

Impact of Print Speed and Nozzle Temperature on Tensile Strength of 3D Printed ABS for Permanent Magnet Turbine Systems

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ABSTRACT

Operational parameters must be integrated into turbine systems' main components, which are determined by turbine systems' functional requirements. The need for producing component designs more effectively raises the possibility of using additive manufacturing. The study focuses on the optimization of the mechanical properties of the principal components of magnetic turbines manufactured with 3D printers using Acrylonitrile Butadiene Styrene (ABS), by changing the temperature and speed of the nozzle. The approach consisted of modeling a standard test piece in CAD software and producing ABS-based test pieces using a 3D printer with print speeds of 50, 70, 90, and 110 mm/s and temperatures of 230, 240, 250, and 260 °C. The tensile properties of the samples were determined according to ASTM D638-14 Type I, and the results reveal a consistently greater tensile strength for the parts with high nozzle temperatures of approximately 250 °C and lower print speeds of 50 and 70 mm/s. At higher speeds of 90 and 110 mm/s, though the nozzle temperature has little effect on tensile strength, suggesting that the effect of other parameters is more significant. Whatever the print speed, at higher nozzle temperature (250°C), average tensile strength was improved. Control of nozzle temperature is paramount in increasing tensile strength in the 3D printing process performed at low speeds. Also, the average tensile strength is consistent and normalized. For all print speed values, a 250°C nozzle produces consistently higher average tensile strength than a 235°C nozzle. Analysed the parameters for print speed and nozzle temperature, providing optimal results for stronger and more reliable parts for use in turbines.

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Keywords: 3D printing, additive manufacturing, print speed, nozzle temperature, optimization, tensile strength

I. Introduction

Currently, in this age of awareness, there has been a shift towards using clean energy. Therefore, researchers have started researching the possibility of using nonfossil reserves, commonly known as renewable resources, like wind energy, solar energy [1], [2], water energy, etc. A novel unutilized energy source is the repulsion force from a pair of the same pole permanent magnets, which can supplant the function of water energy found in water turbines [3], thus producing permanent magnet steering systems. The working principle of the permanent magnet turbine system is an improvement over the working principle of the water turbine system, such that most of the working parameters of the two systems are relatively similar. The permanent magnet turbine system's working parameters include the



repulsion force strength, attack angle, torque, rotational speed, and its power produced by the permanent magnet turbine system. This means that, in this system, the configuration of the main components of the turbine system must maximize the working parameters, which makes the shape of the main elements of the device more complex and leads to complications in the manufacturing process [4]. The basic components of a permanent magnet turbine system are rotor and stator disks, which possess cylindrical holes serving as receptacles for permanent magnets. A rotor/stator disc is as shown in Figure 1. The rotor/stator disc involves many manufacturing attributes and complex manufacturing processes. Thus, advanced manufacturing methods such as Fused deposition modeling (FDM) are a potential candidate for future studies of permanent magnet turbine systems [5].

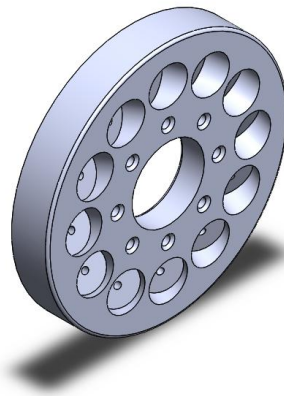


Fig. 1. Rotor/Stator disk of permanent magnet turbine systems.

The last decade has seen the rapid development of FDM, or additive manufacturing, particularly three-dimensional (3D) printing technology [6], [7]. It has become a well-accepted approach for rapid prototyping with acceptable margins of error [8]. This technology allows to change of design models of devices into functional parts, but with low precision output [9]. Despite being extensively studied in various operational parameters to enhance the quality of 3D-printed parts or products, the strength characteristics are less explored [10], [11].

