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Layer adhesion investigation of three dimension printed parts by controlling the environment temperature

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ABSTRACT

Layer adhesion refers to the evaluation of the bond strength between layers in a 3D-printed part. Generally, 3D printed products are built layer by layer, where the adhesion between layers may vary depending on many factors, also according to the materials used. Furthermore, all the 3D printed parts experience layer separation over time. This issue mainly mainly stems from the effect of temperature during 3D printing operations. In this research, a new technique that focuses on studying and controlling the temperature of the environment around the 3D printer was developed. This approach aims to enhance the adhesion or welding process between printed layers, wherein the proper temperature the layer becomes more elastic, which facilitates the fusion process of the new layer with existing ones, thereby increasing the mechanical properties of the 3D printed parts. There are many techniques applied to control the temperature. In this study, the implemented control system consists of a digital thermostat equipped with sensors. The system monitors and adjusts the temperature by using an electrical wire heater placed inside the enclosure. Many materials are used as base material in 3D printers, e.g. PLA, ABS, PETG, etc., and each of these materials has a different optimum temperature. This study focused on PLA as the test material, even though it is widely used in 3d printer field, having a good printing flexibility. On the other hand, this material is affected by the weather conditions to the greatest extent, which can lead to failure between layers after a short while of time. The experiments were done by selecting three environment temperatures (40, 45 and 50 °C), the number of walls (4, 6, and 8 walls), and finally printing speed (70, 80 and 90 mm/sec) to test the adhesion between layers. The results exhibited that the effect of enclosure temperature on the 3d printer process was 62.07% over all the other printer parameters, Notably, the increase in the strength of adhesion for the printed parts reached 32.37% at an enclosure temperature of 40 °C.

Keywords: 3D-printer, PLA filament, layer adhesion strength, environment temperature.

INTRODUCTION

3D printing is one of the newest advanced technologies in recent years, revolutionizing many fields, from industry and manufacturing to medicine and architecture. This technology relies on generating three-dimensional models by building successive layers of materials, resulting in complex and detailed objects that could not have been achieved using traditional manufacturing methods. 3D printing technology is rapidly evolving, making it a powerful tool for enhancing creativity and innovation. This technology provides cost-effective solutions, reduces material waste, and opens up new horizons for customizing products according to individual needs [1].

