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Research Article

Examining the Effect of Annealing Parameters on Surface Quality and Tensile Strength of ABS 3D-Printed Materials

Mohd Nizam Sudin[1,2a], Shamsul Anuar Shamsudin[1,2b], Nazri Md Daud[1,2c] Mohd Asri Yusuff[1,2d]
[1] Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia.
[2] Centre for Research on Energy (CARe), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia

nizamsudin@utem.edu.my

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ORCID: [a]0000-0001-7513-3826; [b]0000-0003-1740-8021; [c]0009-0007-0007-1430; [d]0000-0001-6736-8705.

Abstract : The primary objective of this research is to examine the effects of annealing temperature and duration on the surface quality and tensile strength of ABS-printed materials. ASTM 638 Type IV specimens were created in SolidWorks, sliced using Ultimaker Cura 4.4, and printed with a Creality Ender 3 3D printer using 1.75 mm ABS filament. The samples were subjected to thermal annealing at temperatures ranging from 120°C to 180°C. The annealing durations were set at 20, 40, and 60 minutes, after which the samples were cooled down to room temperature. The TR200 roughness tester and Instron 5585 tensile testing machine were utilized to measure surface roughness and tensile strength, respectively. The smoothest surface (0.622μm) was obtained when the temperature was set at 120°C for a duration of 20 minutes. On the other hand, the roughest surface (3.246μm) was observed when the temperature was increased to 180°C and maintained for a longer period of 60 minutes. The highest tensile strength of 75.681 MPa was observed at a temperature of 180°C for a duration of 60 minutes, indicating an optimal condition for maximizing the strength of ABS. However, there may be a limit, as suggested by previous research conducted at temperatures of 160°C and 180°C. In conclusion, it can be observed that the relationship between annealing temperature, duration, and surface roughness is not solely linear. The variations observed indicate the presence of interactions between these factors.

Keywords : ABS, Annealing parameters, FDM, surface roughness, tensile strength.

1 Introduction

Fused deposition modelling (FDM) is an economically viable additive manufacturing methodology that employs thermoplastics to fabricate personalized products. Despite being a cost-effective manufacturing technique, FDM exhibits certain limitations, including a restricted range of material choices, rough surface textures, and subpar mechanical characteristics. FDM parts are sensitive to slicing parameters. For example, infill density has the greatest impact on the tensile strength of 3D printed PLA+ samples (90.7%), followed by print speed and infill pattern. Previous research has shown that the diamond infill pattern demonstrates superior performance in influencing the structural strength of 3D printed objects [1], [2]. In investigating the wear behavior of gears, Kalani et al. [3] concluded that 3D-printed PA-12 Nylon gears manufactured using SLS exhibit reduced durability at high torque and rotational speeds, leading to failure due to increased contact surface at 1400 rpm and 2.4 Nm torque. They also found a higher specific wear rate at low rotational speeds. However, at low torque and speed, the gears operated smoothly without significant issues. The nozzle diameter has also affected the tensile properties of FDM-printed parts. However, the findings of [4] contradict those of [5]. Kartal and Kaptan [6] employed milling for post-processing and determined the optimum cutting tool for CNC milling of 3D-printed PLA parts.

Nevertheless, it is possible to overcome these limitations by implementing post-processing techniques that enhance both the mechanical properties and surface finish [7]. Annealing is a frequently utilized post-processing methodology that enhances the mechanical strength and crystallinity of parts produced through FDM [8], [9] but not at excessive temperature [10]. The methodology entails the application of gentle heat to the substance, elevating its temperature slightly beyond the threshold at which it transitions from a rigid to a more pliable state. The temperature is maintained at an elevated level for a specified duration, following which the substance is gradually cooled. The process of reheating and subsequent gradual cooling facilitates the development of substantial crystalline structures within the polymer, leading to the redistribution of internal stresses and, ultimately, an enhancement in crystallinity, strength, and stiffness [11].