Within additive manufacturing, the 3D printer is considered an archetypal technology, particularly in serving the activities of rapid prototyping and reverse engineering [12]. The last decade has been a game-changer in this regard with 3D printing, which perfectly bridges the gap between digital model and real-world replica in the domain of prototyping by allowing the direct fabrication of the final product without needing molds, dies, or other intermediate tools [13], [14]. The ability to retrain and fabricate scarce or nonexistent spare parts is substantial for reverse engineers, code red rendering maintenance and restoration of key plant and machinery into lightning-fast drives [15]. Advances in additive manufacturing through the use of 3D printing technology enable engineers and designers to maximize the benefits of reverse engineering, resulting in high-end and customized products [16], [17].

Manufacturers need to identify the optimal production parameters that can provide the desired strength [18]. Therefore, understanding the strength properties of 3D-printed parts is an essential task for manufacturing engineers. If this subject of research had been studied in more extensive detail, suitable parameters would have been determined quickly to achieve the necessary strength in the printed parts/products [19]. Therefore, manufacturing experts struggle with tuning the working parameters, and they cannot capitalize on the true potential of additive manufacturing [10] in producing high-strength elements.

Therefore, it is a priority to improve the currently limited knowledge about understanding the influence mechanism of operational parameters (like nozzle temperature and printing speed) on the strength property of 3D-printed Acrylonitrile Butadiene Styrene (ABS) materials. The relationship between these parameters and the published tensile strength of printed products will provide valuable information that allows manufacturers to improve the quality and mechanical properties of printed parts [20]. The work in this paper is an evaluation of the influence of the different 3D printing parameters, namely, layer height (LH), print speed (PS), print temperature (PT), and infill line direction (ILD) on the surface roughness of parts produced through a process called FDM along with the tensile property of the printed part [21]. Specifically, the study highlights the importance of the influence of parameters such as LH and ILD on crucial properties like surface roughness and tensile strength, thus facilitating a better understanding of how these parameters can be fine-tuned to achieve the best possible quality of 3D component printed parts. Nano graphite-reinforced polylactic acid (PLA): Nano graphite-reinforced PLA improves the mechanical properties of printed parts. The employed materials are rather less reported in the existing literature and novel with respect to their combined assessment with optimized printing parameters in regard to their biomedical applications.

Research needs to be conducted on the optimization of surface roughness factors, especially in the domain of 3D printing using PETG (Polyethylene Terephthalate Glycol) [22]. To address this matter, this study investigates the influence of significant variables (nozzle temperature, infill geometry, layer height, and fan speed) on the surface finish of PETG prints, which is a fundamental property for its applications in medicine and personalised body accessories. Although the effect of layer height on the surface roughness is intuitively understood, the comprehensive quantification of the relationship between layer height and surface roughness, in particular for PETG, is lacking in the literature. The study reveals that layer height is responsible for 82.3% of the variance in surface roughness, and the remaining parameters contribute less than 7%, respectively, in accordance with a Taguchi experimental design. Through a clear correlation of these factors on the level of impact, the study provides valuable insights to increase the quality of PETG prints, which in turn would benefit various industrial applications.

Three-dimensional (3D) printing has received great interest from many fields given its ability to manufacture complex geometries with favorable accuracy and material versatility. However, due to the rapid cooling of materials upon extrusion, the resultant polymers often fail to obtain optimum polymer crystallinity, leading to poor mechanical properties compared with the original polymer in the bulk state. Previous articles have reported on modifying material formulations, such as the addition of additives like PLA nanofibers, while other work has shown that mechanical properties can be greatly impacted by changes in printing parameters. This study fills this important gap in the evidence base and empirically investigates how certain inputs to the 3D printing process (e.g., infill types and percentages) affect the mechanical strength of printed samples. The results confirm that parameter optimizations can have a striking impact on performance drivers, offering important insights to find optimal 3D printing process conditions for demanding environments [23].