The newest research in the 3D printer process field reveals many aspects, and some of these studies have been illustrated here. For instance, Goh et al., (2024) [2] explored the challenges and solutions related to strong interlaminar adhesion achieved in multi-material 3D printing, specifically between PLA and TPU filament using Fused Deposition Modeling FDM. The essential focus was on optimizing printing parameters, such as temperature, speed, and layer height, to enhance layer bonding. The researchers have highlighted the significance of surface treatments, like plasma treatment and UV exposure in increasing surface integrity and enhancing adhesion. Additionally, the use of intermediate layers of compatible materials and the optimization of infill patterns have shown significant improvements in mechanical interlocking and tensile strength. Long, 2023 [3] introduced the structure types of FDM 3D printers and studied the temperature control issue of FDM printers as well as the influences of temperature on the printed parts using PID control. The researcher adopted the SIMULINK to model and simulate the nozzle temperature control system, then the results showed that PID control can enhance the temperature control accuracy of FDM printers, thus improving the precision and surface quality of the printed parts, Abdulridha et al. (2023) [4] focused on the impact of printing parameters on the mechanical and physical properties of polylactic acid (PLA) specimens fabricated using the fused deposition modeling (FDM) technique on a CREALITY Ender-5 Pro machine. A 3D model was designed in SolidWorks, and six printing parameters were varied: infill pattern, infill density, overlap percentage, layer thickness, shell thickness, and top/bottom layer count, each with five levels. The results demonstrated the influence of these parameters on ultimate tensile strength (UTS), surface roughness (Ra), and tensile average deviation percentage. A comparison of predicted and measured results showed excellent accuracy, with maximum errors of 0.54%, 0.3%, and 1.36% for UTS, Ra, and tensile deviation percentage, respectively. Le et al., (2023) [5] showed the enhancement of the tensile strength of TPU throughout the optimization of 3D printing parameters such as infill angle, infill density, temperature, and layer thickness. Utilizing the Taguchi method, the researchers identified the optimal parameters to realize maximum tensile strength for the temperature of 210 °C, an infill angle of 45°, 100% infill density, and a layer thickness of 0.1 mm[1]. Furthermore, the study explored the effects of these parameters on the elastic modulus and elongation at fracture, providing a comprehensive understanding of how to improve the mechanical properties of TPU through precise control of the printing operation. Abdulrazaq et al. (2023) [6] focused on optimizing the mechanical strength of polylactic acid (PLA) printed parts throughout the material extrusion process, using artificial neural network (ANN) models. These models impact experimental data to predict and optimize printing parameters, such as temperature, extrusion width, layer height, and infill density. Researchers have shown that higher extrusion temperatures and optimized infill patterns can significantly enhance tensile and compression strengths. By utilizing ANN models to predict the mechanical properties of PLA parts, mean errors of 0.42% for tensile strength were achieved. Abeykoon et al., 2020 [7] identified critical parameters, such as nozzle temperature, extrusion speed, layer height, and infill density that significantly influence tensile strength and structural integrity. Highest nozzle temperatures and slowest extrusion speeds have been shown to enhance interlayer bonding, conducted in stronger parts. Additionally, advanced techniques like Artificial Neural Networks (ANNs) have been being utilized to predict and optimize these parameters effectively, leading to more robust and reliable printed structures. This optimization is critical for expanding the applications of PLA and ABS in various industries, ensuring they meet the necessary mechanical performance standards. Pandzic et al., 2020 [8] showed the test specimens printed with five different 3D printer models of the same manufacturer with the same material and 3D printing parameters and their influence on the strength properties of the 3D printed PLA material. The results of this study could be useful for users and researchers in order to select appropriate printer model for a particular purpose, considering optimal relation of PLA material strength properties and FDM 3D printer model. Hafidh et al., 2024 [9] evaluated and optimized the medical-grade polymethylmethacrylate PMMA by examining the effect of three printing parameters: layer height, infill density, and skewing angle on flexural strength. The flexural strength rises significantly with decreased layer height, and the skewing angle is in the zero direction. Genetic algorithms have been utilized to optimize the FDM process parameters. Joseph Dei Rossi et al., 2022 [10] explored a setup that uses externally induced mechanical vibrations to the nozzle tip as a potential method of improving the quality of 3D-printed parts. The induced vibration is expected to decrease the porosity of printed parts and enhance the adhesion between print layers, ultimately improving their mechanical properties. Also, the other objective was to understand the positional accuracy, porosity, and mechanical properties of the prints with the added vibration and then to determine the optimum vibration level to achieve the prints of the best quality. Hind H. Abdulridha et al. (2024) [11] focused on predicting the mechanical properties of FDM parts made from PLA using ANNs. The flexibility and cost-efficiency of FDM in producing complex geometric designs are countered by challenges in part strength due to anisotropic fabrication. The study employed the Taguchi design of experiments (L25 orthogonal array) and a neural network model with two layers and 15 neurons to analyze the impact of key printing parameters: layer thickness, infill density, top/bottom layer count, shell thickness, and infill overlap percentage. Analysis of variance (ANOVA) revealed infill density as the most influential factor on ultimate tensile strength (UTS) and compressive strength (UCS), contributing 67.183% and 40.198% to their variations, respectively. The ANN model demonstrated strong predictive accuracy, with mean squared errors of 0.098 for UTS and 0.326 for UCS, offering flexibility in optimizing settings for specific applications. Hira et al., 2019 [12] introduced a 3D finite element simulation of a FDM printer nozzle region by using COMSOL Multiphysics software. The polymer exiting from the nozzle of the FDM printer was also included in this simulation in order to capture the dimensional behavior of the polymer. The domain of the simulation consisted of a nozzle, printer table, and also the surrounding air. In this simulation also, the mass and momentum equations were solved to determine the non-Newtonian flow characteristics of the polymer. The interface between the polymer and ambient air was modeled using the level set method. Jandyal et al., 2022 [13], discusses numerous 3D printing processes with their advantages and disadvantages. Also, a comprehensive description of different materials compatible for each type of 3D printing process was introduced. Besides, the researcher presented various application areas of each type of 3D printing process. Abdulridha et al., 2024. [14] explored the methods of improving the surface quality of parts produced by FDM, which often have a rough finish due to their layered construction. The properties of the material and the structural design play an essential role in choosing the appropriate material for the application, followed by the field of application and the implementation stage [15]; this study focused on the PLA material. It involved printing test specimens using various parameters, including infill density, shell thickness, layer height, the number of top and bottom layers, and the percentage of infill overlap. To analyze the data, the researchers employed the Taguchi method (specifically, the L25 orthogonal array) and performed ANOVA. This allowed them to assess the significance of the different parameters and identify the optimal settings for production. The study found that vapor smoothing using dichloromethane significantly improved surface quality at a microscopic level, while keeping dimensional variations to a minimum. The best surface finish was achieved with 50% infill density, 0.1 mm layer thickness, 2.8 mm shell thickness, five top and bottom layers, and 0.25 infill overlap.

