricated to compare the properties with and without annealing processing. Post-process annealing was performed in the plastic annealing oven. The annealing was performed at two temperatures 80 $^{\circ}C$ & 120 $^{\circ}C$. First heat the oven to the desired temperature. Place the specimen to the location, heat it for 30 minutes, and then cool it in the oven to room temperature. A total of 18 specimens were prepared as shown in Table 3. A 12 specimens were undergone an annealing process out of which 6 specimens were annealed at 80 ˚C and six specimens were annealed at 120 ˚C and 6 specimens does not undergo in annealing process so that the difference in the properties of before and after annealing can be find out.

Table 3 Experimental plan

Density	Layer size	Post-processing
1	1	-
1	1	1
1	1	2
1	2	-
1	2	1
1	2	2
1	3	-
1	3	1
1	3	2
2	1	-
2	1	1
2	1	2
2	2	-
2	2	1
2	2	2
2	3	-
2	3	1
2	3	2

3. Results and discussion

The tensile test setup, specimens before and after fractured are shown in Figure 4 (a), (b) and (c) respectively. Figure 5 shows the tensile strengths of un-annealed and annealed specimens with varying layer thickness and infill densities.

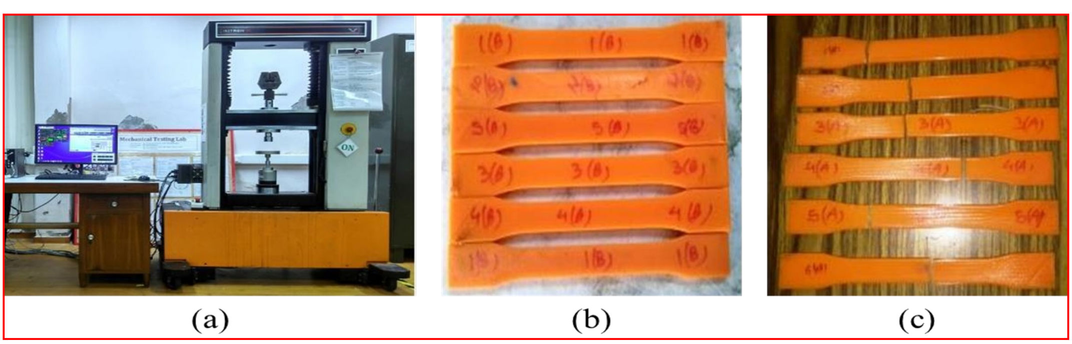

Fig.4. (a) Test setup 100kN UTM and set of specimens (b) before (c) after the fractured

The test results are summarized in Table 4. The specimens with 60% infill density, provided 2.4 MPa, 4.3 MPa, and -0.6 MPa more strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, 0.4 mm respectively. Similarly, the specimens with 90% infill density, provided 3.5 MPa, 3.7 MPa, 2.6 MPa more strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, and 0.4 mm respectively. The declining of strength with annealed at 120 ºC is due to the increasing in layer height to 0.4 mm from 0.2 mm. The higher layer height creates the voids and lesser number of bonds that causes the failure at lower load.

Table 4 Resulted mechanical strengths with and without post processing

Improvement in response (%)						
Layer size (mm)	Infill density 60%			Infill density 90%		
	Un-annealed	Annealed at 80 ºC	Annealed at 120 ºC	Un-annealed	Annealed at 80 ºC	Annealed at 120 ºC
0.2	37.5	38.6	39.9	48.2	48.0	51.7
0.3	32.3	34.5	36.6	47.8	48.0	51.5
0.4	33.3	35.5	32.7	45.3	47.7	47.9