Further studies have methodically covered the effects of infill pattern, density, and layer thickness on the mechanical properties of 3D-printed acrylonitrile butadiene styrene (ABS) using FFF techniques. Past research focused on single aspect of mechanical performance of thermoplastics, and in particular PLA, which frequently surpasses ABS. Exploring the interplay of these printing parameters, the study found that larger infill densities,

approximately 80%, resulted in improved bonding between the layers and greater mechanical strength due to minimized voids and better inter-layer bond strength. In addition, the results of the study reveal that the best-practice parameters (including concentric infill pattern and 100 μm layer thickness) can positively affect tensile strength and overall performance. This study is crucial to practitioners in additive manufacturing for AF-105978-0, as it first helps to better understand the spectrum open for vat-based printing (VBP) in ABS and, secondly, to present how to take advantage of the information obtained to improve the performance of products based on ABS [24]. Thus, it can be concluded that there are still only a handful of studies on the effects of operational parameters on 3D printed ABS product strength, and further research is required. The present study attempts to address this issue through the systematic analysis of the influence of nozzle temperature and printing speed, along with their interactions, on the tensile strength of 3D-printed ABS components. Data analysis will further enhance the knowledge of strength properties as a reaction to different operational parameters, paving the way for the manufacturing specialist to set up a correct printing process to produce strong and durable products.

II. Materials and Methods

In this section, the experiments are described, which form the essential basis for determining the procedure, experimental procedure, and materials used for the performance of the investigation [25]. This section outlines the efforts taken to reproduce this work by researchers and validate main findings, allowing other researchers to build upon this work. The method section organizes and describes the materials, equipment, and procedures in such detail that others can reproduce the experiment, thus enabling scientific transparency and integrity. Moreover, a detailed documented methodology is useful in identifying and controlling sources of bias or other potential sources of error, which increases the reliability and validity of the results of the experiment. It also ensures that the study is properly documented and archived, making it easier for future reference and comparison. It offers readers an insight into the research process, allowing them to determine the level of rigour of the work and to judge the strength of the conclusions. This transparency, reproducibility, and quality of the experimental research are assured by properly written and elaborate methodology.

The experiment was designed to see how nozzle temperature and print speed influence the tensile strength of 3D-printed PETG specimens. Input variables include nozzle temperature (230°C, 240°C, 250°C, and 260°C) and print speed (50 mm/s, 70 mm/s, 90 mm/s, and 110 mm/s), and the output variable is the tensile strength of prints. Based on the theory of variety, we created samples based on 4 temperature levels \times 4 speed levels, a total of 16 parameter combinations, each parameter combination was replicated 3 times, for a total of 48 samples. After all the sampling action was completed, ensuring the statistical reliability of the sample. The optimal parameters were determined by evaluating the combination of nozzle temperature and speed, which resulted in the highest average tensile strength, to ensure the flow of material was optimal with no overheating and degradation between layers.

1. Material Selection

The material chosen for this study was Acrylonitrile Butadiene Styrene (ABS) from SUNLU 3D Maker, China. ABS is a common thermoplastic polymer and one of the most widely used materials in 3D printing since it has good mechanical properties and high impact resistance.

2. Experimental Setup

A desktop 3D printer (type Ender-3, made in China) with a heated build platform and a single extruder was used to perform the printing process. The printer model and specifications (including the nozzle diameter: 1.75 mm (retrofitted); layer height and build volume).

3. Printing Parameters

Response surface methodology was applied to a systematic experimental design to study the effect of temperature and print speed on the tensile strength of 3D-printed ABS parts. Table 2 summarizes the heating and cooling parameters used in the experimental test for the MATT, which were planned based on preliminary findings and previous studies. The combinations of temperature and print speeds that were defined are statistically significant, and the number of replications at each combination was planned appropriately. This study used the temperature of the nozzles for 230 °C, 240 °C, 250 °C, and 260 °C; the speed of the nozzles for 50 mm/s, 70 mm/s, 90 mm/s, and 110 mm/s; and 3 measurements in the replications.

