Journal of Engineering and Technological Sciences

Research Paper

Effect of Shot Peening Parameters on PLA Parts Manufactured with Fused Deposition Modeling

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Abstract

Fused deposition modeling (FDM) is a technology with potential benefits such as material versatility, user-friendliness, and cost-effectiveness. However, the mechanical properties of FDM-printed specimens are relatively low. To address this issue, post-processing techniques such as shot peening can be employed. Shot peening is utilized as a post-treatment for metal-based and ABS materials, but its application to PLA material has not been explored yet. This study aimed to evaluate the effect of shot peening on the mechanical properties of FDM-printed PLA samples. A full factorial experimental design was employed with shot peening speed, duration, and number of outer shells as parameters. The tensile strength of 72 samples after the shot peening process was measured and evaluated. Analysis of variance (ANOVA) revealed that all parameters had a significant influence on tensile strength. Additionally, the interaction of speed*time and speed*number of shells also had a significant influence. Meanwhile, the interaction of time*number of shells and speed*time*number of shells had no significant influence. The findings of this study demonstrate the potential of post-processing techniques to enhance the mechanical strength of FDM components, particularly those composed of PLA material.

Keywords: *3D printing; fused deposition modelling; post processing; printing parameter; shot peening.*

Introduction

Fused deposition modeling (FDM) is a popular additive manufacturing technique that is favoured by many industries to produce customised complex parts [1]. FDM is promising because it can print various types of materials, including plastics, ceramics, metals, and composite s[2]. The printing process by FDM does not waste a significant amount of material [3]. Besides, FDM is also inexpensive and simple to use [4].

One of the most used filaments in FDM is poly-lactic acid (PLA). This is a biodegradable material that has a low melting temperature and is non-toxic and low-cost [5]. Besides, it also has a high tensile modulus that makes it stable at high temperature [6]. However, PLA is a brittle material and has low toughness [7]. Thus, many studies have attempted to develop PLA properties by mixing it with other materials such as nanocrystalline cellulose [7] and flax fiber woven fabric [8].

PLA is a suitable material in bone tissue engineering [9]. Grémare *et al.* [10] printed a PLA scaffold to plant steam cells to promote the bone regeneration process. In automotive companies, using PLA as car interior material was introduced by Ford Motor [11]. Printed PLA honeycomb has successfully been applied as structural component in a small UAV (unmanned aerial vehicle) constructed by Brischetto [12].

ISSN: 2337-5779
J. Eng. Technol. Sci. Vol. 55, No. 5, 2023, 513-523
DOI: 10.5614/j.eng.technol.sci.2023.55.5.1

Despite the wide range of FDM applications, similar to other additive manufacturing technology, FDM also has a drawback in its surface roughness [13]. Another problem is that the mechanical properties of printed specimens are relatively poor for structural parts [14]. This problem not only applies to FDM but also to conventional manufacturing [15]. Various studies have attempted to overcome this problem by adjusting the printing parameter, for example, Kumar [16] found that raster orientation significantly affects the impact strength. Wang [17] investigated the effect of print speed, nozzle temperature, layer thickness, and bed temperature on the mechanical properties.

Post-processing is another approach that can be applied. For instance, acetone vapor bath [18], spray painting [19], and coating [20]. However, these treatments are mainly focused on refining the surface roughness. Besides, they use chemicals that can be toxic and dangerous to operators and the environment. Other post-processing methods that are usually used to enhance mechanical strength are shot peening, sand blasting, linishing (abrasive brushing), and heat treatment [21]. However, these methods mainly apply to metal-based material and ABS (acrylonitrile butadiene styrene).

Shot peening is considered an effective treatment to improve the mechanical strength of metal specimens [22]. Shot peening can be performed by blasting the specimen with peening media, such as small stainless-steel balls that move at high velocity. The balls with high kinematic energy repeatedly impact the specimen's surface with multi-directional shots. As a result, reinforcement of the surface grain is induced [23], which leads to a decrease in compressive residual stress, thus reducing fatigue crack initiation [24]. By this method, improvement of the specimen's strength can be obtained. The shot grains from the peening process can be a disadvantage for surface roughness. Arifvianto *et al.* [25] showed that shot peening treatment increased the surface roughness and hardness of 316L stainless steel. However, the negative effect on surface roughness is outweighed by the enhancement of fatigue strength resulting from shot peening [24].