The studies in this field are extensive to help find the best printing parameters conditions and also to obtain the best possible 3D printing parts, or even withstand difficult working condition by increasing the mechanical properties of 3D printed parts. This study investigated the adhesion between layers of 3D printed parts under different environmental temperatures. The aim was to eliminate the important reason that caused failure in these parts, especially when using PLA filament. In addition, the layer separated over time because of the inherent properties of PLA, and hence improving the mechanical properties of the 3D-printed parts.

EXPERIMENTAL WORK

In this study, the idea of determining the degree of adhesion between printed layers was executed depending on the differences between the printed tensile specimen at room temperature (at 25 °C) and the tensile specimen printed at the tested environment temperature, where the result from this many factors focused primarily on the temperature of environment surrounding the 3D printer, while in the second order, they focused on 3D printed parameters that directly concern layer adhesion, like number of walls and printer speed, while fixing all the reset parameters, like the layer thickness 0.3 mm, infill density 100% with zigzag pattern, nozzle diameter 0.4 mm, and bed temperature 70 °C, etc., where these parameters were essentially chosen depending on the provided information in the help instruction of the PursaSlicer software and also the previous research. The significance of changing the number of walls on the perimeter, even with a 100% infill density, lies in the fact that the infill pattern is not always circular or peripheral. Increasing the number of walls enlarges the surface area where each layer adheres to the next, thereby enhancing the bonding strength. In addition, further walls provide better structural integrity, preventing warping and reinforcing the overall solidity of the printed object. On the other hand, adjusting the infill density to 100% means that the inner area of the printed part is entirely solid, with no cavities or hollow spaces. This enhances bonding between layers and ultimately increases the strength of the specimen.

Genichi Taguchi developed the Taguchi Method, a statistical engineering approach focusing on tough design and continuous quality improvement. This method aims to optimize product and system performance by recognizing and addressing design as well as production defects contributing to variability and unpredictability [16]; this methodology was used to design the experiments for the chosen parameters, as detailed in Table 1. Table 1 depicts the testing parameters that were adopted in this study. The tensile specimen was chosen depending on the ASTM D638 of the PLA (Polylactic Acid) materials [17, 18], where the rounded shape dog bone specimen was chosen. Furthermore, this tensile specimen printed in a vertical position, where in the vertical situation the layers build in a direction normal to the tensile load [19]. Figure 1 depicts the tensile specimen sliced in the vertical situation by using ULTIMAKER CURA slicer software. Additionally, Figure 2 depicts the differences between the tensile samples with varying wall counts of 4, 6, and 8.

Table 1. The adopted testing parameters

Environment temperature ℃	No. of walls	Printing speed mm/s
40	4	70
40	6	80
40	8	90
45	4	80
45	6	90
45	8	70
50	4	90
50	6	70
50	8	80

3D printer

The 3d printer that was adopted in this study is an (ERYONE er-20) 3D printer. The specification of this printer is illustrated in Table 2, while Figure 3 depicts the ERYONE er-20 3D printer machine. Also, Figure 4 illustrated the tensile specimen printed at room temperature in vertical situation.

After printing the tensile specimen by the 3D printer, the next step was testing by tensile tester device (WDW-200E Computerized Electronic Universal Testing Machine), as shown in Figure 5. Figure 5 depicts the tensile printed sample fixed on the Universal Testing Machine WDW-200E.

