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# Hardness and microstructure of FDM 3D printed parts using self-made PLA-brass filaments

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***Abstract***
*Technological advancements in the industrial sector have led to rapid developments in 3D printing technology, enabling the creation of three-dimensional prototype models. Various filaments, including polyethylene terephthalate glycol, nylon, and polylactic acid, have been widely adopted in the industry. However, filaments composed of metal mixtures are relatively scarce in Indonesia, primarily available only through select online shops worldwide. The production and sale of such filaments present lucrative opportunities within the manufacturing industry. In this research, an experimental study was conducted to examine the hardness of test specimens fabricated using PLA-brass filament. The objective was to identify the optimal hardness value of the specimens. The study focused on three key parameters: nozzle temperature, layer height, and print speed, each at two different levels. The Taguchi L4($2^3$) experimental design was employed, along with S/N ratio and ANOVA analysis, to evaluate the results. The findings revealed that specific combinations of parameters yield favorable hardness values, as determined by the Taguchi Method. The optimal set of parameters for achieving good hardness values was determined to be a nozzle temperature of 230°C, a layer height of 0.2 mm, and a print speed of 40 mm/s. These results enhance the understanding of PLA-brass filament properties and facilitate the utilization of 3D printing technology in the manufacturing industry.*

***Keywords:***
*3D Printing;*
*Hardness;*
*PLA-brass.*

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## INTRODUCTION

The industrial world has seen the rapid development of technology usher in the era of Industry 4.0, marked by dynamic changes in many business and manufacturing areas. This technical potential has increased consumer demand and heightened rivalry in the manufacturing sector. Rapid prototyping is a technology that enables the creation of product prototypes through Computer-Aided Design (CAD) software, followed by the production of physical prototypes to allow for direct visual evaluation of computer-generated 3D models to help manufacturers meet consumer demands [1].

Fused Deposition Modelling (FDM), a 3D printing technique, has become one of the most widely used additive manufacturing processes globally [2]. FDM is favored for its adaptability in prototyping a variety of industrial goods, user-friendliness, economic effectiveness, and environmental friendliness [3]. As the primary component of the printing process, filaments are essential to 3D printing [4]. Three-dimensional printing (3D printing) uses a variety of filaments, such as nylon [5], polylactic acid (PLA) [6], polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) [7]. Among these, PLA stands out because of its advantageous chemical and mechanical characteristics, making it ecofriendly. Transparency, a grain-like structure, rigidity, resistance to moisture, and high thermoplasticity at a melting temperature of about 190°C are just a few of the qualities that PLA possesses [8].

Despite the benefits of pure PLA, it has drawbacks, such as poor thermal and electrical stability, that limit its use in some applications [9]. Adding metal contents to PLA can improve the quality of pure PLA material [10], such as its hardness. Heat treatment can improve the hardness in pure metal or alloy [11]. Conversely, high hardness may damage the tool in machining [12]. In FDM 3D printing, hardness can be improved by using metal content filament. The PLA-brass filament is uncommon in Indonesia mostly because it is only sold in a few specialized online stores worldwide, which has shown to be a successful business. The cost of these filaments, essential to the functioning of 3D printers in 3D printing, is still relatively high. Standard PLA filaments are sold globally for between $20 and $30 per 1 kg roll [13].

The author has analyzed earlier studies as references and experimented with filament extruder machines to produce filament. The extruder machine's temperature parameter was discovered to have the most significant impact on filament quality. Due to a need for more information regarding its strength and hardness parameters, PLA-brass filament was used. This study used PLA-brass filament to make hardness test specimens and calculate their hardness.

Numerous studies have examined the impact of mixing PLA with materials like aluminum on tensile strength [14]. This study aims to identify the ideal combination that produces the best hardness values when utilizing the Taguchi method. It focuses on the influence of three parameters: layer height, print temperature, and print speed. Our study, which examines the hardness characteristics of PLA-brass filament, will provide crucial new information about the development and use of 3D printing technologies in manufacturing [15].

## METHOD

### Research Methods

In order to evaluate the impact of 3D printing process parameters on the hardness test of a composite material made of Polylactic Acid (PLA) and brass powder, an experimental and analytical research methodology is used in this work. The experimental setup makes it possible to examine different 3D printing settings and how they affect the PLA-brass composite's hardness properties. The quantitative analysis entails gathering numerical data from the executed trials, enabling a methodical assessment of the correlation between the 3D printing process parameters and the obtained hardness values. The study offers insightful information about optimizing the 3D printing procedure for PLA-brass composite materials, with possible applications in numerous industrial fields [16].

