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OPTIMIZATION OF HEAT TREATMENT PARAMETERS FOR MECHANICAL STRENGTH AND SURFACE QUALITY OF FDM-PRINTED ABS

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ABSTRACT

Fused Deposition Modeling (FDM) of ABS is a cost-effective and versatile additive manufacturing technique; however, it is often constrained by residual stresses and poor surface finish, limiting its applicability in dimensionally critical components. Controlled heat treatment as a post-processing approach can relieve internal stresses and improve interlayer bonding, yet its combined effect on dimensional accuracy, mechanical performance, and surface quality remains insufficiently quantified. In this study, an experimental study combined with statistical analysis was conducted to investigate the effects of annealing temperature (100–140 °C) and holding time (20–60 min) on the dimensional stability, tensile strength, and surface roughness (Ra) of FDM-printed ABS specimens. Dimensional changes were expressed through the Dimensional Stability Index (DSI), tensile properties were measured according to ASTM D638, and surface roughness was characterized via contact profilometry. A Response Surface Methodology (RSM) approach coupled with Analysis of Variance (ANOVA) was employed to model and interpret the parameter effects. The results showed that temperature is the dominant factor influencing both DSI and tensile strength. The DSI values were minimal at 100 °C, showed moderate dimensional deviation at 120 °C, and increased sharply at 140 °C, demonstrating pronounced warpage and shrinkage near higher annealing temperatures. Tensile strength increased from 26.74 MPa in the untreated condition to a maximum of 30.82 MPa after annealing at 140 °C for 60 min, corresponding to a 15.3% improvement. In contrast, holding time showed a comparatively minor influence within the studied range. Although the minimum Ra was 4.72 µm at 120 °C for 40 min, representing a 30.1% decrease compared with the untreated specimens, surface roughness showed no statistically significant dependence on temperature or time. These findings demonstrate that controlled annealing can substantially enhance the mechanical performance of FDM-printed ABS parts, while moderate temperatures are preferable when dimensional accuracy must be preserved.

Keywords: Heat Treatment, Surface Roughness, DOE, Acrylonitrile Butadiene Styrene (ABS), FDM.

1. INTRODUCTION

Additive Manufacturing (AM) is an innovative production technology that fundamentally differs from traditional subtractive manufacturing methods by building components layer by layer, rather than removing material. Owing to its inherent capabilities, AM enables the fabrication of highly complex geometries that are either difficult or impossible to produce in a single process using conventional manufacturing techniques [1]. This technology supports a broad range of materials from polymers to metals using the same fundamental principles [2]. The underlying knowledge and process fundamentals derived from conventional methods such as sintering, welding, powder metallurgy, and heat treatment continue to play a critical role in the development and optimization of additive manufacturing processes [3].

Although all AM processes are fundamentally based on the layer-by-layer deposition of material, they are systematically classified into subcategories according to specific process parameters, including the physical form of the feedstock material and the nature of the applied

energy source [4]. Among these, Fused Deposition Modeling (FDM) has emerged as one of the most extensively utilized techniques due to its operational simplicity and cost-effectiveness [5, 6]. FDM operates by extruding a thermoplastic filament through a heated nozzle, where the material is softened to a semi-molten state and subsequently deposited layer by layer to construct the desired geometry [7]. Traditionally, this process has been primarily limited to polymeric materials owing to their relatively low melting temperatures and favorable rheological behavior. However, recent advancements in material formulation and process adaptation have facilitated the use of metallic feedstocks, including copper and stainless steel, within FDM platforms [8-10].

Heat treatment in FDM is not limited to applications involving metal-based filaments. With the transition of polymer-based FDM products from hobbyist use to commercial and industrial applications, expectations regarding mechanical strength, surface finish, and overall part quality have significantly increased [11]. Although advancements in filament formulations and composite materials have broadened the range of available feedstocks to meet these performance demands, the need for post-processing has grown in parallel. Surface treatments, annealing processes, and chemical smoothing techniques are increasingly applied to polymer-based FDM parts to improve dimensional stability, reduce surface roughness, and enhance mechanical properties [12]. This shift reflects a broader trend in additive manufacturing, where achieving functional end-use parts often necessitates a combination of optimized material selection and appropriate post-processing strategies [13].