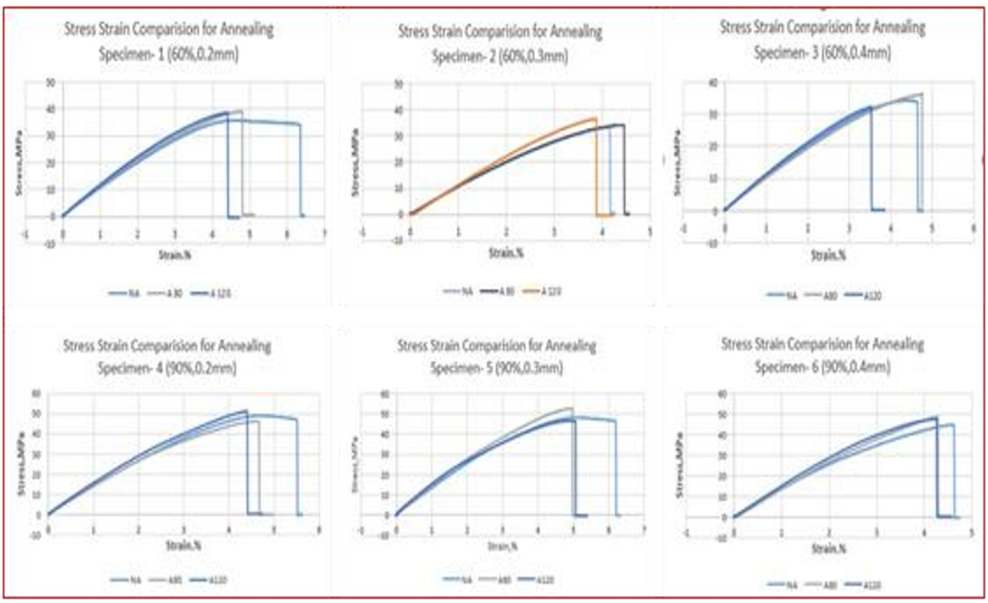

Fig.5. Comparison of Stress-Strain curve for Annealing vs Non-Annealing Specimen

The value of peak stress increases with the application of annealing and it also varies with the maximum annealing temperature. Annealing done at 120 ˚C gives higher value of peak stress while annealing at 80 ˚C gives the lower value of peak stress but still greater than the non-annealed samples. Annealing decreases the toughness as well as ductility of the material, as it is evident from the graphs. Figure 6 shows the strength of un-annealed specimens at different infill density and layer thickness. Figures 7 and 8 show the tensile strengths of annealed specimens at 80 ˚Cand 120 ˚C with different infill density and layer thickness. In general, if we discuss the process's effect and post- process parameters, we find that the peak stress is maximum (51.7 MPa) in the case of a specimen having 90% density,0.2mm layer thickness. Annealing at 120 ˚ C and minimum in case of the non-annealed specimen having 60% densityand 0.3mm layer thickness.

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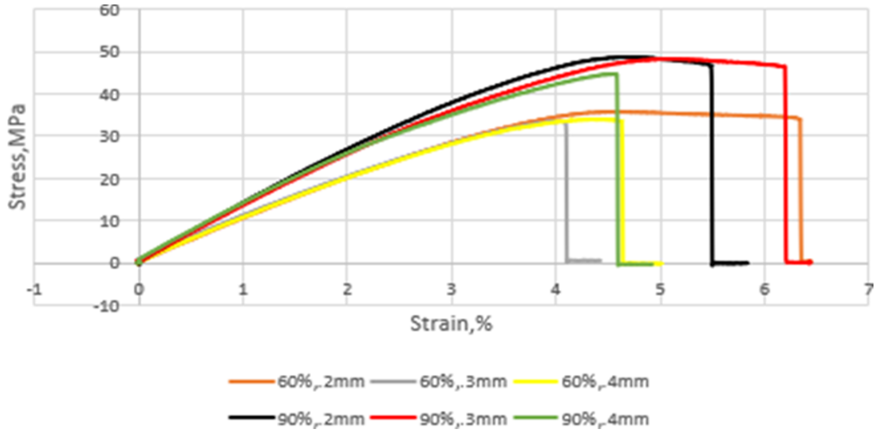