Following the ASTM D2240 testing standard, the specimens were put through a hardness testing machine with PLA (Polylactic Acid) material mixed with brass to determine the test values. With 12 specimens to be evaluated, the researcher used an orthogonal matrix L4(2^3) for this study. Three elements, each having two levels, were examined. The Taguchi method was used to analyze the data, and Minitab was used to conduct the study variation [17].

The study's objective was to assess the impact of the chosen 3D printing parameters on the hardness qualities of the PLA-brass composite material through the use of ASTM D2240-compliant hardness tests and the Taguchi method for data analysis. The orthogonal matrix design made systematic and practical testing possible to optimize the 3D printing process and improve the composite material's mechanical properties. The accurate and thorough data analysis made possible using Minitab software led to a solid comprehension of the connections between the components and the outcomes related to hardness.

### Tools and Materials

The experimental study was carried out using various tools and materials. The tools included a Shore D-type hardness testing machine for determining hardness specific to the polymer [18]. The Creality Ender-3 V2 3D printer uses the Fused Deposition Modeling (FDM) process. The test specimens were created on a computer using Autodesk Inventor and Ultimaker Cura 5.1. Tweezers were also used to remove the finished 3D printed specimens, and a Feller gauge was used to assess the separation between the bed and nozzle tip of the 3D printer.

The research used PLA pellets and brass powder as its main building blocks to create PLA-brass filament. The PLA pellets and brass powder were combined and extruded to create the PLA-brass filament. The mixture contained 40 grams of brass powder, with a particle size of about 100 mesh, and 60 grams of polylactic acid (PLA), with a particle size range of 8 to 10. These components served as the foundation for carrying out the hardness tests and researching the characteristics of the PLA-brass filament.

### Research Procedures

Five critical components of the study approach are (1) filament manufacture, (2) selecting the suitable size filament, (3) printing the specimens, (4) Shore D hardness testing, and (5) finally, analysis of the results. The procedure of the research flow is presented in Figure 1.

Weighing the PLA pellets and brass powder according to the predetermined mix is the first step in the filament production process. The band heater temperature is adjusted, the hopper is cleaned to ensure no leftover dust, and the filament extruder machine is turned on. When the motor is turned on, the materials are pushed toward the screw to begin the extrusion process. The PLA pellets and brass powder are alternately fed into the hopper once the band heater reaches the correct temperature. Following the extrusion operation, the hopper and nozzle are cleaned to remove any remaining material.

The method for 3D printing the test specimens begins with the design being created on a computer using the Autodesk Inventor software, and then the design is exported into STL format. The Ultimaker Cura 5.1 program sets up the 3D printing parameters, and the output is sliced to export into G-code format. The correct Z-axis position is established on the Creality Ender-3 V2 3D printer, and the distance between the nozzle and bed is adjusted. Smooth filament extrusion is made possible by the pre-set temperature of the heated nozzle. The sliced G-code design file is loaded into the Creality Ender-3 V2 3D printer, and the appropriate file is chosen for printing. Once the specimens are completed, they are removed from the bed using tweezers.

The process for the Shore D hardness test begins with setting up the Shore D hardness testing apparatus. The specimens are set up, and the space between them and the testing device is adjusted appropriately.

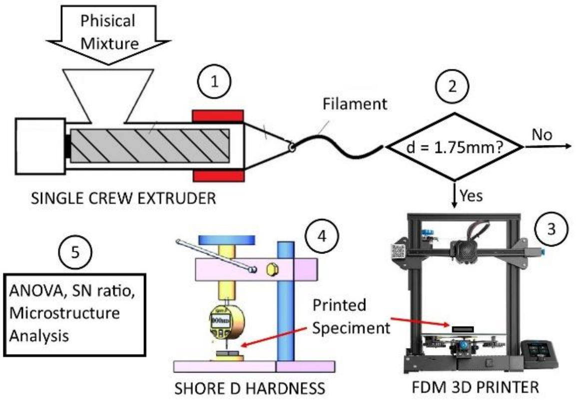


Figure 1. Schematic of the research procedure

The test is started by depressing the start button on the Shore D hardness testing device. Following completion, the hardness test results are shown on the screen of the testing device, and the information gleaned from the hardness testing of the specimens is examined.