Among the wide variety of thermoplastic materials utilized in FDM, Acrylonitrile Butadiene Styrene (ABS) stands out as one of the most widely used engineering polymers due to its balanced combination of mechanical strength, thermal resistance, and processability [14]. ABS is particularly favored in applications requiring higher impact resistance and dimensional stability compared to other commonly used polymers such as PLA. However, despite its widespread adoption, printed ABS parts often exhibit suboptimal interlayer adhesion and surface roughness, which can adversely affect their functional performance in load bearing or precision-demanding applications [15].

Several studies have investigated the effects of heat treatment on FDM-printed ABS components under different processing conditions. Sudin et al. applied heat treatment at temperatures ranging from 120 to 180 °C for durations of 20–60 min and reported that tensile strength increased with temperature, reaching 75.68 MPa at 180 °C for 60 min, although surface roughness significantly deteriorated at higher temperatures [16]. Torres et al. investigated heat treatment at 100–110 °C for 30–90 min and observed that it generally increased ductility while slightly reducing tensile strength, with only limited improvements in surface roughness [17]. Nguyen et al. employed an in-situ thermal treatment approach at approximately 240 °C during printing and reported a 62% increase in tensile strength along with a reduction in porosity from 3% to 1.6% [18]. Hussam et al. performed heat treatment at 85–125 °C and showed that temperatures below the glass transition improved tensile strength by 7.6%, while higher temperatures enhanced ductility and significantly improved dimensional stability when constrained conditions were applied [19]. Despite these findings, the reported results remain inconsistent, with some studies indicating strength enhancement while others report strength reduction under similar thermal conditions. Furthermore, most of the current research concentrates on just one parameter, such as mechanical strength, surface finish, or microstructure alteration, without giving a thorough analysis of several factors. In addition, the combined effects of temperature and time have not been examined within a single statistical framework.

To address these limitations, thermal annealing has emerged as a particularly effective post-processing technique for improving the structural performance of FDM-manufactured ABS parts [20]. By subjecting printed components to controlled heating cycles internal residual stresses generated during the layer-by-layer deposition process can be effectively relieved [21]. The duration of the annealing process, which generally varies between 30 minutes to several hours depending on part geometry and wall thickness, also plays a critical role in determining the extent of stress

relaxation and resulting mechanical improvements [22]. This thermal treatment promotes enhanced interlayer diffusion and improves the dimensional stability of the printed part, thereby contributing to better interlayer adhesion and increased tensile strength [23]. Recent studies further demonstrate that annealing near the glass transition temperature reduces internal voids and enhances interlayer bonding, leading to improved mechanical performance and overall component reliability [24]. Kösemen et al. conducted heat treatment at 90, 105, and 120 °C for 15 min and reported that temperatures near the glass transition region (90–105 °C) improved tensile strength and impact resistance, whereas treatment at 120 °C led to microstructural degradation and reduced mechanical performance. Furthermore, the authors demonstrated that optimized annealing conditions reduce internal voids and enhance interlayer bonding, thereby improving the overall reliability of FDM-printed ABS components [25]. Consequently, a well-calibrated annealing protocol is essential for optimizing the mechanical performance of ABS components manufactured via FDM, particularly for applications requiring high reliability and structural integrity.

The present study aims to systematically investigate the effects of thermal annealing temperature and duration on the tensile strength and surface roughness of ABS specimens fabricated by FDM. The experimental design involved three different annealing temperatures and three distinct holding times, which were analyzed using Response Surface Methodology (RSM) to model and optimize the process parameters. By exploring the relationship between annealing conditions and the resulting mechanical and surface properties, this research seeks to identify optimal post-processing protocols that enhance the functional performance and aesthetic quality of FDM-manufactured ABS parts. The findings are expected to contribute to the broader understanding of thermal treatment strategies in polymer-based additive manufacturing and support the development of reliable, high-performance components for industrial applications.

2. MATERIAL AND METHOD

2.1. Fabriation of Test Specimens

All test specimens were fabricated using a Bambu Lab H2D Combo FDM 3D printer (Bambu Lab, China) as shown in Figure 1. The H2D Combo system provides a build volume of 350 × 320 × 325 mm in dual-nozzle configuration and is capable of reaching nozzle temperatures up to 350 °C and a heated build plate temperature up to 120 °C, enabling reliable processing of engineering-grade thermoplastics such as ABS. The printer employs a CoreXY motion system and features an actively heated chamber (up to 65 °C) to minimize warping and interlayer delamination during printing.