The enclosure with controlled temperature

To control the temperature of the environment surrounding the 3D printer, a wooden enclosure was designed and made depending on the working volume of the 3D printer. The control system

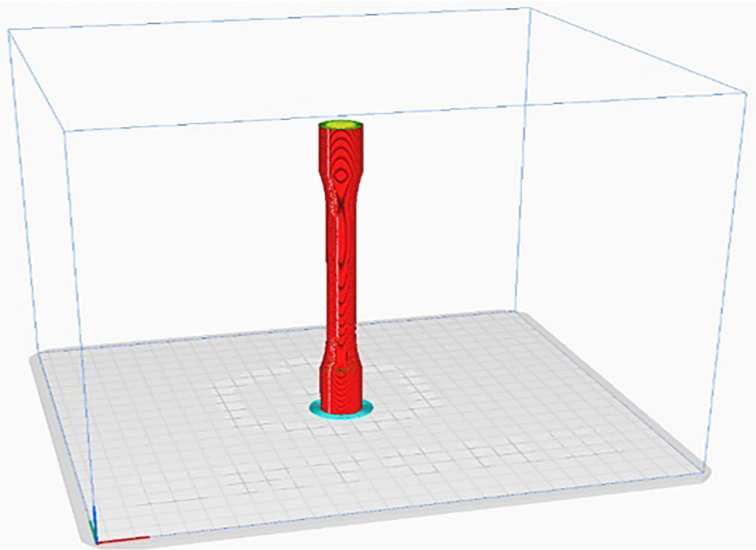

Figure 1. Tensile specimen sliced in ULTIMAKER CURA slicer

Table 2. ERYONE er-20 FDM printer specifications

Specification	Details
Layer resolution	0.05–0.3 mm
Positioning accuracy	X/Y 0.0125 mm, Z 0.002 mm
Supported print materials	PLA, ABS, PTU, PETG
Print speed	20~100 mm/s (recommended speed 60%)
Travel speed	150 mm/s
Nozzle diameter	0.4 mm
Build size	210 × 210 × 200 mm
Operational extruder temperature	Max 250 °C
Ambient operating temperature	8–50 °C
Input formats	STL, OBJ, DAE, AMF
Slicer software	Cura

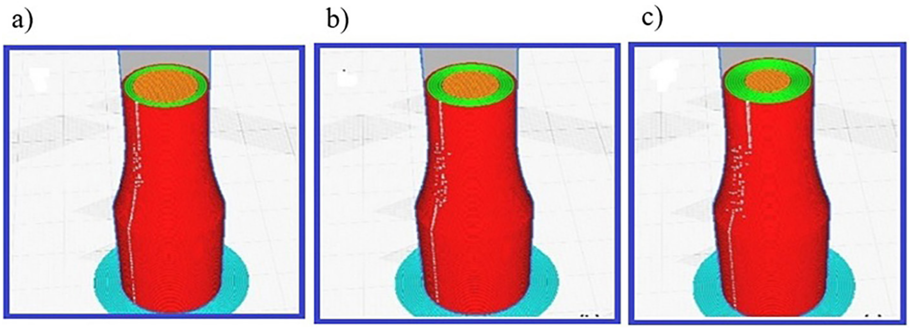

Figure 2. The difference between number of walls for each tensile sample: (a) 4walls, (b) 6 walls, (c) 8 walls

Figure 3. ERYONE er-20 3D printer

of temperature adopted in this study consists of an electronic thermostat with two heater sensors [20], where this system is connected with an electrical wire heater added inside the enclosure to control the temperature depending on the selected values in Table 1. In this study, A thermal control system is composed of an STC-3008 thermostat, which monitors and regulates the temperature in an enclosed environment of the 3D printer. This system uses sensors to constantly trace the temperature connected to a digital thermostat (as a brain) to adjust the heat by controlling an electrical wire heater [21]. This ensures that the environment maintains the selected temperature for processes during 3D printing, as shown in Figure 6. Figure 6 illustrates the 3D printer placed inside the enclosure that contains the control temperature system. After all the tensile sample were printed and tested on tensile tester machine, the results were recorded for analyses. Figure 7 depicts some of tensile samples after testing which indicated the fracture zone and the shape of fracture.