### Research Variables

In this study, some factors were considered as researchers looked at the effects of 3D printing settings on the PLA-brass composite material's hardness qualities. The three changes of the independent variables-nozzle temperature (230°C and 240°C), layer height (0.2 mm and 0.3 mm), and print speed (30 mm/s and 40 mm/s)-were selected by the researcher. These factors were anticipated to impact the 3D-printed specimens' hardness value, which was the dependent variable.

The control variables, on the other hand, were meticulously handled and maintained throughout the research to guarantee accurate and trustworthy outcomes. Fan speed (0 mm/s), bed temperature (100°C), and infill percentage (10%) served as the controls. These managed variables attempted to reduce outside effects and preserve uniformity throughout the studies.

The study aimed to understand how the chosen 3D printing parameters affect the PLA-brass composite material's hardness properties by analyzing the independent variables' variations, the constant control variables, and the resulting hardness values of the 3D printed specimens. The results of this work would provide vital information for improving 3D printing procedures for such composite materials and advancing their potential industrial uses [19].

## RESULTS AND DISCUSSION

### Research Data

Brass and PLA were combined to make the study's filament, which comprised 60% PLA and 40% brass powder. The extrusion process produced a filament diameter of 1.75 ± 0.05 mm at temperatures of 180°C and 190°C. Figure 2 illustrates how the extruded filament appears. Some filament segments do not meet the desired specifications. Therefore, filaments that are either too small or too big are excluded from the next step. Figure 2 illustrates three types of filaments. Only the middle filament would be used for the 3D printing feed.

The PLA-brass filament was created especially for the 3D printing tests, enabling the analysis of the printed specimens' hardness characteristics.

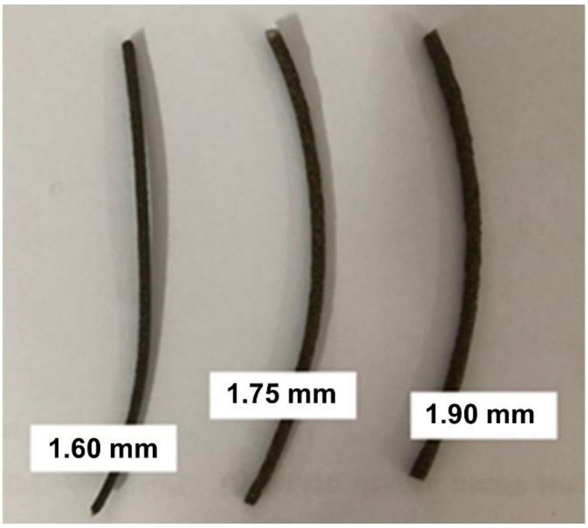


Figure 2. Filament PLA-brass

It was suitable for the research goals because of its well-balanced PLA and brass powder combination. The uniform filament diameter made a precise hardness test and analysis of the 3D printed specimens possible, guaranteeing stable and reliable printing performance [20].

The hardness test specimens were printed using Creality Ender-3 v2 and measured 20 mm in length, 20 mm in width, and 6.4 mm in thickness (Figure 3). The hardness tests were carried out at five positions of the specimen, as shown in Figure 3 (left).

Two samples of hardness test results were performed on each specimen using a Shore D Hardness Tester (Figure 4). Each sample represents the hardest and the softest specimens, i.e., 53.6 HD and 35.2 HD, respectively.

Based on the L4(2^3) orthogonal matrix design, the nozzle temperature (NT), layer height (LH), and print speed (PS) were adjusted. The results showed lower layer heights and suitable print speeds boosted hardness values.