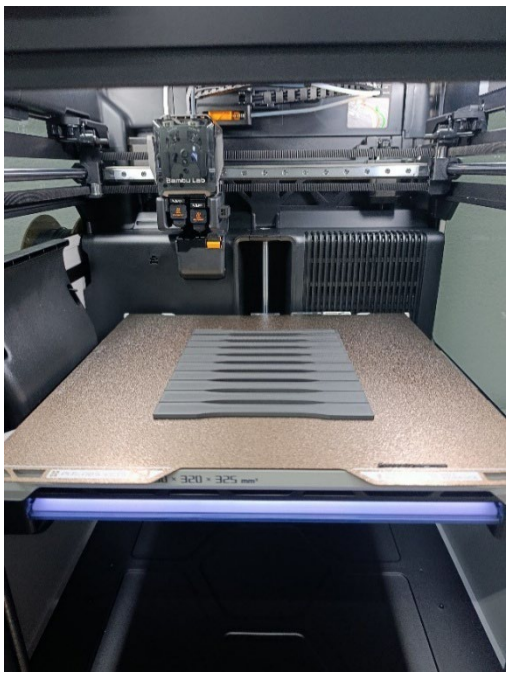


Figure 1. Bambu Lab H2D Combo FDM 3D printer.

The feedstock material was ESUN ABS filament (Shenzhen Esun Industrial Co., Ltd., China) with a nominal diameter of 1.75 mm and a recommended extrusion temperature range of 230–250 °C. Printing parameters were kept constant across all samples to isolate the effect of post-processing. The key process settings were as follows: nozzle temperature 240 °C, build plate temperature 100 °C, build chamber temperature 65 °C, layer height 0.16 mm, nozzle diameter 0.40 mm, infill density 100%, print speed 100 mm/s, and a ±45° raster orientation between successive layers. A brim was applied to enhance bed adhesion, and the printed parts were allowed to cool gradually on the build plate to reduce residual stresses.

Standard tensile test specimens were prepared according to ASTM D638 Type I geometry (Figure 2). The fabrication process was conducted in three separate batches, with 10 specimens positioned on the build platform during each production cycle to maintain consistent processing conditions.

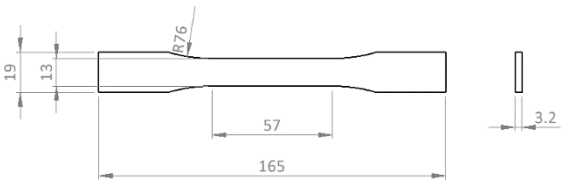


Figure 2. ASTM D638 Type I tensile test specimen.

2.2. Heat Treatment and Experimental Design

To investigate the effect of post-processing on mechanical strength and surface quality, a systematic heat treatment study was conducted on the FDM-printed ABS specimens. Heat treatment was performed in a convection oven (Nüve FN 500) with ±1 °C temperature control accuracy (Figure 3). The specimens were placed horizontally on a flat aluminum plate to minimize deformation and allow uniform heat distribution. Two primary process variables were selected: heat treatment temperature and holding time. Based on the thermal properties of ABS and preliminary trials, three levels were defined for each factor. Temperature levels were set at 100 °C, 120 °C, and 140 °C, while holding times were 20 min, 40 min, and 60 min.

Unlike some previous studies in which printed ABS specimens were directly introduced into a preheated oven at the target annealing temperature [26], the present study employed a gradual heating strategy by placing the specimens in the furnace at room temperature and increasing the temperature at approximately 3 °C/min until the desired setpoint was reached. After the prescribed holding time, the specimens were removed from the furnace and allowed to cool naturally to ambient room temperature in still air. This controlled heating–cooling approach was adopted to reduce thermal shock, minimize distortion, and improve process consistency during annealing.

A Response Surface Methodology (RSM) approach was employed to model and optimize the relationship between the process parameters and the measured responses. The design matrix generated in Minitab 21 enabled efficient evaluation of both main effects and interaction effects while minimizing the number of experimental runs (Table 1).