RESULTS AND DISCUSSION

After all the tensile specimens were built by the 3D printer that was placed inside the adopted enclosure equipped with a controlled temperature

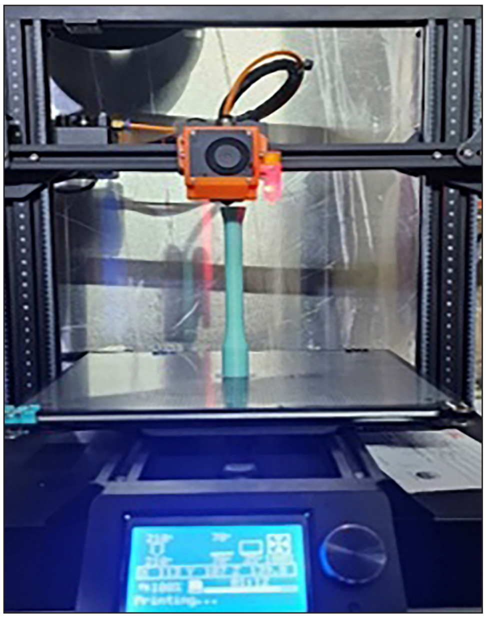

Figure 4. Tensile test specimen printed on the 3D printer

Figure 5. Universal Testing Machine WDW-200E examine the printed sample printed specimen

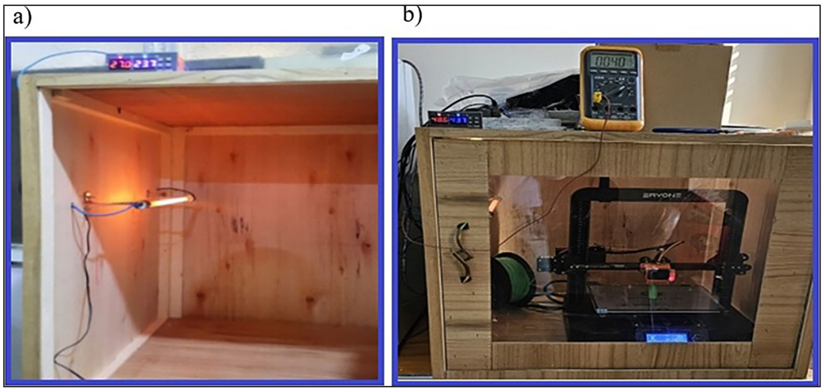

Figure 6. The adopted system: (a) heater fixed inside the enclosure connected with thermostat stc-3008 above the enclosure, (b) 3D printer inside the enclosure

system, all the tensile specimens were tested on the Computerized Electronic Universal Testing Machine WDW-200E. The stress-strain curve for each tensile specimen was obtained and the ultimate tensile strength was detected.

Printing at room temperature may result in uneven cooling of the 3D-printed layers, leading to internal stresses and weak layer adhesion. This can cause the sample to fail at many points where the layers do not bond well, which is the main reason for the printed sample failure in two zones, as shown in Figure 7. a), where the fracture occurs in two zones of the printed sample. It is important to mention that the value of ultimate tensile strength for a sample printed under room temperature conditions was 25.68 MPa. This value was used as the base value for comparison with values of ultimate tensile strength for samples printed under adopted parameters, and finally, the adhesion improvement percentage was obtained as illustrated in Table 3. Table 3 illustrates the ultimate tensile strength obtained from the tensile tester machine with the adopted printer parameters; also, the percentage of the adhesion between layers was presented. From Table 3, it was observed that the maximum tensile strength was 35.6 MPa for sample 2, printed at 40 °C, with 6 walls, and 80 mm/sec printing speed. When sample 2 was compared with a 28.68 MPa base value, the obtained increase in adhesion between layers reached 32.37%. Conversely, it was noticed that the ultimate tensile strength was lower

Table 3. The ultimate tensile strength with the percentage of the adhesion improvement percentage between layers and the adopted printer parameters

No of sample	Encloser temperature, °C	No. of wall	Speed, mm/sec	Ultimate tensile strength, MPa	Adhesion improvement, %
1	40	4	70	34.10	28.17
2	40	6	80	35.60	Max 32.37
3	40	8	90	34.20	28.45
4	45	4	80	30.26	16.375
5	45	6	90	28.53	10.51
6	45	8	70	29.88	15.11
7	50	4	90	32.23	22.62
8	50	6	70	22.81	Decrease 11.83
9	50	8	80	27.97	8.53