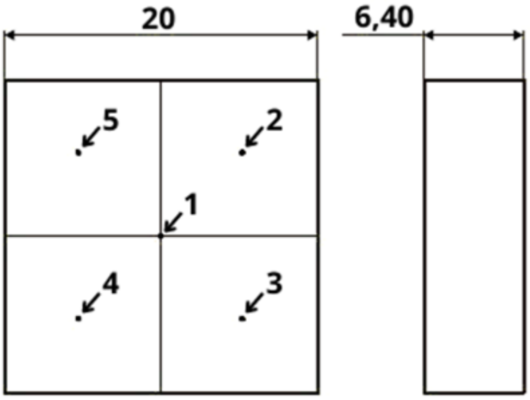
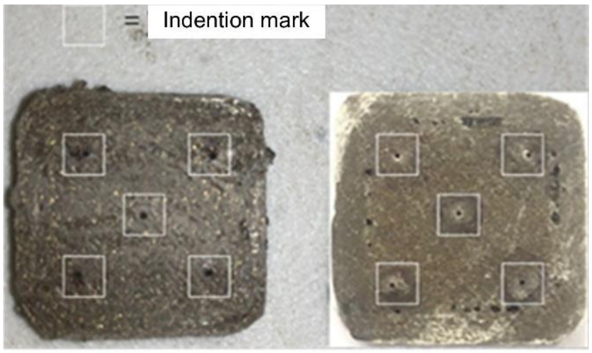


Figure 3. Specimen hardness test



(a) 53.6 HD (b) 35.2 HD

Figure 4. Specimens after tested: (a) the hardest, and (b) the softest

A layer height of 0.2 mm, a print speed of 40 mm/s, and a nozzle temperature of 230°C were ideal parameters for producing good hardness values. Data from the hardness test is presented in Table 1.

In this work, the signal-to-noise (S/N) ratio is employed to examine the hardness of the 3D printed specimens and the performance stability of output features. An excellent S/N ratio denotes better performance concerning hardness. The S/N ratio for hardness is calculated based on larger-is-better quality criteria. Higher hardness levels are preferred since they signify better specimen quality. In the first experiment, the S/N ratio was calculated for every combination of nozzle temperature, layer height, and print speed. For each combination, many replications were carried out to determine the hardness. The calculation of the S/N ratio of large-is-better from each hardness testing experiment can be seen in Table 1 of the last column.

Figure 5 shows the average plot of the S/N ratio at each level of the variation in parameters used in this study, namely nozzle temperature, layer height, and print speed. The most affected factor is LH (layer height), with a broader interval between the highest and the lowest values. Meanwhile, NT (nozzle temperature) and PS (print speed) have the same interval.

Table 1. Hardness test result data and S/N ratio

| Exp. No. | Parameter Control | | | Hardness Test (HD) | | | Ave. | S/N ratio |
|---|---|---|---|---|---|---|---|---|
| | NZ (°C) | LH (mm) | PS (mm/s) | Replication | | | | |
| | | | | 1 | 2 | 3 | | |
| 1 | 230 | 0.2 | 30 | 52 | 50 | 51 | 51.2 | 34.18 |
| 2 | 230 | 0.3 | 40 | 47 | 50 | 48 | 48.4 | 33.69 |
| 3 | 240 | 0.2 | 40 | 53 | 50 | 54 | 52.3 | 34.36 |
| 4 | 240 | 0.3 | 30 | 35 | 43 | 45 | 40.9 | 32.09 |

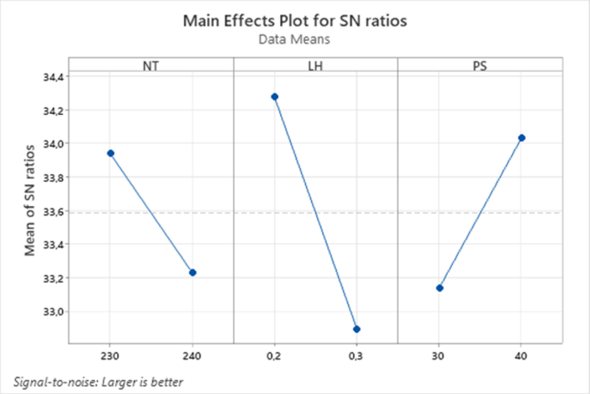


Figure 5. Chart of S/N ratio

Superior hardness values for the related 3D printed objects are indicated by the more excellent S/N ratios attained for particular combinations. Understanding how various parameter settings affect hardness attributes requires knowledge of these discoveries. The S/N ratio analysis offers essential information into the functionality of the PLA-brass filament 3D printing process. The study attempts to maximize the hardness values of the printed specimens by concentrating on the larger-is-better quality characteristic, thereby improving the overall quality and acceptability of the 3D printed goods for their intended applications [21].