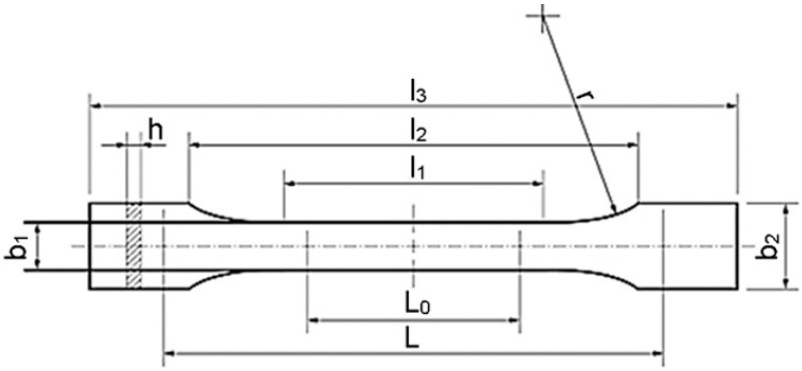
A number of studies have been conducted to examine the impacts of various annealing parameters on thermoplastic materials. The point being illustrated was demonstrated by [12] through the implementation of tensile and compressive tests on FDM-printed volcano Polylactic Acid (PLA). The material underwent annealing for durations of 20 and 60 minutes at a temperature of 110°C. As a result, the compressive strength of the PLA exhibited an increase, while its elongation demonstrated a decrease. Slavkovi'c et al. [13] conducted an experiment wherein annealing was carried out at a temperature of 75°C on a shape memory polymer composed of PLA. The researchers observed a significant increase in both tensile and compressive strength. The observed improvement can be attributed to the augmentation in crystallinity, mitigation of residual stress, and enhancement of interlayer bonding. In a similar vein, the authors Singh et al. [14] employed an annealing-based heat treatment methodology to enhance the surface characteristics of acrylonitrile butadiene styrene (ABS) components produced through FD). The implementation of this particular approach resulted in a decrease in porosity and interlayer gaps observed in the printed components. The predictive accuracy pertaining to tensile strength, flexural strength, and Charpy impact strength was found to be minimal. In a study conducted by [15], the manufacturing process of PLA was examined using FDM and subsequent annealing at temperatures above the glass transition temperature. The aforementioned methodology yielded a significant augmentation in flexural stress, a phenomenon that can be ascribed to the heightened crystallinity of the material. The findings presented in this study provide empirical evidence supporting a correlation between the mechanical properties of PLA and its crystalline structure. Butt and Bhaskar [7] conducted a recent study that demonstrated the efficacy of annealing treatments in improving the surface properties of ABS components produced through FDM. The annealing process is primarily influenced by temperature and time. The annealing process, when performed at temperatures below the glass transition temperature (Tg), serves to mitigate the residual stresses that arise from the printing process. Nevertheless, the process of annealing performed above the glass transition temperature (Tg) serves the purpose of not only relieving internal stresses but also modifying the molecular orientation. However, it has been demonstrated in prior studies that the impact of annealing on the properties of materials is intricate, resulting in different consequences depending on the precise annealing temperatures and durations [16], [17]. The phenomenon of annealing, carried out at temperatures surpassing the glass transition temperature (Tg), in the case of ABS, facilitates the consolidation of separate filament layers, consequently augmenting the material's pliability and adhesion properties. This phenomenon has the capability to reduce the occurrence of stress concentrations, thereby potentially enhancing the mechanical properties and surface finish of a material. To attain an optimal equilibrium between the augmentation of properties and the potential distortion of the structure, it is imperative to exercise prudence in the selection of annealing parameters. The preservation of the original form requires the utilization of molds or bracing techniques [17].

FDM components have improved mechanical properties and surface quality after annealing. To achieve the desired results while minimizing side effects, annealing parameters must be carefully adjusted. Our primary objective is to investigate how annealing parameters such as temperature and time affect the surface roughness and tensile strength of ABS-printed materials. The effect of processing parameters of abrasive water jet on the surface roughness of ABS and PLA 3D printed parts was investigated by [18]. In contrast to previous studies, which focused on annealing near the glass transition temperature (Tg), our research ranges from temperatures slightly above Tg to those near the melting point of the ABS material, with varying annealing times. Our research is based on three hypotheses: 1) Annealing above Tg improves interlayer adhesion and mechanical strength; 2) Annealing reduces surface imperfections such as porosity and interlayer gaps, thereby enhancing surface finish; and 3) The mechanical properties and surface quality of FFF-printed parts are dependent on annealing parameters. We expect that this research will aid in optimizing annealing for FDM applications.