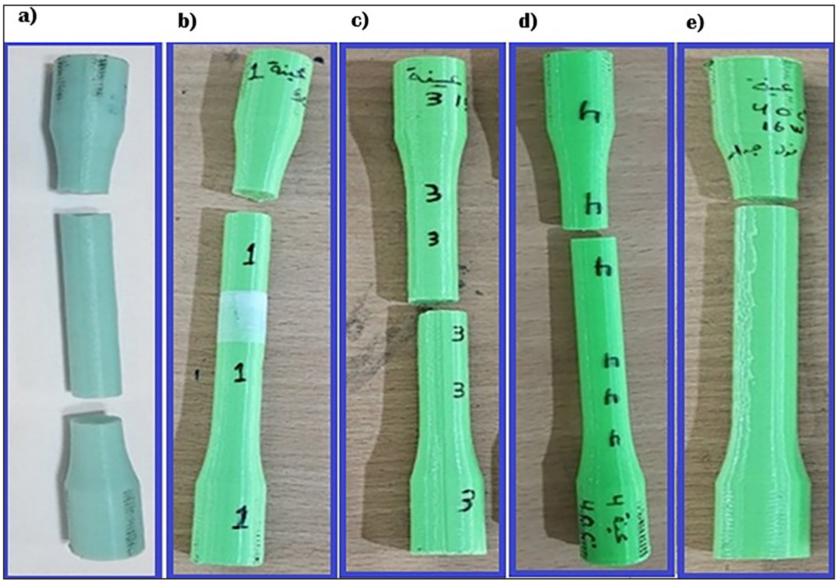

Figure 7. Some examination of tensile samples: (a) printed at room temperature, (b), (c), (d) and (e) printed at selected ambient temperate

than the base value, where the reason for lowered adhesion strength percentage was attributed to the high temperate inside the enclosure at 50 °C. At this temperature, the PLA filament started to soften and become stickier in the feeder tube. In addition, the PLA filament jammed in the heat sink zone that joined with the extruder nozzle. Furthermore, analysis of the Taguchi design shows that the effect of enclosure temperature occupied the first parameter that affects the adhesion strengthening percentage between layers. Table 4 shows the influences of each printing parameter on the adhesion strengthening percentage. On the other hand, it was noticed that the number of walls and speed have approximately the same effect. Table 4 shows the percentage effect of each parameter on the percentage of adhesion strength.

To determine if there are any statistically significant differences between the means of different groups, statistical Analysis of Variance (ANOVA) was performed. This method is particularly useful when comparing the means of three or more groups to recognize any notable variations [22]. Figure 8 depicts the influences of each parameter on the ultimate tensile strength by adopting the ANOVA method.

In addition, from the full factorial analysis, the results showed the standardized effect of all printer parameters when the influences were together analyzed. It should be noted that the enclosure temperature has the maximum effect on increasing the strength of adhesion between layers, where Figure 9 illustrates the standardized effect of the three printer parameters.