Tensile strength was measured using a Dartec hydraulic universal tensile testing machine at a crosshead speed of 20 mm/min in accordance with ASTM D638. Three tensile specimens were tested for each of the nine experimental groups, resulting in a total of 27 tensile specimens. The tensile strength values reported for each group represent the mean of three replicate measurements, and the statistical analyses were performed using the nine group mean responses.

Table 1. Experimental design matrix for heat treatment temperature and duration.

Group	Temp. (°C)	Duration (min)
HT-0	-	-
HT-1	100	20
HT-2	100	40
HT-3	100	60
HT-4	120	20
HT-5	120	40
HT-6	120	60
HT-7	140	20
HT-8	140	40
HT-9	140	60



Figure 3. Placement of ABS specimens on the aluminum tray inside the Nüve FN 500 convection oven during heat treatment.

Surface roughness (Ra) was determined using a Taylor Hobson Surtronic 3+ contact profilometer (Taylor Hobson, UK) by taking three measurements along each specimen's gauge section and reporting the mean value.

To quantitatively evaluate the dimensional changes caused by heat treatment, a Dimensional Stability Index (DSI) was defined (Eq. 1). This index combines the relative variations in thickness and width into a single dimensionless parameter, providing a holistic

measure of geometric stability. Lower DSI values indicate minimal deviation from the as-printed reference dimensions, while higher values reflect increased shrinkage or distortion due to thermal exposure. By condensing the two primary dimensional responses into one variable, DSI facilitates a more robust statistical analysis and response surface modeling of heat treatment effects.

$$DSI = \sqrt{\left(\frac{T_i - T_{HT-0}}{T_{HT-0}}\right)^2 + \left(\frac{W_i - W_{HT-0}}{W_{HT-0}}\right)^2} \quad (1)$$

Where;

- DSI is the Dimensional Stability Index.
- T_i is the average thickness of the heat-treated specimen in group i (mm).
- T_{HT-0T} is the average thickness of the untreated reference group (HT-0) (mm).
- W_i is the average width of the heat-treated specimen in group i (mm).
- W_{HT-0W} is the average width of the untreated reference group (HT-0) (mm).

3. RESULTS AND DISCUSSION

3.1. Effect of Heat Treatment on Dimensional Stability

Dimensional measurements were performed on all heat-treated ABS specimens to evaluate the influence of post-processing on part geometry. Thickness and width were recorded at the gauge section of each specimen, and the mean values of the three replicates were calculated and used for the subsequent statistical analysis to minimize measurement variability. The averaged dimensional data for all experimental groups are presented in Table 2.

Table 2. Average dimensions and DSI of heat-treated ABS specimens.

Group	Thickness (mm)	Width (mm)	DSI
HT-0	3.30	12.85	0
HT-1	3.36	12.85	0.018
HT-2	3.35	12.82	0.015
HT-3	3.40	12.80	0.030
HT-4	3.50	12.62	0.063
HT-5	3.53	12.55	0.073
HT-6	3.54	12.53	0.076
HT-7	3.89	11.70	0.199
HT-8	3.93	11.44	0.220
HT-9	3.96	11.30	0.233

Compared to the as-printed reference group (HT-0), moderate heat treatment conditions generally resulted in limited dimensional changes, whereas exposure to higher temperatures (≥120 °C) produced more pronounced variations in both thickness and width. These changes are attributed to the relaxation of residual stresses and localized polymer chain rearrangement when the material is heated near or above its glass transition region [19]. Overall, the data indicate that carefully selected temperature–time combinations can maintain acceptable dimensional stability, while excessively high annealing temperatures increase the risk of shrinkage and geometric distortion.

The dimensional response of the heat-treated ABS specimens is presented in Table 3 and graphically illustrated in Figure 4. The data clearly indicate that heat treatment temperature is the dominant factor affecting the Dimensional Stability Index (DSI). Up to 100 °C, dimensional changes remained relatively small (DSI ≤ 0.07), reflecting limited polymer chain relaxation and stable part geometry. However, when the temperature increased to 120 °C and above, a sharp rise in DSI was observed, with values exceeding 0.20 at 140 °C. This trend suggests that heating closer to or beyond the glass transition temperature of ABS triggers more extensive stress relaxation and molecular rearrangement, leading to shrinkage and warping. By contrast, holding time exhibited only a minor influence on dimensional stability. Increasing the exposure time from 20 min to 60 min resulted in only modest incremental increases in DSI relative to the dominant effect of temperature. These visual observations are consistent with the ANOVA results (Tables 3 and 4), where temperature contributed over 98% of the total variation in DSI, while time showed no statistically significant effect ($p = 0.079$).