2 Materials and Method

2.1 Material and Modelling

SolidWorks, a computer-aided design (CAD) application, was used to create a precise 3D model of the specimen. The design strictly adhered to the dimensions outlined in ASTM D638's dogbone configuration, as depicted in the Fig. 1. Specifically, it maintained the Type IV dimensions, ensuring precision with a length of 115mm, a grip width of 19mm, and a gauge width of 6mm, which all significantly contributed to the data's accuracy. The created model was saved in the STL file format to ensure compatibility with Ultimaker Cura 4.4 slicing software. The primary objective of this software platform is to optimize various critical parameters, encompassing layer height, wall thickness, top and bottom layers, infill density, and pattern. In order to achieve precision in the realm of 3D printing, these parameters must be accurately adjusted. The slicing of the specimen's 3D model was executed using Ultimaker Cura 4.4 software, a critical step in the process. After uploading the file, careful consideration was given to the creation of parameters and printing settings to ensure the accuracy of the printing procedure. Key printing parameters as in Table 1, including a layer height of 0.2 mm, were determined in order to achieve printing of standard quality. The wall thickness was determined to be 1.6mm, with four wall lines, and the top and bottom layers shared a thickness of 0.8mm, mirroring the wall thickness, with the number of lines matching the wall thickness for consistency. In addition, the infill density was set to 100% and the infill pattern was "lines," which had significant implications for the top and bottom layers, where a grid pattern was fully integrated into each layer. Fig. 2 provides further insight into the infill density (100%) and infill pattern (lines). The material chosen for this study is Acrylonitrile Butadiene Styrene (ABS)..



Size	Type I	Type II	Type III	Type IV	Type V
Full length, l_3	165	185	165	115	
Parallel length, l_2	57	57	57	33	63.5
Gauge length, l_1	50	50	50	25	
Parallel section width, $strong_1$	13	6	19	6	7.62
Thickness, h	7 mm or less		7mm to 14 mm	4 mm or less	
Grip section width, $strong_2$	19	19	29	19	9.53
Distance between grips	115	135	115	65	25.4

Figure 1: ASTM specimen dimension [19]

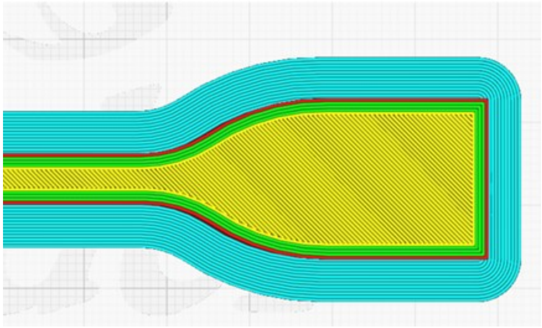


Figure 2: Infill density (100%) and the infill pattern (lines)

2.2 Printing Process

To ensure proper adhesion to the build plate, a raft with precise dimensions and a surface separation of 0.3 mm was implemented. Using this design, the printed object demonstrated a high degree of detachability. Following the slicing procedure, the G-code for the project was saved and sent to the Creality Ender 3 3D printer (Fig. 3a). Consequently, the bed was accurately levelled using a sheet of paper to ensure the proper nozzle-bed distance (Fig. 3b). To ensure consistency, three identical specimens were subsequently replicated three times. The scaffolding used to support the specimens was carefully removed following the printing process in order to preserve their structural integrity. Sample of printed specimens is shown in Fig. 4.