This experimental design used the Taguchi approach to determine the ideal ratio of variables impacting the hardness of the 3D specimen printed with PLA-brass filament [22]. Layer height and print speed greatly influenced the hardness, whereas nozzle temperature had no discernible impact, according to the signal-to-noise (S/N) ratio computation.

The ANOVA analysis further substantiated layer height and print speed as essential factors in the hardness variation (Table 2). Layer height had the most significant impact (50.67%), followed by print speed (18.64%) and nozzle temperature (10.14%), according to the percentage contributions of each factor. The nozzle temperature at level 1 (230°C), layer height at level 1 (0.2 mm), and print speed at level 2 (40 mm/s) were found to be the most essential elements for reaching the ideal hardness. With a 95% confidence interval spanning 52.26 HD to 58.66 HD, the anticipated hardness utilizing the ideal combination was roughly 55.46 HD. It implies that the hardness of 3D-printed specimens is anticipated to fall within this range when using the stated combination of parameters.

Table 2. ANOVA

| Factor | DoF | SS | MS | F | P | Contribution (%) |
|---|---|---|---|---|---|---|
| NT | 1 | 30.4 | 30.4 | 3.95 | N-S | 10.14 |
| LH | 1 | 151.94 | 151.94 | 19.72 | S | 50.67 |
| PS | 1 | 55.9 | 55.9 | 7.25 | S | 18.64 |
| Error | 8 | 61.65 | 7.7 | | | 20.56 |
| Total | 11 | 299.89 | | | | 100 |

Denotes: N-S = not significant, S = significant

## Parameter Effects

This study looked into how different variables affected the hardness of specimens that were 3D printed using PLA-brass filament. Layer height, print speed, and nozzle temperature were examined parameters. Therefore, the type of S/N ratio used is "large is better", while for the hardness test itself, the greater the hardness value, the better. Therefore, the type of S/N ratio used is "large is better" in the Taguchi method [23]. Hardness was most significantly influenced by layer height, contributing 50.67% of the total. Due to increasing layer density at lower layer heights, more challenging values were obtained [24]. The newest research also proved that the thinner the layer height, the stronger the printed specimen [25]. In this research, the maximum hardness was achieved when applying a layer height of 0.2 mm.

Another essential element, print speed, contributed 18.64% of the variation in hardness. Surprisingly, the most rigid material was produced at a print speed of 40 mm/s. This finding conflicts with earlier research on carbon fiber-reinforced PLA, which found that more challenging prints were produced at slower print speeds [26]. The difference may be due to different materials used. On the other side, it was discovered that nozzle temperature contributed just 10.14% to hardness, making it insignificant. 230°C was the ideal nozzle temperature for maximum hardness.

Layer height and print speed significantly affected hardness, according to an ANOVA analysis, while nozzle temperature had no significant impact. The result differed when using only PLA, where temperature profoundly influences the hardness [27]. The possible reason is that adding brass (a conductive metal) absorbed the heat from the nozzle, and less heat was needed to melt the PLA. In these experiments, the layer height of 0.2 mm, print speed of 40 mm/s, and nozzle temperature of 230°C were the best combinations for producing the highest hardness value, yielding a hardness value of 53.6 HD.

## Microstructure of PLA-Brass Hardness Test Specimen

The microstructure of PLA-brass specimens was examined using an optic microscope. PLA pellets and brass powder were mixed to create the specimens. The specimens from experiments 1 and 2 with the highest and lowest hardness ratings were used to collect microstructure data. A 0.6 mm nozzle was used to melt the filament at 230°C and 240°C. Figure 6 depicts the microstructure test with various nozzle temperatures. Figure 6 demonstrates how PLA-brass filament used in 3D printing had a similar microstructure at nozzle temperatures of 230°C and 240°C [26]. This finding confirms the findings of the earlier described ANOVA study, which showed that the hardness test results were unaffected by nozzle temperature.

According to Figure 7, the specimens with the lowest hardness values had holes and poor edge-to-surface adhesion. These flaws may have been caused by inconsistent filament feeding into the 3D printer's extruder, which led to insufficient specimen filling [28].

High print speeds and low nozzle temperature may also have contributed to the flaws. These flaws might be fixed, and the general quality of the PLA-brass 3D printed specimens could be enhanced with further optimization of the printing parameters, such as nozzle temperature and print speed [29].