Table 3. Regression model summary for DSI.

S	R-sq	R-sq(adj)	R-sq(pred)
0.007527	99.64%	99.28%	98.19%

Table 4. ANOVA results for DSI under different heat treatment conditions.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	0.0625	0.03126	551.69	0.000
Time	2	0.0005	0.00029	5.12	0.079
Error	4	0.0002	0.00005		
Total	8	0.0633			

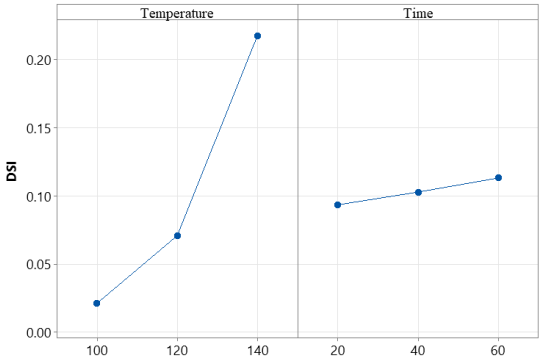


Figure 4. Variation of DSI with heat treatment temperature and time.

3.2. Effect of Heat Treatment on Surface Roughness and Tensile Strength

The influence of heat treatment on the surface morphology and mechanical behavior of the specimens is summarized in Table 5. The measured surface roughness and tensile strength values demonstrate that thermal processing induced notable variations across the test groups. In several cases, a decrease in surface roughness was accompanied by an increase in tensile strength, suggesting that the applied heat treatment parameters contributed to improved microstructural uniformity and bonding integrity. Conversely, certain specimens exhibited relatively higher roughness values without a corresponding enhancement in strength, indicating that the relationship between surface quality and mechanical performance may not follow a direct proportionality. The statistical significance of these experimental observations was subsequently evaluated through ANOVA analysis in the following section.

Table 5. Effect of heat treatment on surface roughness and tensile strength.

Group	Roughness (Ra)	Strength (MPa)
HT-0	6.75	26.74
HT-1	6.70	26.87
HT-2	6.55	27.95
HT-3	5.82	28.53
HT-4	9.61	27.08
HT-5	4.72	28.20
HT-6	5.86	27.69
HT-7	7.40	30.07
HT-8	7.64	30.24
HT-9	8.51	30.82

Analysis of variance (ANOVA) results for the regression model are presented in Tables 6 and 7. The results show that heat treatment temperature had a statistically significant effect on the response ($F = 42.01$, $p = 0.002$), explaining most of the observed variation. In contrast, holding time exhibited a smaller and statistically non-significant influence at the 95% confidence level ($F = 5.00$, $p = 0.082$), although its contribution was not negligible. The error term was low (Adj MS = 0.1683), confirming good experimental repeatability and reliability of the measurements. These findings indicate that temperature is the dominant factor governing changes in the measured property, while time plays a secondary role.

Table 6. Regression model summary for tensile strength.

S	R-sq	R-sq(adj)	R-sq(pred)
0.410237	95.92%	91.84%	79.34%

Table 7. ANOVA results for tensile strength under different heat treatment conditions.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	14.1398	7.0699	42.01	0.002
Time	2	1.6844	0.8422	5.00	0.082
Error	4	0.6732	0.1683		
Total	8	16.4974			

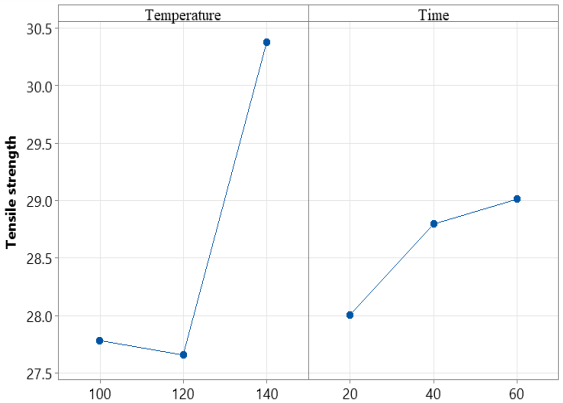


Figure 5. Variation of tensile strength with heat treatment temperature and time.