2.3 Annealing Process

Annealing is a post-processing technique used to enhance the strength of printed parts. In this process, the specimens, printed layer by layer, were placed on a flat Teflon-coated baking pan inside a forced convection bench oven. They were subjected to heating at temperatures of 120°C for durations of 20, 40, and 60 minutes and then allowed to cool to room temperature. The

Table 1: Parameters used for slicing the 3D model

Parameter	Value
Layer Height	0.2mm
Wall Thickness	0.8mm
Print Speed	45mm/s
Build Plate Adhesion	Raft
Nozzle Temperature	230^0 C
Infill Density	100%
Infill Pattern	Lines
Material	ABS

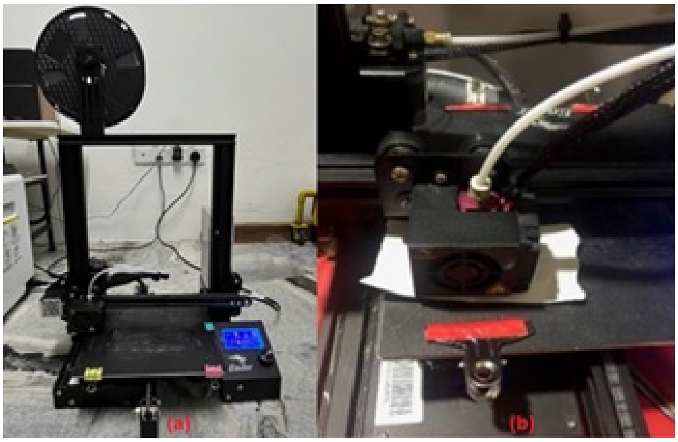


Figure 3: (a) Creality Ender 3 3D printer (b) The bed levelling process

Figure 4: Samples of printed specimens for various annealing times: 20, 40 and 60 min (from left to right)

process was then repeated for temperatures of 140°C, 160°C, and 180°C. Detailed information about the annealing temperature and duration for the specimens can be found in Table 2. This process was applied to samples printed with ABS wire filament with infill densities of 100%. Fig. 5 illustrates an example of an annealed 3D printed specimen for testing purposes.

2.4 Surface Roughness

The surface roughness tester, model TR200, with a measuring range of Ra from 0.005 to 16.000μm and Rz from 0.02 to 160.00μm, was utilized to record the average surface roughness. Three different spots on the sample were recorded, and the average of these three values was calculated. During the measuring procedure, the sensor moved linearly along the measured length, while the probe adapted to the surface profile. These movements were then converted into electric signals, subsequently amplified, filtered, and transformed into digital signals by an A/D converter. The main processor further processed these digital signals to provide Ra and Rz values (or Rq and Rt metrics), which were displayed on the screen. Fig. 6 depicted the surface roughness tester, model TR200.

2.5 Tensile Test

The tensile test was conducted on each specimen using an Instron 5585 Floor Model Testing System. The primary technical characteristic of the machine is its load cell capacity, which can reach up to 250 kN, making it suitable for conducting the tests in this research. The setup for the tensile test is illustrated in Fig. 7. In the tensile test, each specimen was subjected to a defined rate

Table 2: Parameters for annealing process

Experiment	Annealing temperature (^{0} C)	Annealing time (min)
1	120	20,40,60
2	140	20,40,60
3	160	20,40,60
4	180	20,40,60

Figure 5: Samples of specimens after annealing process at variuos temparatures and times: (a) 20 min, (b) 40 min, (c) 60 min.

Figure 6: Portable surface profilometry

Figure 7: Instron 5585 tensile testing machine

Table 3: Parameters used for the tensile test

Parameter	Value
Distance between grip	115mm
Thickness of specimen	4 mm
Speed	4 mm/min
Temperature	25^0 C
Humidity	60%

of extension until it reached failure. A total of thirty-six samples were evaluated, with three for each combination of annealing temperature and time. This experiment aimed to determine the mechanical properties of the specimens. Using the test results, parameters such as tensile strain, tensile strength, and modulus of elasticity were calculated. The experiment involved several key parameters, including gauge length, gauge width, thickness, specimen grip distance, and testing speed. These parameters were determined prior to conducting the experiment. Table 3 provides an overview of the tensile test parameters.