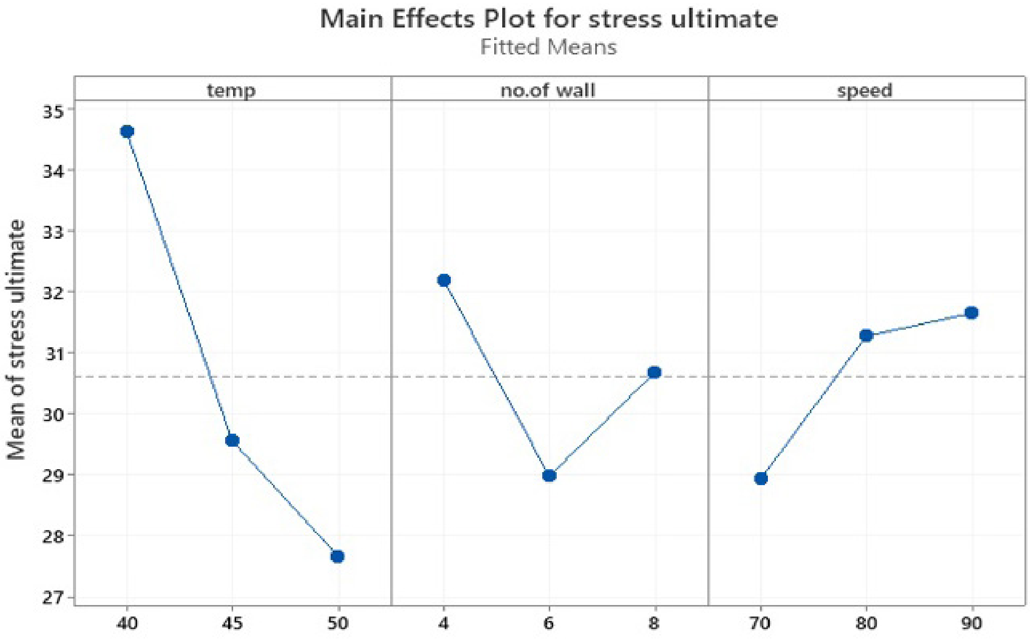

Figure 8. The influences of each parameter on the ultimate tensile strength

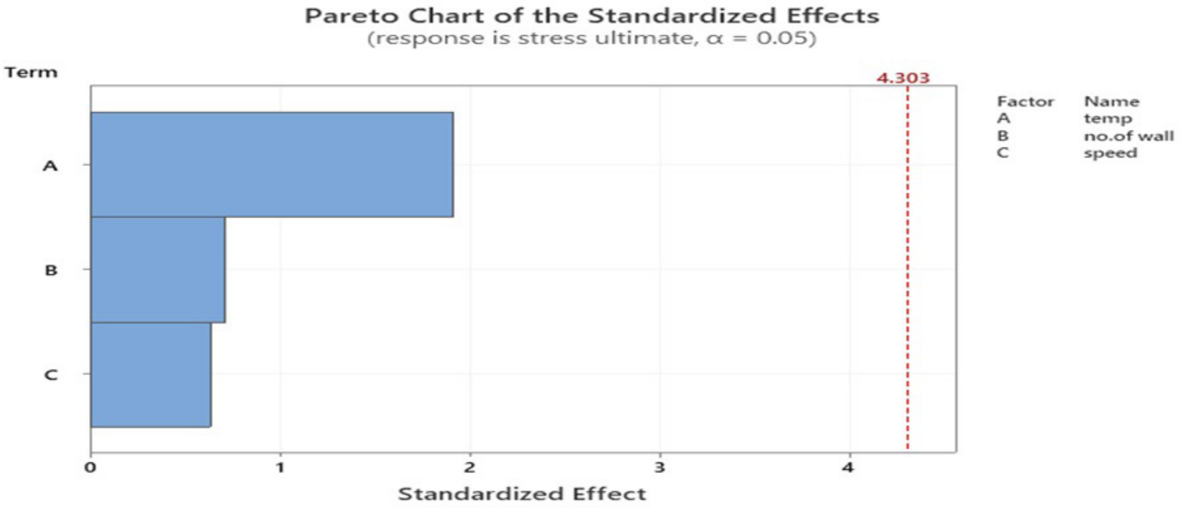

Figure 9. The standardized effect of the three printer parameters

Table 4. The percentage effect of each parameter on the percentage of adhesion strength

Parameter	Percentage effect, %
Encloser temperature	62.07
No. of wall	12.39
Speed	10.42

CONCLUSIONS

The study highlighted the significant role of 3D printing parameters on mechanical properties, especially the layer adhesion of printed specimens and ultimate tensile strength. The experiments reveal that the enclosure temperature, number of walls, and printing speed influence the strength and quality of the printed samples. The study uncovered several key findings related to the selected parameters on the mechanical properties of PLA printed parts:

- optimal conditions: the highest ultimate tensile strength of 35.6 MPa was accomplished at an enclosure temperature of 40 °C, with 6 walls, and a printing speed of 80 mm/sec, giving a 32.37% improvement indication of

adhesion compared to the compared value of 25.68 MPa at room temperature.
- effect of enclosure temperature: increasing the enclosure temperature up to (50 °C) adversely affected the adhesion strength, causing softening and sticking of the PLA filament to the feeder tube walls and reducing the flow rate of filament from the nozzle.
- parameter contribution: The Taguchi design analysis specified that the enclosure temperature is the most powerful parameter, contributing 62.07% to adhesion strength improvement, followed by 12.39% number of walls and 10.42% printing speed.
- full factorial analysis: the overall effects of all printer parameters emphasize the significant influence of enclosure temperature on layer adhesion strength, which is consistent with the results from Taguchi's analysis.

In conclusion, adopting the new technique of controlling the enclosure temperature for 3D printer machines, can obtain high-quality, durable prints with strong layer adhesion. This adoption is critical for optimizing the performance and reliability of printed parts. Future studies should examine the effect of the adopted technique on other 3D filament materials and geometries to further enhance the understanding and application of additive manufacturing techniques.

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