The main effects plot for tensile strength illustrates that heat treatment temperature had a pronounced influence on the mechanical performance of the ABS specimens (Figure 5). Tensile strength remained nearly unchanged between 100 °C and 120 °C but increased sharply at 140 °C, reaching approximately 30.5

MPa, corresponding to an improvement of about 8.9% compared to the lower temperature condition. This suggests that higher annealing temperatures promote improved interlayer bonding and polymer chain mobility, leading to enhanced strength when the material is heated sufficiently close to or slightly above its glass transition temperature. In contrast, holding time had a comparatively weaker but positive effect. Tensile strength showed a gradual increase from about 28 MPa at 20 min to around 29 MPa at 60 min, representing an increase of approximately 3.6%. Although the trend indicates some benefit from longer exposure, the change is modest compared to the impact of temperature.

The regression analysis for surface roughness is summarized in Table 8, where the model exhibited limited explanatory and predictive capability. This indicates that the selected heat treatment parameters alone were insufficient to describe the variation in Ra. The corresponding ANOVA results (Table 9) confirmed that neither temperature ($p = 0.542$) nor holding time ($p = 0.505$) had a statistically significant effect on surface roughness within the studied range, as reflected by low F-values and high p-values. The relatively large error term suggests that surface roughness was likely influenced by other uncontrolled factors such as local melt flow behavior, residual surface texture from the FDM process.

The Ra plot also does not display a consistent or strongly directional trend (Figure 6). Roughness values fluctuate across the temperature–time domain, and no statistically significant effect of either parameter was detected in the ANOVA ($p > 0.05$). This finding is consistent with the inherent nature of the FDM process, where surface roughness is predominantly governed by deposition-related parameters such as layer thickness, raster pattern, and extrusion conditions rather than post-processing treatments. The characteristic stair-stepping effect and layer-by-layer deposition create a surface morphology that cannot be substantially altered through thermal annealing alone [17].

Table 8. Regression model summary for Ra.

S	R-sq	R-sq(adj)	R-sq(pred)
1.58888	43.40%	0.00%	0.00%

Table 9. ANOVA results for Ra under different heat treatment conditions.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	3.624	1.812	0.72	0.542
Time	2	4.119	2.059	0.82	0.505
Error	4	10.098	2.525		
Total	8	17.841			

Previous studies have also reported that annealing treatments primarily influence internal stress relaxation and interlayer bonding, with only limited or inconsistent effects on surface roughness [27]. For instance, it has been shown that annealing provides only modest improvements in Ra compared to more aggressive surface-modifying techniques, and in some cases may even introduce variability depending on treatment conditions [28]. In contrast, significant reductions in surface roughness are generally achieved through chemical or vapor-based treatments that directly modify the outer surface geometry [29]. Therefore, the absence of a statistically significant change in surface roughness observed in this study is in agreement with the literature and indicates that heat treatment alone is not an effective approach for improving surface finish in FDM-produced ABS components, but rather primarily affects bulk and interfacial properties.

The contour plots in Figure 5 provide a visual representation of how heat treatment temperature and holding time simultaneously affect the dimensional stability (DSI), tensile strength, and surface roughness of the FDM-printed ABS specimens. For the DSI plot, a clear gradient is observed with increasing temperature: dimensional distortion remains minimal below 120 °C but rises sharply as the annealing temperature approaches 140 °C, regardless of exposure time. This indicates that temperature is the primary driver of dimensional change, consistent with the ANOVA findings showing temperature as highly significant ($p < 0.001$).

In contrast, the tensile strength plot shows a progressive improvement as the heat treatment temperature increases, with the highest strength values (> 30 MPa) achieved near 140 °C. Holding time exhibits a smaller but positive effect, with slightly higher tensile strength at 60 min compared to 20 min. These results suggest that moderate annealing enhances interlayer

diffusion and chain mobility, improving mechanical performance. This behavior is consistent with previous studies, which report that thermal treatment promotes stronger interfacial bonding between adjacent rasters and layers by facilitating polymer chain rearrangement. Higher temperatures and longer exposure times contribute to the reduction of internal voids and increased densification within the printed structure, resulting in more efficient load transfer and enhanced tensile strength. It has been shown that improved mechanical performance in FDM-printed ABS parts is closely associated with the strengthening of interlayer adhesion and the progressive elimination of interfacial defects under thermal treatment conditions [30].