3 Results and Discussion

3.1 Effect of Annealing Temperature on the Surface Roughness

The findings of surface roughness measurements conducted on annealed components produced through the FDM technique are presented in Table 4. The obtained measurements demonstrate a noticeable pattern of fluctuations in surface roughness, which can be attributed to the different annealing temperatures. This claim is supported by the noticeable differences in measurements of average roughness. Our study presents a notable departure from previous research by establishing a clear and positive association between the annealing temperature and the surface roughness of the specimens. The current findings are in opposition to the results documented by [7] and [20], who observed a decrease in surface roughness for 3D-printed ABS components when the annealing temperature was increased slightly above the glass transition temperature of ABS (ranging from 105°C to 115°C to 125°C). Conversely, the findings derived from our research demonstrate a divergent outcome. As an example, the surface roughness was measured to be 0.622μm after subjecting it to a heating duration of 20 minutes at a temperature of 120°C. Nevertheless, it was observed that there existed a clear relationship between the surface roughness and the annealing temperature. Specifically, as the annealing temperature increased to 140°C, 160°C, and 180°C, while maintaining a constant duration, the surface roughness values correspondingly increased to 1.576μm, 2.72μm, and 2.863μm. The abrupt transition in surface roughness is observed when the annealing temperature is increased from 120°C, which is in close proximity to the glass transition temperature (Tg), to 180°C, a temperature that is significantly distant from Tg. Singh et al. [17] have proposed that the application of annealing at a temperature of 120°C shows potential in reducing the occurrence of the "staircase effect" by facilitating the reflow of build material, leading to enhancements in surface roughness. Nevertheless, when subjected to temperatures outside of the optimal range or excessive heat, such as 180^0C in the specific context mentioned, the material may undergo degradation, resulting in the appearance of surface irregularities, the generation of bubbles, or the development of roughness. The decrease in quality that has been observed can be attributed to the thermal decomposition of ABS. Therefore, the meticulous selection of the appropriate annealing temperature is imperative in order to achieve the optimal surface roughness of the specimen.

Table 4: Effect of annealing parameters on surface roughness

Annealing temperature (°C)	Annealing time (min)	Surface roughness (µm)
120	20	0.622
120	40	0.640
120	60	0.635
140	20	1.576
140	40	1.886
140	60	1.748
160	20	2.725
160	40	2.919
160	60	3.134
180	20	2.863
180	40	3.124
180	60	3.246

3.2 Effect of Annealing Time on the Surface Roughness

Two distinct patterns were identified with regards to the influence of annealing duration on the surface roughness of ABS-printed components. The results revealed a positive correlation between the length of the annealing process and the level of surface roughness. This was apparent based on the observed upward trend at both temperatures of 120°C and 140°C. However, a deviation from this established trend became apparent following a duration of 60 minutes, as a noticeable reduction in surface roughness was observed. For instance, the annealing temperature was established at 120°C, and the duration was systematically adjusted in 20-minute intervals, starting at 20 minutes, progressing to 40 minutes, and ultimately concluding at 60 minutes. Upon initial observation, there was a noticeable increase in surface roughness, as evidenced by an initial measurement of 0.622μm, which later advanced to a final reading of 0.640μm. Nevertheless, it is crucial to acknowledge that a subsequent marginal reduction in surface roughness occurred, leading to a final measurement of 0.635μm. A similar pattern was observed when the temperature was modified to 140°C.

On the other hand, the second pattern arose due to the elevation of the annealing temperature to 160°C and 180°C. Under the prevailing conditions, an increase in the duration of the annealing process led to a corresponding increase in surface roughness. The existence of an optimal duration for annealing at a particular temperature can explain the two patterns that have been observed. This enables the material to achieve the desired improvements in both its structural and mechanical properties, while also preserving its surface quality. Beyond this optimal duration, there exists the potential for encountering over-annealing, a phenomenon that may result in the deterioration of the material or the formation of imperfections on its surface. The decrease in surface roughness observed after a duration of 60 minutes implies that the material may have attained its optimal annealing state, subsequently experiencing a gradual degradation as a result of prolonged heat exposure. Furthermore, when exposed to elevated temperatures, specifically at 160°C and 180°C, acrylonitrile butadiene styrene (ABS) experiences significant softening and increased malleability, leading to the flow and deformation of the material. As a result, this phenomenon plays a role in the development of surface irregularities and a general augmentation in roughness.