Several studies have investigated the application of shot peening on 3D-printed parts. Maamoun [26] reported that shot peening could significantly improve the fatigue strength of AlSi10Mg components. Research by Kahlin *et al.* [27] showed that shot peening is an effective method to enhance the mechanical properties of Ti6Al4V specimens. Kanger *et al.* [28] observed the impact of shot peening on ABS mechanical properties.

Most studies on the application of shot peening are limited to metal-based and ABS material components. Based on the effect of shot peening on 3D-printed sample reinforcement, it can also be a promising treatment for PLA specimens. In this study, shot peening was employed as post-processing treatment for PLA specimens printed with FDM. The effect of shot peening parameters such as velocity and duration on mechanical strength was evaluated. The influence of the outer shell number of the specimens was also investigated. Finally, the parameters that considerably affect mechanical properties could be obtained. This study proposes adaptable post-processing to increase the mechanical strength of FDM parts.

Methods

Method Introduction

This research was conducted with an experimental method. The samples were printed using an FDM 3D Printer and treated using the shot peening technique. The tensile strengths of the samples were measured and compared to analyze the parameters that significantly influence the mechanical properties.

Samples Fabrication

In this study, the experiment was started by designing a three-dimensional model of a sample adapted from a standard design of ASTM D638 type V (Figure 1). The model was then sliced with the Ultimaker CURA software to obtain G-code, which the FDM printer can read to create a 3D object. In this software, the printing parameters can also be set. The number of the shells (Figure 2) was the only printing parameters that was differentiated into one and three outer shells, while the parameters detailed in Table 1 were fixed. The outcome was then exported as a *.stl file and transferred to the FDM printer. The samples were printed using FDM 3D printer core XY:

DOI: 10.5614/j.eng.technol.sci.2023.55.4.8

HALTech-02 by CV Acta Techno Inava. The material used was a commercial PLA by eSun (Shenzhen Esun Industrial Co. Ltd) with a diameter of 1.75 mm.

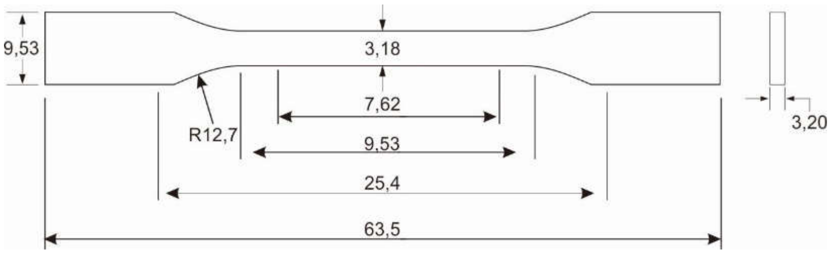


Figure 1 Detailed dimensions of samples following ASTM D638 type V.

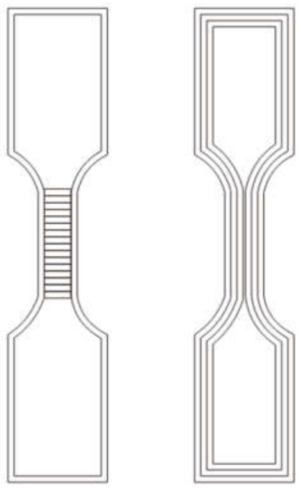


Figure 2 Number of outer shells 1 (left) and 3 (right).

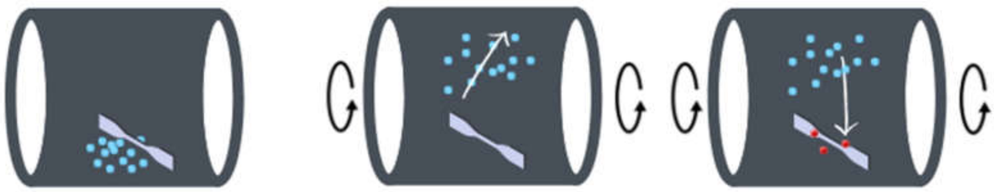
Table 1 Printing parameters.