4. Sample Preparation

The test specimens were designed on computer-aided design (CAD) software (CATIA version 5, Dassault System, France), such that specific IDs, dimensions, and geometries were created based on ASTM D638-14 Type I (LO=165, WO=19, L=57, W=13, T=3.2±0.4 and R=76 as shown, dimensions in mm above) (Figure 2). In this regard, the specimen types defined in the ASTM D638 standard [26] are considered when preparing samples for tensile performance testing for the 3D printed ABS materials. Within these preferences, the Type I designation, more commonly referred to as the Dogbone specimen, seems to take interest. This selection is supported by the unique dogbone thermal construction, which is constructed to generate an even distribution of stress throughout the specimen during tensile testing. Developing and employing gears with this geometry is mainly attributed to its ability to keep the same stress state on the sample section 3, which leads to accurate and reproducible tensile strength values. Carefully selecting the right Dogbone specimen indicates a focus on producing accurate and repeatable results; this is fundamental in evaluating the mechanical characteristics of the additively manufactured ABS material. The design files were then exported into STL (Standard Tessellation Language) format, which is compatible with 3D printing software. Test specimens were printed with selected ABS material and selected printing parameters. The printing process was tracked to ensure consistent printing quality and accuracy.

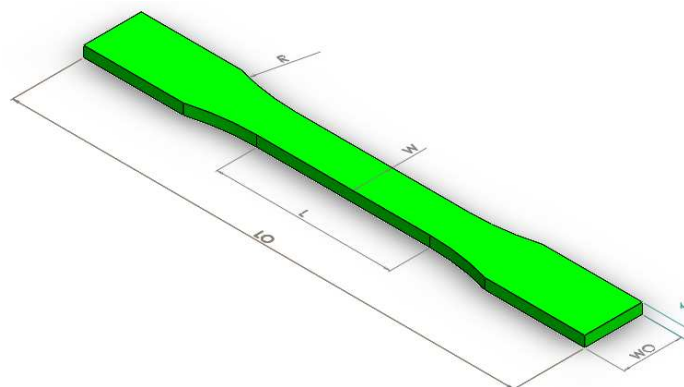


Fig. 2. Tensile test specimen ASTM D638-14 Type I

5. Tensile Testing

The tensile tests of printed specimens were conducted using a universal testing machine. Tensile tests were performed according to the standard for tensile testing of plastics (ASTM D638). The specimens were tested under tensile loading at the same crosshead speed (5 mm/min) until failure. For each specimen, yield strength, tensile strength, and elongation at break were recorded.

Introduction tensile testing is a chronicled procedure that determines the mechanical properties of a material under a bona fide axial tensile load. 3–7; test data of load (F) and extension (ΔL) are collected to derive variables of interest. The stress (σ) is calculated as the applied load divided by the original cross-sectional area of the specimen (A_0) (Eq. (1)).

$$\sigma_t = \frac{F}{A_0} \dots \dots \dots (1)$$

Strain (ϵ) is determined by the ratio of the change in length to the original length (L_0) of the specimen (Eq.(2)):

$$\epsilon = \frac{\Delta L}{L_0} \dots \dots \dots (2)$$

The load-extension curve represents how the material behaves with further load on it, where σ_{max} , the maximum tensile strength, is positioned at the leading edge of the curve. Now, this is like I mentioned there. This is the region after which the material will try to take on and absorb the strain hardening, which also refers to the ability of the material to sustain stress and deform and etc. The tensile test methods/techniques are helpful to investigate the material mechanical characteristics, which are essential to have an insight into the material behaviour in the working environments.

6. Data Analysis

Tensile Strength: Regarding the analysis of data obtained, two-way analysis of variance (Two-way ANOVA), which required statistical methods, was used to statistically substantiate how tensile strength is influenced by nozzle temperature and speed with a significance level of 5%. Results were generated in graphs and tables to enable a better understanding of the data.

7. Control Experiments

Control experiments were performed using standard printing parameters for reference and comparison. These results were utilized as a reference to compare the tensile strength of parts manufactured under various nozzle temperature and speed settings.

III. Results and Discussions

In this research, ABS 3D printable material tensile strength is investigated based on the print speed (Nozzle_Speed) and nozzle temperature (Nozzle_Temp). This allows for greater observability of how these characteristics influence the mean tensile strength of three measurements under the statistical pump investigation.