3.3 Effect of Annealing Temperature on the Tensile Strength

The data presented in Table 5 and Fig. 8 offers valuable insights into the influence of annealing parameters on the tensile strength exhibited by ABS material. A noticeable pattern emerges as the annealing temperature varies between 120°C and 180°C, demonstrating a consistent increase in tensile strength. This observation suggests that increasing annealing temperatures has a positive effect on the tensile properties of ABS material. This result aligns with the discovery made in reference [21], which examined how different annealing temperatures affect the properties of PLA-printed components. Significantly, the shift from 120°C to 140°C demonstrates a noteworthy augmentation in tensile strength measurements, emphasizing the advantageous impact of higher annealing temperatures on the strength of the material. Nevertheless, when subjected to elevated temperatures of 160°C and 180°C, the tensile strength values display fluctuations, suggesting that there may be other contributing factors, apart from temperature alone, that impact the material's tensile properties. The heightened molecular mobility of the ABS material is considered to be a significant contributing factor to the observed trend of increased tensile strength at higher annealing temperatures. Increased temperatures impart higher thermal energy to polymer chains, thereby promoting enhanced mobility and reconfiguration. The heightened molecular mobility results in enhanced alignment of chains, diminished internal stresses, and augmented intermolecular interactions, ultimately leading to improved tensile properties, including heightened strength. Nevertheless, when exposed to extremely elevated temperatures, specifically 160°C and 180°C, the fluctuations in tensile stress that are observed can be ascribed to the initiation of material degradation or other complex interactions that impact the behavior of the material. This suggests that there may be a limit to the advantages of utilizing higher temperatures.

3.4 Effect of Annealing Time on the Tensile Strength

The data presented in Table 5 demonstrates a consistent pattern across various annealing temperatures, suggesting that longer durations of annealing generally lead to higher levels of tensile strength and, as a result, enhanced tensile properties. The

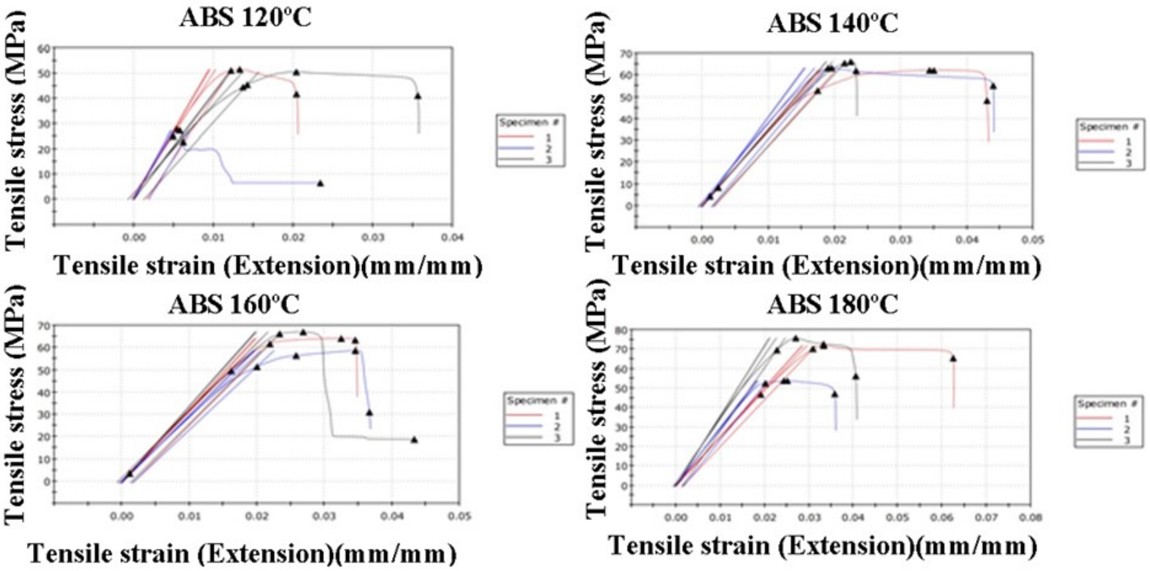


Figure 8: Graph of stress-strain for ABS specimens annealed at various temperatures (9 plots in each graphs reflecting 3 samples tested in each combination of annealing temperature and time