Parameters	Value
Nozzle diameter (mm)	0.4
Layer height (mm)	0.2
Infill density (%)	100
Bed temperature (°C)	60
Nozzle temperature (°C)	200
Cooling fan (%)	100
Speed (mm/s)	60
Outline under speed (%)	50
Solid infill under speed (%)	80
x/y axis movement speed (%)	80

Post Processing

After the printing process, post-processing was carried out with the shot peening technique. Shot peening was performed with the KT-6808 Mini-Tumblr by Kingty Jewelry Machine. The 3D object and the stainless-steel peening media were put inside a Mini-Tumblr (Figure 2a). When the Mini-Tumbler rotates, the peening balls are lifted by the rotational motion, generating inertial energy (Figure 2b). After reaching a certain height, the peening balls are pulled down by gravitational force, striking the 3D object with their potential energy (Figure 2c). In this study, parameters in shot peening process such as speed and duration of treatment were formulated to investigate the effect of each parameter. The experiment parameters applied in this study can be seen in

Table 2. After the treatment was undertaken, the samples were tested using an IMADA MX-1000 N machine to calculate the tensile force.



(a) (b) (c)

Figure 3 Shot peening process: (a) before the Mini-Tumblr rotates; (b) the peening balls moving upward by inertia; (c) the peening balls moving downward by gravitational force and releasing potential energy.

Table 2 Experimental parameters.

Parameters	Level	Value
Shot peening speed (S)	1	110 rpm
	2	140 rpm
	3	230 rpm
Shot peening time (T)	1	1 hour
	2	2 hours
	3	4 hours
Number of the outer shell (N)	1	1 outer shell
	2	3 outer shells

Measurement and Analysis

The aim of this study is to evaluate the influence of shot peening on the tensile properties of 3D-printed samples. Tensile strength is calculated by dividing the tensile force obtained from the machine measurements by the cross-sectional area of the damaged part. Besides evaluating the influence of shot peening, the effect of each parameter listed in Table 2 will also be compared. To quantify and validate the comparison, the experiment was carried out with full factorial design for four replications. The full factorial design method determines the characteristics and influence of all parameters used. There were four replications for three factors with 2-factor-3-levels and 1-factor-2-levels (Table 2), so 72 experiments were carried out in this research.

Results and Discussion

Prior to statistical processing, normality and homogeneity tests were conducted. The normality (Figure 4) and homogeneity tests (Table 3) showed a P-value of >0.100, so the data was normal and homogeneous. The statistical software analysis of the research data produced the following regression model for tensile strength testing:

$$\text{Tensile Strength} = 54.730 - 0.655\,S_1 + 0.555\,S_2 + 0.100\,S_3 + 0.371\,T_1 - 0.533\,T_2 + 0.162\,T_3 + 1.763\,N_1 - 1.763\,N_2 \quad (1)$$

Eq. (1) represents the regression model for tensile strength as a function of the three studied parameters, where S is speed, T is time, and N is number of outer shells. A positive sign indicates a synergetic influence, while a negative sign indicates a reverse antagonistic effect. Then, analysis of variance (ANOVA) was performed to assess the statistical significance of each process parameter’s effect on tensile strength. Parameters with a P-value less than 0.05 ($P < 0.05$) in the model were considered to have a statistically significant effect.