Figure 3 shows the average stress-strain diagrams for different nozzle temperature and speed combinations. This is the average stress-strain diagram for all applied levels of temperature and print speed. Strain data was plotted along the X-axis and average tensile stress data along the Y-axis on the different levels of the print speed (Figure 2). The maximum average tensile strength cannot be achieved at 230 °C when a nozzle is used,

which indicates possible instability. This means that at low print speeds (50 and 70 mm/s), it creates material with lower maximum tensile strength. At higher speeds (90 mm/s and 110 mm/s), material becomes more brittle, and printed materials with higher maximum tensile strength go ductile. Printed material is characterized by a higher maximum tensile strength and ductility when nozzles are set to higher process temperatures (i.e., 240 to 260 °C).

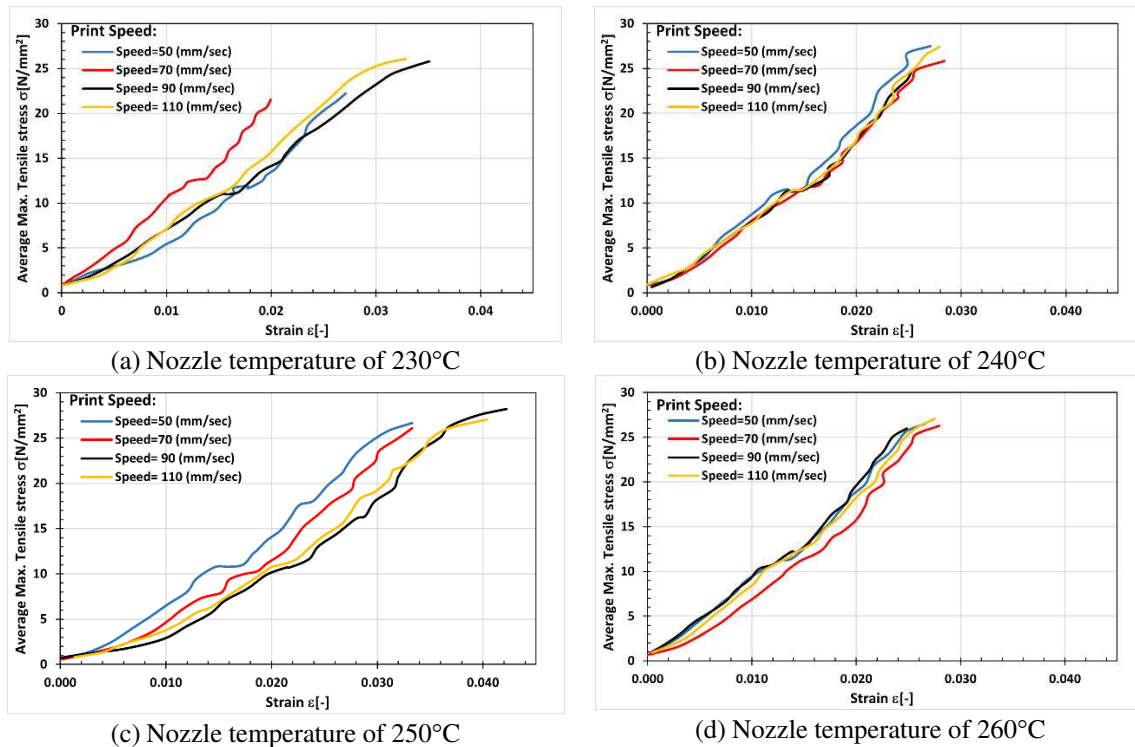


Fig. 3. Average stress-strain diagram of printed material for each combination of nozzle temperature and speed.

An average maximum tensile strength value for the material printed under these conditions is obtained from all temperature–print speed graph combinations together, and different graphs were generated that illustrate the influence respective temperature and the nozzle velocity have on the mechanical performance of the material printed. Figure 4 illustrates the relationship between the nozzle temperature and average tensile strength of 3D-printed materials tested at different print speeds (50 mm/s, 70 mm/s, 90 mm/s, and 110 mm/s). A peculiar dependence of the tensile strength on the nozzle temperature is evidenced, with an early peak, but decrease when nozzle temperature surpasses a particular threshold. Such behaviour is characteristic of the calibration of the 3D-printed compositional materials regarding mechanical properties as a function of thermal environments.