Fig.6. Strength of un-annealed specimens at different ID and LT

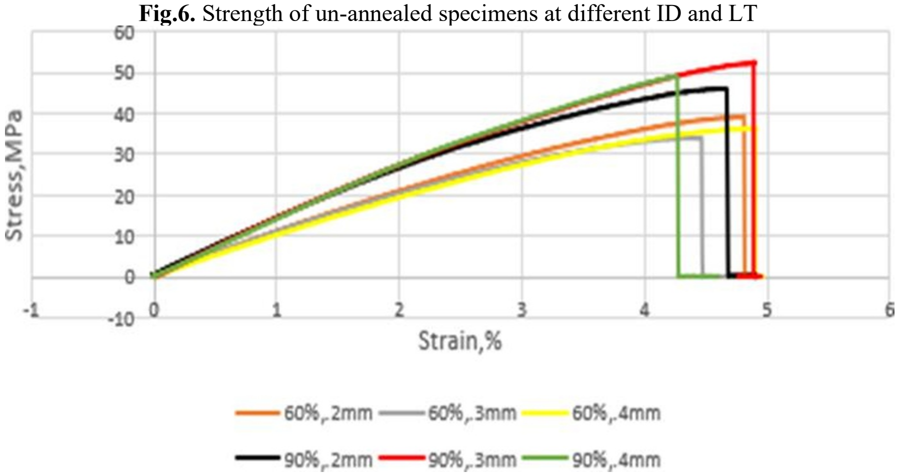

Fig.7. Strength of annealed specimens at 80 ˚C with different ID and LT

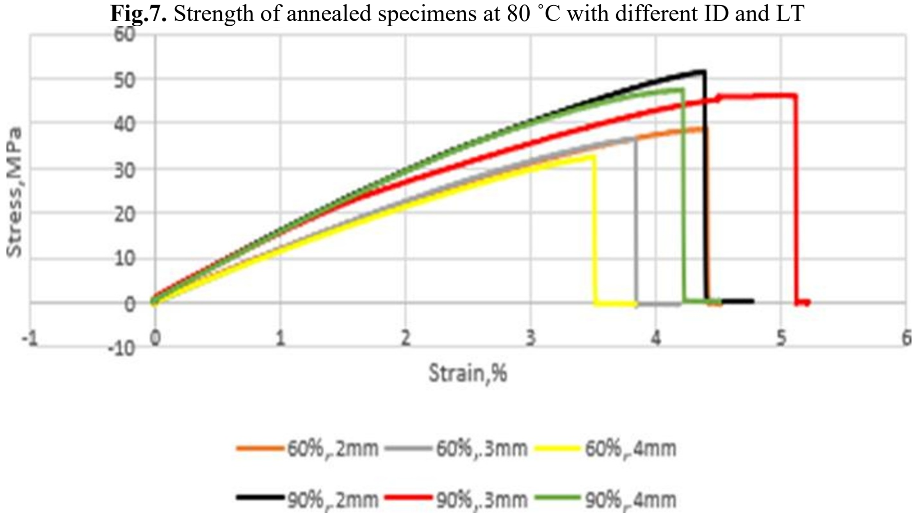

Fig.8. Strength of annealed specimens at 120 ˚C with different ID and LT

Three types of layer thickness 0.2 mm, 0.3mm & 0.4mm are evaluated. The results found that the peak stress is maximum in case of layer thickness of 0.2 mm then for 0.4 mm and minimum for 0.3 mm. The same trend is followedfor peak load and yield strain. Higher the infill density, higher will be mechanical property value. This trend is quite obvious as the strength of the material increases with increase in the value of density. The density is expressed in terms of percentage value. The toughness will be maximum for a non-annealed specimen having 90% density. Ductility is maximum for the specimen having the least density and is non-annealed and having layer thickness of 0.2mm, but the ductility decreases with annealing and the annealing temperatures have very little effect on ductility. Thefindings of the present study are comparable with former researches. [28] Butt and Bhaskar performed the study to investigate the impact of annealing on the end parts of ABS and PLA for mechanical properties. The results of studyare inline with present research work. Ziemian *et al* [29] investigated the FDM process for mechanical properties withrespected different process parameters. The results obtained are similar to the current analysis.

The improvement in results are summarized in Table 5. Results show that the specimens with 60% infill density, provided 6.015%, 11.748% MPa, and -1.834% MPa improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, 0.4 mm respectively. Similarly, the specimens with 90% infill density, provided6.761 %, 7.184 %, 5.427% MPa improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, 0.4 mm respectively.

Table 5 Overall improvement in results

Layer height	Improvement in strength at different infill densities (%)	
	Infill density (60%)	Infill density (90%)
0.2	6.015	6.761
0.3	11.748	7.184
0.4	-1.834	5.427

4 Conclusions

The mechanical strength of engineering components such as knuckle joints, gear and nut bolts are very important from application perspectives. The main aim of the study is to examine the effect of processing conditions on the properties of PLA parts processed through FDM technology. Additionally, the effect of post-processing is also analyzed on same parts. The infill density, layer thickness, and post processing i.e. annealing are the variables that define the part characteristics. The results show that the post-processing positively affects the mechanical properties of PLA products for engineering applications. The specimens with 60% infill density, provided 6.015%, 11.748%, and -1.834% improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, and 0.4 mm respectively. Similarly, the specimens with 90% infill density, provided 6.761 %, 7.184 %, 5.427% improved strengths than un-annealed specimens, corresponding to layer thicknesses 0.2 mm, 0.3mm, 0.4 mm respectively. The increasing of layer height to a limit declines the strength, even with annealing at 120 ^{0}C. The findings of the study will be beneficial to the designers of mechanical engineering fields. The results provide an idea about the role of post-processing on the final product's performance for selected application.

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