DOI: 10.5614/j.eng.technol.sci.2023.55.4.8

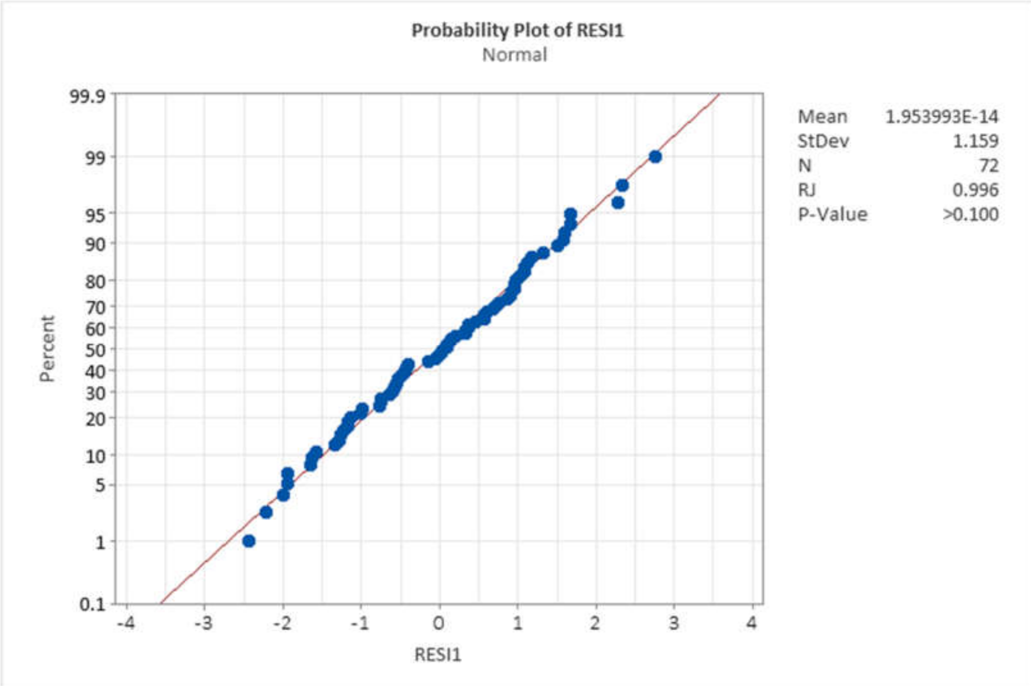


Figure 4 Normality test.

Table 3 Homogeneity test result.

Method	Test Statistic	P-Value
Multiple comparisons	—	0.362
Levene	1.25	0.258

The analysis of variance presented in Table 4 indicates that the P-values for all parameters (speed, time, and number of outer shells) were less than 0.05, suggesting that each parameter has a statistically significant effect on tensile strength. The interaction between pairs of parameters also affects tensile strength, with the exception of the interaction between time (T) and number of outer cells (N). Meanwhile, it can be observed that 3-way interactions have an insignificant influence on the outcome. Figure 5 presents a Pareto chart of the standardized effects of the process parameters on the tensile strength response.

Table 4 Analysis of variance.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Remark
Model	17	287.531	82.66%	287.531	16.914	15.14	0.000	Significant
Linear	5	252.475	72.58%	252.475	50.495	45.19	0.000	Significant
Speed	2	17.927	5.15%	17.927	8.964	8.02	0.001	Significant
Time	2	10.749	3.09%	10.749	5.374	4.81	0.012	Significant
Number of outer shells	1	223.799	64.33%	223.799	223.799	200.30	0.000	Significant
2-way interactions	8	33.588	9.66%	33.588	4.198	3.76	0.001	Significant
Speed*time	4	15.346	4.41%	15.346	3.837	3.43	0.014	Significant
Speed*number of outer shells	2	12.664	3.64%	12.664	6.332	5.67	0.006	Significant
Time* number of outer shells	2	5.578	1.60%	5.578	2.789	2.50	0.092	Non-significant
3-way interactions	4	1.467	0.42%	1.467	0.367	0.33	0.858	Non-significant
Speed*time* number of outer shells	4	1.467	0.42%	1.467	0.367	0.33	0.858	Non-significant
Error	54	60.336	17.34%	60.336	1.117			
Total	71	347.866	100.00%					