For lower nozzle temperatures (230–240 °C), the tensile strength from all print speeds tended to exhibit relatively low values. Inadequate material flow and weak interlayer adhesion are the main reasons behind this phenomenon, as at such relatively low temperatures, the amount of thermal energy supplied is not enough for melting of the material or complete fusion between two successive layers. At these temperatures, the parts do not bond optimally, reducing the mechanical strength of printed parts considerably.

When temperature rises into the range of 240–250 °C (specially from 230 °C), a sharp increase in tensile strength is visible for every print speeds. This is defined as the best temperature for deposition and bonding of material. At a print speed of 90 mm/s for such

cases, in fact, the tensile strengths were observed to be the maximum values of almost 27.5 N/mm² at nearly 245 °C, indicating that this temperature with this particular speed factor evinced a proper equilibrium of sufficient material flow and layer heat absorption, consequently improving quality through interlayer adhesion. A similar trend is noted for other print speeds, while maximum tensile strengths vary slightly, which is likely attributed to differences in heat input and deposition rate of the material. Yet with operating working < 250 °C, the increase of nozzle temperature further decreases the tensile strength. This may be caused by overstress on the brittle material during contact with the mold or overheating, which weakens the polymer structure and interrupts the layer bonding. This inability to pasteurize is a good example of the folly of over nozzling in the name of strength improvement.

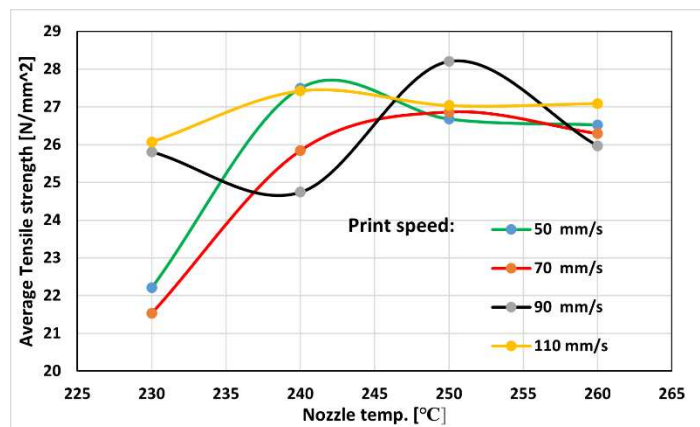


Fig. 4. The effects of nozzle temperature on tensile strength

Print speed will also affect the tensile strength, but plays an even more crucial role. At lower speeds (50 mm/s and 70 mm/s), tensile strength relatively slowly rises with the rise of temperature, and the peak value is relatively close. On the other hand, at higher speeds (110 mm/s), the tensile strength is lowest at its peak, possibly due to the fact that there is not enough time for the layers to properly bond as the nozzle is moving too quickly. The consistent pattern across the tested speeds shows that 90 mm/s yields the highest tensile strength, suggesting this as the optimal speed for balancing heat absorption and deposition rate. These conclusions show that the nozzle temperature and print speed are important parameters that need to be optimized to obtain better mechanical properties in 3D-printed specimens. For instance, keeping the nozzle temperature in the 240–250°C range and using a moderate speed (90 mm/s) are suggested for optimum tensile strength. As such, this finding offers important guidelines for the fabrication of high-performance 3D printed materials, especially when mechanical durability in demanding environments is concerned.

The influence of print speed on tensile strength of 3D-printed materials studied at four distinct temperatures (230°C, 240°C, 250°C, and 260°C) is depicted in Figure 5. These results indicate that print speed has a significant impact on tensile strength, especially at elevated temperatures where bonding is critical, which is most significantly determined by the deposition process dynamics. At low nozzle temperature of 230°C, tensile strength is consistently low across all print speeds, improving slightly with higher speeds. This means insufficient thermal energy at this temperature restricts the material from flowing and bonding adequately, independent of deposition rate. At 240°C, a similar phenomenon is noted, but a slight increase in tensile strength is seen with an increasing print speed that is

maximized to 110 mm/s, however, the tensile strength at this temperature is lower than the tensile strength achieved at higher nozzle temperatures.