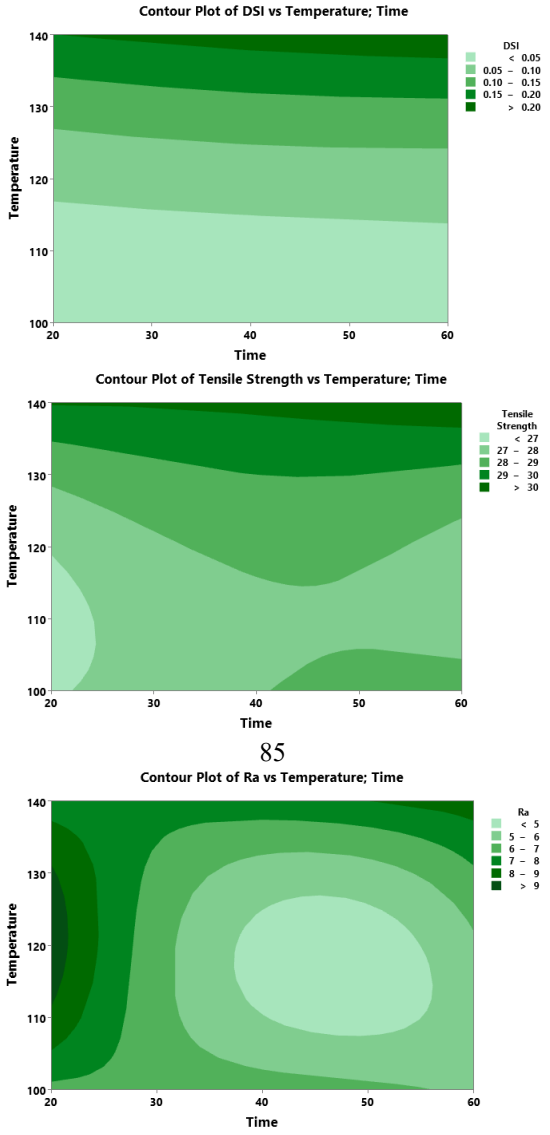


Figure 6. Contour plots of DSI, tensile strength, and surface roughness as a function of heat treatment temperature and holding time for FDM-printed ABS specimens.

4. CONCLUSION

This study systematically investigated the effect of post-processing heat treatment on the dimensional stability, tensile strength, and surface roughness of FDM-printed ABS specimens. A controlled experimental design supported by Response Surface Methodology was used to analyze the influence of two key parameters: heat treatment temperature and holding time.

The results demonstrated that temperature is the primary factor affecting both dimensional stability and mechanical strength. The Dimensional Stability Index remained low and nearly unchanged up to 120 °C but increased sharply at 140 °C, indicating significant geometric distortion at higher annealing temperatures. Tensile strength improved with increasing temperature, rising from 26.74 MPa in the untreated condition to a maximum of 30.82 MPa at 140 °C, corresponding to an increase of approximately 15.3%. This improvement highlights the effectiveness of thermal annealing in enhancing interlayer bonding and load transfer capability. While the effect of holding time was comparatively minor and statistically less significant, the dominant role of temperature was clearly evident. In contrast, surface roughness was not significantly influenced by either temperature or time within the studied range, showing that the as-printed surface texture of ABS is not easily modified through simple thermal annealing.

The experimental findings emphasize that controlling annealing temperature is essential to achieve a balance between dimensional accuracy and mechanical improvement in FDM-printed ABS parts. Heat treatment between 100 °C and 120 °C was found effective in relieving internal stresses and improving tensile strength without inducing measurable distortion, whereas higher temperatures enhanced strength further but compromised dimensional stability.

Moreover, the negligible variation in surface roughness across all conditions suggests that alternative post-processing techniques such as vapor smoothing, or mechanical finishing are required when surface quality improvement is desired. The regression and ANOVA analyses developed in this study provide a quantitative

framework for selecting post-processing parameters and optimizing the performance of polymer components produced by material extrusion.

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