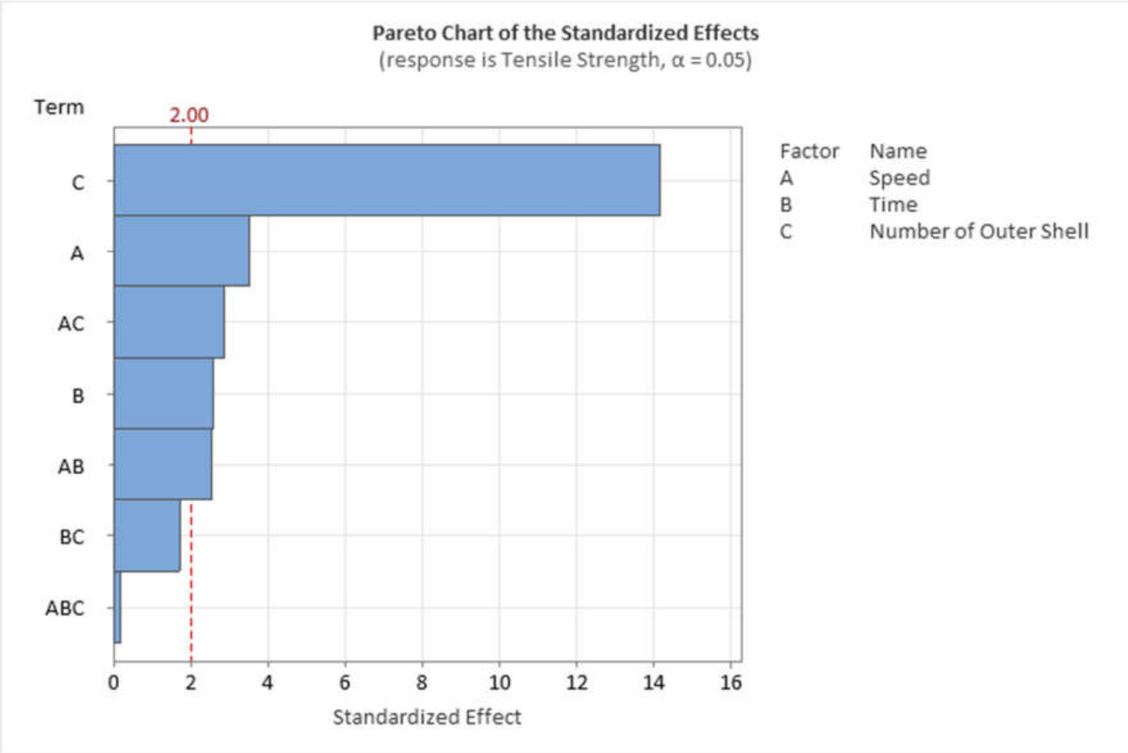
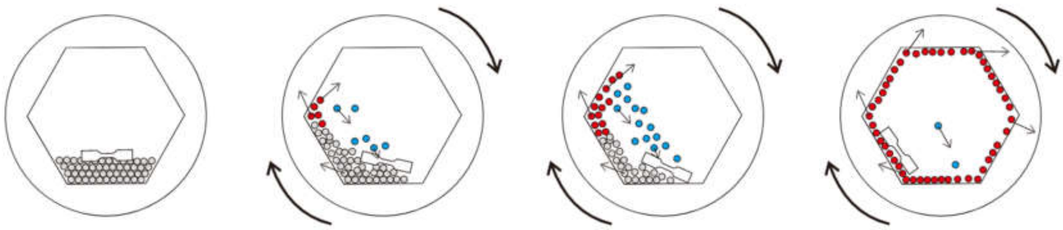


Figure 5 Pareto chart.

Speed

The shot peening process involves the impact of peening balls on the target object. Figure 6 illustrates the collision process, with red peening balls representing movement due to the machine's rotational speed and blue peening balls representing movement due to gravity. The laws of kinetic and potential energy apply in this case. The machine's rotational speed imparts kinetic energy to the peening balls, but at a certain height, their potential energy, determined by height, gravity, and mass, exceeds their kinetic energy, causing them to fall or roll onto the target object.



(a) (b) (c) (d)

Figure 6 Illustration when the shot peening is stopped: (a) Speed 1 (b); Speed 2 (c); and Speed 3 (d).

Based on Figure 7, Speed 2 has the greatest effect on tensile strength, while tensile strength decreases at Speed 3, approaching the value observed at Speed 1. At Speed 1, the height of the falling ball is smaller than that of Speed 2. Meanwhile, the number of balls dropped is also relatively less than the Speed of 2. As a result, the collisions at Speed 1 have lower energy and occur less frequently than those at Speed 2. Meanwhile, at Speed 3, the high rotational speed causes the kinetic energy of the peening balls to exceed their potential energy. Thus, collisions primarily occur at the beginning of the process, with few subsequent impacts. Some peening balls may fall but miss the target object due to object's upward movement. Therefore, Speed 2 is the optimal speed for achieving the most effective collision process. Further analysis revealed significant differences between Speeds

DOI: 10.5614/j.eng.technol.sci.2023.55.4.8

1 and 2, while no significant differences were observed between Speeds 2 and 3 or between Speeds 1 and 3 (see Figure 8).