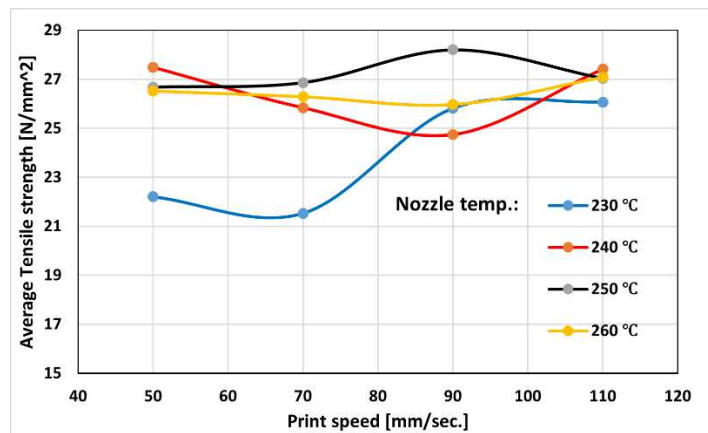


Fig. 5. The effects of print speed on tensile strength

The highest tensile strength values are obtained at 250 °C, with considerable peaks available for print speeds of 90 and 110 mm/s, thus confirming temperature of 250 °C as the optimized temperature for tensile strength as it provides the right heat necessary for the bonding of the materials and provides sufficient filament to be deposited. Notably, at 260°C, tensile strength continues to rise with the print speed, though it is slightly lower than at 250°C, possibly due to degradation or material overheating that reduces interlayer adhesion.

In general, results show that higher print speeds (90–110 mm/s) provide favorable conditions for maximum tensile strength, especially in combination with optimal temperatures (250°C). However, at sub-optimal temperatures (230 °C and 240 °C), there is less impact on the mechanical performance with increased print speed, demonstrating the complexity between speed and temperature in 3D-printed mechanical performance. These results serve as key information for optimizing the process of 3D printing to obtain mechanically strong parts. The tensile strength of the 3D-printed material was assessed for different combinations of nozzle temperature and print speed to determine how the combinations of such parameters relate to mechanical performance. This means that there is a dependence between the factors; that is, the effect of one factor (e.g., cement) on tensile strength is not equal to the effect of the other factor if they are at different levels.

At low nozzle temperature, namely 230°C, the effect of print speed is negligible on tensile strength. A constant tensile strength can be observed at every tested speed (50–110 mm/s), with only minor improvements for high speeds. This indicates that insufficient thermal energy, which leads to inadequate melting and/or interlayer bonding, is the major limiting factor at lower temperatures. In such situations, increasing the speed will not compensate for the deficiency of material softening due to a low temperature. Unlike lower nozzle temperatures, especially with 250°C nozzle, the influence of print speed is much more prominent. In contrast, tensile strength improves dramatically as print speed increases from 50 mm/s to 70 mm/s, achieving the peak at 90 mm/s, followed by 110 mm/s, suggesting that a trade-off between thermal energy and rapid deposition window provides the best molecular flow of the material and strengthens the inter-layer bonding. At this temperature, faster speed and higher nozzle temperature coexist to produce a synergetic effect and increase tensile strength, confirming the interdependence of the parameters.

Moreover, at the greatest nozzle temperature (260°C), the advantages of print speed increase are not as pronounced compared to 250°C higher speed improves tensile strength but the maximum values at this temperature is lower than at 250°C, this decline can be attributed to the greater degradation of the material due to overheating, resulting in worse properties of the printed parts. It shows that strain rate and temperature have to be optimized to avoid having negative effects on tensile strength. Clearly, nozzle temperature has a significant effect on tensile strength as well, which is consistent with the earlier work carried out by Weng et al. (2016) [27]. The results are evidence that a higher nozzle temperature improves the adhesion of the layers in 3D printing, thus increasing the tensile strength.