Table 5: Effect of annealing parameters on tensile strength

Annealing temperature (°C)	Annealing time (min)	Tensile strength (MPa)
120	20	51.629
120	40	27.452
120	60	50.619
140	20	62.159
140	40	63.191
140	60	66.062
160	20	64.071
160	40	58.655
160	60	66.938
180	20	71.810
180	40	53.863
180	60	75,681

observed phenomenon is particularly prominent when the annealing process reaches the 60-minute mark, as the tensile strength values consistently surpass those observed at shorter durations of 20 and 40 minutes. When considering different annealing temperatures, such as 120°C and 140°C, the impact of varying annealing times ranging from 20 minutes to 60 minutes exhibits a complex pattern. A clear positive correlation between longer annealing times and higher tensile strength is observed at temperatures of 120°C and 140°C. This discovery underscores the positive impact of prolonged durations on the tensile strength, corroborating the results observed in reference [22], which used PLA material as the specimen for tensile testing. In contrast, when subjected to temperatures of 160°C and 180°C, the correlation between the duration of annealing and the tensile strength displays a more intricate nature, characterized by fluctuations in tensile strength values and less predictable patterns. The observed intricacy at elevated temperatures implies that there are additional factors, beyond the passage of time alone, that can impact the tensile properties. Stress relaxation is a significant contributing factor to the observed correlation between longer annealing durations and enhanced tensile properties. During the annealing process, the ABS material undergoes prolonged exposure to elevated temperatures, which facilitates the gradual reorganization of polymer chains and the subsequent relief of internal stresses. The aforementioned procedure serves to mitigate residual stresses and imperfections present in the material, thereby leading to an augmentation in its tensile strength. Nevertheless, it is worth noting that there is an optimal duration for annealing, beyond which further enhancements may be constrained. This limitation is evident in the fluctuating stress values observed at exceedingly high temperatures.

4 Conclusions

This research aims to investigate the influence of thermal annealing parameters, specifically temperature and duration, on both surface roughness and tensile strength in ABS material printed parts. Overall, both parameters exhibit significant effects on the studied outcomes. Notably, the lowest surface roughness values are achieved at 120°C with a 20-minute annealing duration, yielding a surface roughness of 0.622μm, suggesting an optimal condition for achieving smoother surface finishes. Conversely, the highest surface roughness values are recorded at 180°C with a 60-minute annealing duration, resulting in a surface roughness of 3.246μm, indicating the roughest finish. It's important to acknowledge that the relationship between annealing temperature, duration, and surface roughness is not purely linear, with interactions between time and temperature leading to observed variations. This data suggests a potential trade-off between enhancing mechanical properties through annealing (as previously noted) and maintaining a smooth surface finish. Longer annealing times at higher temperatures appear to enhance mechanical properties but may result in rougher surfaces. Similarly, the effect of temperature and time on tensile strength is not strictly linear, with potential interactions between these variables. The highest tensile strength values are achieved at 180°C with a 60-minute annealing duration, reaching 75.681 MPa, possibly indicating an optimal condition for maximizing tensile strength in ABS material. However, it's essential to recognize that there may be a threshold beyond which further increases in temperature or annealing time do not lead to enhanced tensile properties, as indicated by variations at 160°C and 180°C. Manufacturers can utilize the results to enhance their annealing procedures for 3D-printed ABS components, achieving an optimal balance between surface quality and mechanical durability according to specific application needs. Further investigation into the microstructural changes induced by different annealing parameters could lead to deeper insights into the mechanisms that control the roughness and tensile stress of materials. To broaden the scope of this research, future studies could examine the effects of surface coatings, chemical treatments, and annealing on the properties of ABS components produced through 3D printing. It's important to note that the scope of this study is limited to ABS material and may not comprehensively reflect the characteristics of other 3D-printed materials. Additionally, this study does not consider the impact of build orientation or part geometry on the efficacy of annealing, which could be significant factors in real-world applications.

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Authors' Contributions

MNBS made contributions to the literature review, experimental investigation, result interpretation, and article writing. NMD participated in result analysis and article writing. MAY played a role in defining the research subject, outlining the scope, handling manufacturing aspects, and contributing to article writing. The final version of the article received approval from all authors.

Competing Interests

The authors declare that they have no competing interests.

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