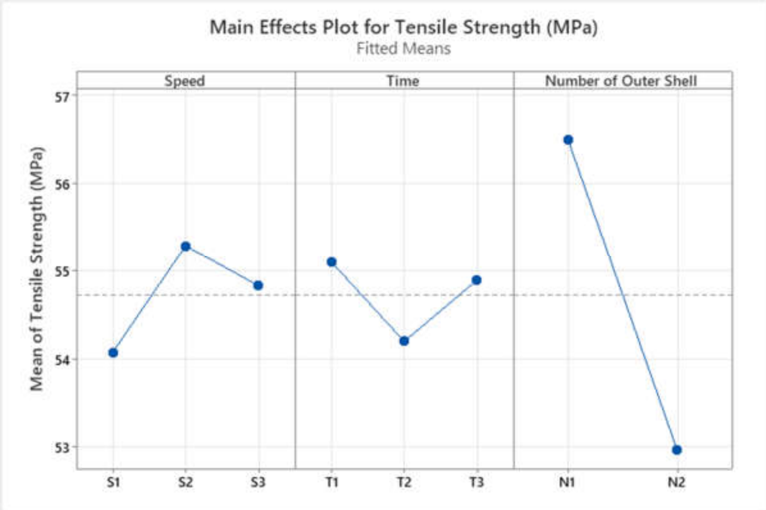


Figure 7 Graphic of the parameters effect on tensile strength.

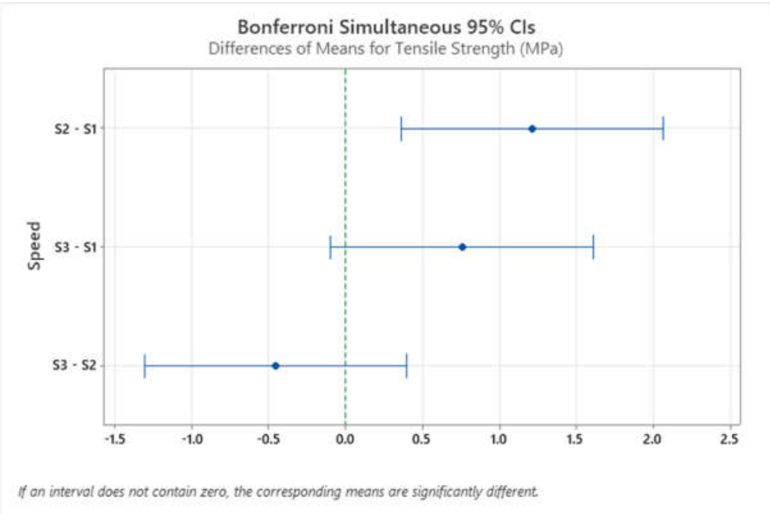


Figure 8 Bonferroni test results against speed parameters.

Time

As shown in Figure 7, the tensile strength of specimens treated for 2 hours was lower than that of specimens treated for 1 hour, while specimens treated for 4 hours exhibited higher tensile strength. The Bonferroni test revealed significant differences between Times 1 and 2, but no significant differences between Times 1 and 3 or between Times 2 and 3. Further research is needed to determine the optimal shot peening time; this issue will be discussed in the analysis of parameter interactions.

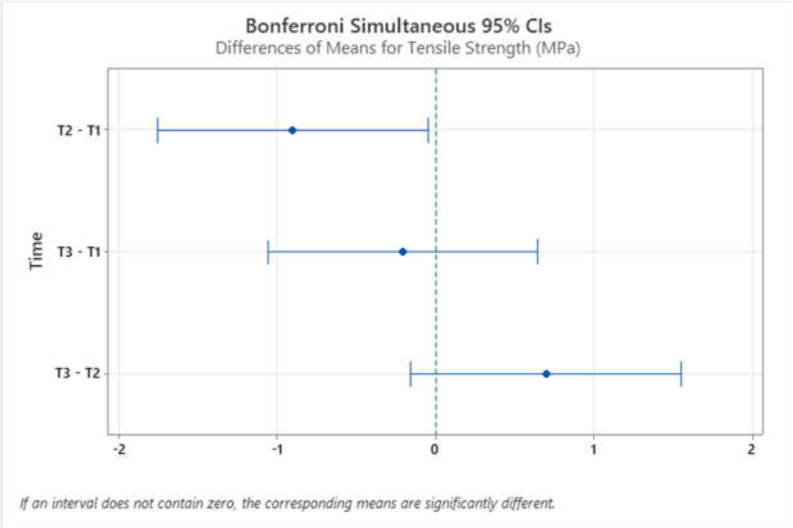


Figure 9 Bonferroni test results against time parameters.