This statistical analysis using Two-way ANOVA, performed to establish whether the observed variation can be accounted for by means of a significant factor, reveals that the model, which includes nozzle temperature (°C), print speed (mm s⁻¹) and their interaction, significantly explains the variation seen in the tensile strength ($F = 7.118$; $p < 0.05$). Scatter plots showing the influence of nozzle temperature and print speed on the PA yield. Collectively, the dataset reveals that nozzle temperature ($p < 0.001$), print speed ($p = 0.007$), and the interaction between nozzle temperature and print speed ($p = 0.001$) were statistically significant effects on the PA yield. In addition, analysis revealed an intricate relationship between speed and nozzle temperature. The mixed results observed in these experimental replications highlight the need for assessing both variables in conjunction. As Abeykoon et al. As noted by [28], the literature demands this empirical relationship be tuned with the print speed, with the nature of the relationship between these parameters being complex.

But when it comes to the nozzle, its temperature and speed are closely related as no such investigation shows the requirement for both to be optimized together for maximum tensile strength. Longer heating times and higher speeds also yield thicker parts, but there is a compromise between the heating effects and preventing overheating at low temperatures, and also degrading the material when using too high of temperature. 250 °C and print speeds in 90–110 mm/s qualified as the best combination for the tested materials and conditions, with best tensile strengths achieved. This knowledge is invaluable to optimizing the 3D printing parameters to improve CM performance in real-world applications.

IV. Conclusions

It had dealt with the effect of Nozle_Temp and Nozle_Speed parameters for the production of 3D Adhesive material over the tensile strength printed earlier. (ii) based on the above-mentioned data, conclusions, and statistical analysis, the following conclusion could be drawn: (1) the nozzle temperature has a major influence on the tensile strength of 3D printed materials. To summarize, three principal conclusions can be drawn: (1) Work is carried out to show that a nominal nozzle temperature of 240–250°C yields 3D printed materials with maximal strength, as both underheating and degradation have been shown to dramatically limit the mechanical performance [4]; (2) Print speed is one of the most significant contributors to tensile yield strength, demonstrating that moderately high speeds (90–110 mm/s) strengthen 3D printed materials at optimal temperatures (250°C), while low print speed results in weak interlayer binding regardless of the operating temperature; (3) 3D printed material strength is significantly correlated with the working combination of print speed and nozzle temperature. It is also probable that the ideal combos in terms of temperature and feeding speed, such as 250 °C, follow along with 90–110 mm/s (where the tensile strength is at the highest). In contrast, combinations that are not their best possible pairing produce less optimal results and do not allow for the maximum bonding or result in material degradation.

In summary, the present study boosts the understanding with regard to the effect of nozzle temperature and velocity of the deposited path upon the ultimate tensile strength of the 3D printing materials. That is some sound advice on how to manipulate tensile strength with the 3D printing process. 3D printing technology is exploding in several industries, including manufacturing, aerospace, automotive, and healthcare, and these results can be used to enhance the quality and performance of printed parts and products. These results help in understanding the influence of varying nozzle temperature and print speed upon this specific mechanical property of 3D-printed ABS parts; however, some limitations should be mentioned. However, it should be noted that the tested materials were all ABS, and due to different thermomechanical behaviours, the results cannot be directly transposed to other thermoplastics. Moreover, no systematic investigation had been conducted for other important parameters such as layer height, infill density, and cooling conditions, which can also influence the mechanical properties of the printed parts. Note that this study is somewhat limited, since it deals with tensile strength, and not with other properties essential for a complete analysis of the service performance, e.g., impact resistance, fatigue behaviour, or thermal stability. Further, environmental factors such as ambient temperature and printer calibration can impact variability not tested in this study. Lastly, whilst it was shown we achieved statistical significance at three biological replicates per test condition, a higher sample size would allow an even better overview of the outcome. These constraints highlight the necessity for further research to expand upon the findings described here.

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