The correlations between nozzle temperature, layer height, print speed, and hardness qualities are better. Manufacturers and researchers can optimize the 3D printing process for PLA-brass filament and improve the composite material's mechanical properties for various industrial applications by comprehending the effects of these factors. Future 3D printing projects using PLA-brass filament can benefit from using the suggested parameter combination as a valuable guide for reaching desired hardness results, advancing the field of additive manufacturing and composite material applications [30].

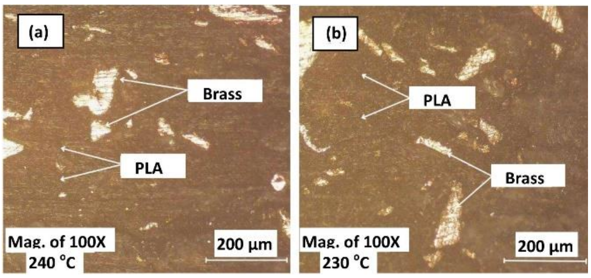


Figure 6. Microstructure specimens PLA-brass

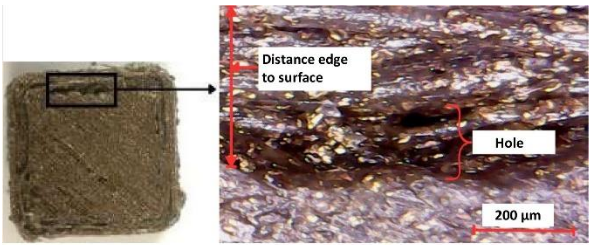


Figure 7. Microstructure defect test

This research enriches the previous result using the PLA-brass filament with the observation of the tensile test of a single filament (pull-out test), which showed that the maximum tensile strength was 5.22 MPa [4].

## Microstructure of PLA-Brass Filaments

This research utilized a filament made of a combination of PLA (Polylactic Acid) pellets and brass powder, weighing 60 grams of PLA and 40 grams of brass powder and roughly 100 mesh in size. Due to the filament's small size, resin printing and extrusion were done before the micro-testing on the PLA-brass filament. We used a microscope with a 100x magnification for the micro-testing. Figure 8 depicts the PLA-brass filament's microstructure.

## Application of Printable Products

The improved filament and specimens could be used for practical purposes even though this research mainly focused on producing 3D-printed specimens for hardness testing. The average hardness values obtained in this investigation varied from 40.9 to 52.3 HD. These products have hardness levels that fall between 40 and 50 on the durometer table, which is considered a hard level. The outsoles or heels of shoes and shopping cart wheels are suggested uses for items in this hardness range [31].

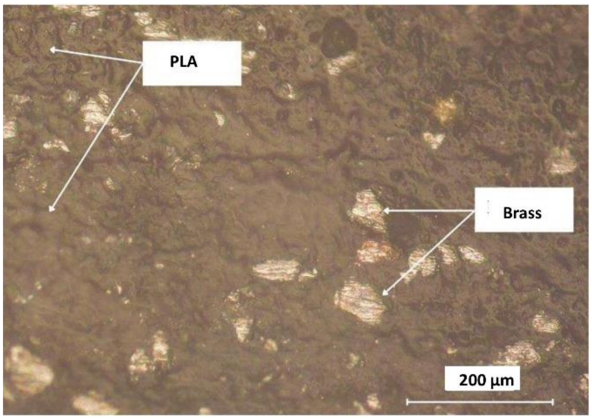


Figure 8. Microstructure of PLA-Brass Filaments

## CONCLUSION

The following research findings are a result of the hardness testing of PLA-brass filament-printed specimens with varying nozzle temperature, layer height, and print speed:

First, the settings used in the 3D printing process significantly impact how hard the specimens are. Notably, a lower layer height improves the surface's quality and the infill's strength, leading to better hardness values. Additionally, a well-chosen print speed contributes to the reduction of printing deviations and produces greater hardness values. Although overly high temperatures may result in a loss of hardness qualities, the nozzle temperature also significantly determines the hardness.

Second, according to calculations made using the Taguchi method, a nozzle temperature of 230°C, a layer height of 0.2 mm, and a print speed of 40 mm/s are the best settings to obtain the highest hardness values. The PLA-brass composite material's hardest values correlate with these parameter settings.

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