Number of Outer Shells

This study provides significant evidence of the effect of the number of outer shells on tensile strength. However, these results differ from those reported by Kanger *et al.* [28], who found that tensile strength increased with the number of outer shells. In contrast, this study found that a larger number of outer shells resulted in a thinner specimen center and reduced internal volume (as shown in Figure 2), leading to a decrease in tensile strength (Table 7).

Interaction between Parameters

The ANOVA results presented in Table 4 indicate that the interactions between speed and time, as well as between speed and number of shells, have a significant effect on tensile strength. In contrast, the interactions between time and number of shells, and between speed, time, and number of shells, do not have a significant effect. The influence of the interaction between parameters on tensile strength can be seen in Figure 10.

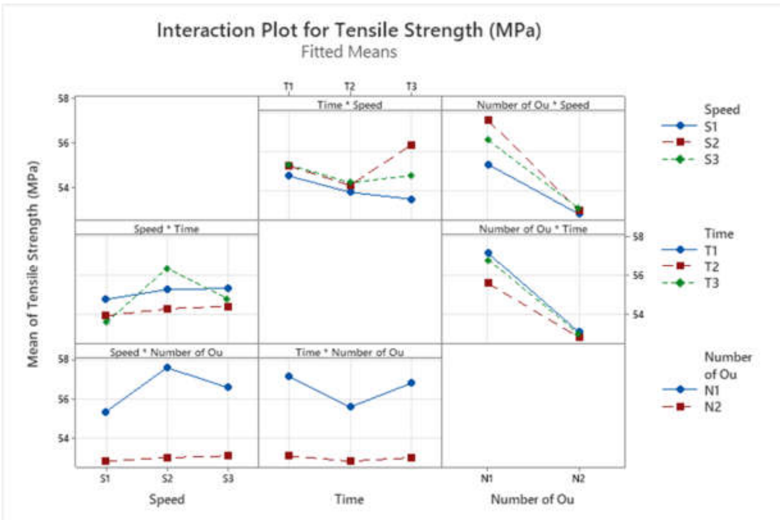


Figure 10 Interaction plot for tensile strength.

DOI: 10.5614/j.eng.technol.sci.2023.55.4.8

Based on the results obtained, in terms of the interaction between time and speed, the data suggests that at Times 1 and 2, the tensile strength remained relatively constant across all speed parameters. However, at Time 3, the tensile strength varied depending on the speed parameter, where speed can affect the tensile strength over a long period of time. This answers the issue regarding the time parameter where the tensile strength was decreasing from Time 1 to 2 but increasing thereafter. At time 3, Speed 3 resulted in a slight increase in tensile strength, Speed 2 resulted in a significant increase, while Speed 1 resulted in a decrease in tensile strength. This indicates that over a longer period of time, speed can have a notable impact on tensile strength.

In Figure 9, it can be observed that speed and time affected the tensile strength of specimens with one outer shell but did not affect the specimens with three outer shells. However, the specimens with three outer shells had a lower tensile strength than the specimens with two outer shells. This has been previously explained due to the smaller size of the central part of the specimen.

Conclusions

This study investigated the effect of shot peening as a post-processing technique for increasing the mechanical strength of fused deposition modeling (FDM) objects. ANOVA revealed significant effects of shot peening parameters such as speed, time, and number of outer shells on tensile strength. However, shot peening speeds that are either too low or too high do not significantly affect the object's tensile strength. Speed 2 resulted in the highest tensile strength value due to the optimal performance of the shot peening process. The number of outer shells is another parameter found to have a significant positive effect on tensile strength. In this study, an increase in the number of outer shells resulted in a thinner specimen center, leading to a reduction in tensile strength. Time was also found to be a significant parameter, with the interaction between speed and time having a positive effect on tensile strength at Speed 2 but reducing tensile strength at Speed 1. This study introduced novel shot peening parameters for fused deposition modeling (FDM) technology and investigated their effects on the mechanical strength of polylactic acid (PLA) material. The results demonstrated that post-processing with shot peening can effectively increase the tensile strength of PLA objects.

Acknowledgments

The authors would like to thank the Center of Excellence in Sustainable Manufacturing, Faculty of Engineering, Universitas Gadjah Mada, Indonesia for providing insight in support of this research.

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Manuscript Received: 9 February 2023
Revised Manuscript Received: 10 July 2023
Accepted Manuscript: 12 September 2023