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Evaluation of hardness and Surface roughness of 3D printed Acrylic Resin Used for Denture Base

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ABSTRACT

The denture base is a critical component of complete or partial dentures, significantly influencing functionality, comfort, and aesthetics. Traditional manufacturing processes for denture bases face challenges such as limited dimensional accuracy, mechanical integrity, and surface quality. To address these limitations, this study aims to evaluate and optimize the effect of digital light processing (DLP) 3D printing parameters on the mechanical properties and surface quality of acrylic resin denture bases. Specifically, the research investigates how layer height and printing orientation influence hardness and surface roughness. Using the L9 orthogonal array of the Taguchi experimental design, nine specimens were fabricated with varying parameter levels (50 mm, 100 mm, and 150 mm for layer height; 0°, 45°, and 90° for printing orientation). Shore hardness (scale D) and surface roughness were measured for each specimen. ANOVA analysis revealed that both parameters significantly impacted the hardness and surface roughness. Maximum hardness (85 HD) and minimum surface roughness (<0.2 μm) were achieved at 50 mm layer height and 0° printing orientation. The study identified comparable contributions of layer height and printing orientation to hardness (51% and 49%, respectively), while layer height exhibited a threefold greater influence on surface roughness (74.25% vs. 25.75%). These findings provide valuable observations for enhancing the parameters of DLP 3D to improve the performance of denture bases.

1. Introduction

Recently, dental prosthetics fabrication technology has received wide attention from researchers and scientists. Additive manufacturing (AM) is considered a powerful technique in this field of fabrication due to its ability to manufacture a wide range of complex and detailed geometries with very high precision. Furthermore, the digital light processing (DLP) 3D printing technique has been raised as one of the most precise and promising 3D printing methods that revolutionized the fabrication of dental prosthetics, especially denture bases. Moreover, many materials are employed in this fabrication technology, for instance, Polyetheretherketone (PEEK) and Polyphenylene sulfone (PPSU). Polymethyl methacrylate (PMMA), an acrylic resin, remains highly favored due to its biocompatibility, flexibility, and ease of processing. On the other hand, the functionality and durability of the mentioned materials are highly affected by their mechanical properties such as surface roughness and hardness. The patient's comfort and hygiene are highly influenced by the surface roughness because smoother surfaces prevent plaque accumulation.

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Likewise, hardness is crucial for wear resistance and the overall longevity of the material [1, 2].

Modern research groups have focused on adjusting the 3d printing process parameters like layer height, printing orientation, and curing time to optimize the mechanical properties of final 3d printed dental prosthetics. Interesting studies have demonstrated that these parameters significantly affect the mechanical behavior and surface properties of printed materials. For example, reducing layer height and optimizing print orientation can minimize surface irregularities and improve surface roughness as well as the hardness of the denture bases [3, 4]. In addition, significant researchers have illustrated that 3d printed denture bases fabricated with advanced dental resins provide improved mechanical properties comparable to or exceeding those achieved by traditional manufacturing methods [5-7].

Noted studies have used statistical methods such as the Taguchi method and response surface method (RSM) to investigate the effects of the 3d printing process parameters on the surface roughness and hardness of dental products. The results show great optimization in the mechanical performance of the targeted specimens that were fabricated using the ideal parameters settings [8, 9]. Typically, hardness test is performed using the Shore D scale, while surface roughness is measured using profilometry, both are common techniques in evaluating the quality of denture bases [10, 11].

Acrylic resins are designed to be ideally suited for dental applications. They have shown magnificent dimensional stability, scratch resistance, and color retention in comparison to traditional heat-cured acrylics. These specialized resins provide better performance in terms of surface roughness and hardness when used in conjunction with optimized post-processing techniques, such as UV curing, [12, 13]. Furthermore, the quality of 3D-printed materials is affected by factors like resin type, curing time, and ambient temperature, which also influence their mechanical and aesthetic properties [14, 15]. The selection of appropriate materials and post-curing processes play a big role in determining the final mechanical properties of 3D-printed denture bases [16-18].

By the same token, the Taguchi method has become an indispensable tool for parameter optimization in various manufacturing fields, including dental 3D printing. It is particularly useful in reducing the number of experimental runs required to optimize parameters, thereby reducing both cost and complexity. Using orthogonal arrays, the Taguchi method efficiently identifies the main effects and interactions between parameters, enabling researchers to determine the optimal settings for surface roughness and hardness of printed denture bases [19, 20]. Similarly, a significant number of studies have demonstrated that using the Taguchi method in conjunction with other optimization techniques, such as response surface methodology, can further enhance the mechanical properties of printed dental prosthetics [21].

Within this scope, the objectives of the current study are to evaluate the mechanical properties and surface quality of acrylic resin denture bases that are produced via DLP 3d printing technology. Furthermore, deep and accurate measurements are made on the influence of layer height, as well as printing orientation, on surface hardness and roughness. By leveraging the Taguchi method, this research aims to provide insights into parametric investigation study for dental applications, enhancing both the durability and performance of denture bases.

2. Materials and Methods

This part clarifies a full description of the utilized materials, processing technique and utilized method in order to perform the experimental work and Compile data for evaluation and discussion in the next part.

The acrylic resin (type Arma Risan) was selected for the 3D printing of samples with predefined dimensions. Arma Risan is superior suitability for dental applications, offering a combination of mechanical strength, biocompatibility, and compatibility with DLP 3D printing technology. Light exposure during the printing and post-curing stages plays a crucial role in ensuring its mechanical performance and surface quality, making it an ideal choice for fabricating high-quality denture bases. The mechanical properties and viscosity are listed in Table 1.

The quality of the DLP 3D printing process is highly affected by specific parameters. Investigating these parameters leads to a successful &d printing process with high-quality products. Furthermore, these parameters as well as their range and effects are listed in the following:

1. Exposure time: represents the time duration, during which each resin layer is exposed. It depends on resin properties and the thickness of the layer. In addition, its range is from 1 to 10 seconds for each layer.
2. Layer thickness: It ranges typically from 25 to 500 microns. 3D printed products with thinner layers have finer details and vice versa. However, thinner layers lead to longer printing time.
3. Base Platform adhesion: illustrate the adhesion strength between the first printed layer and the base platform of the 3d printer. The addition of adhesion agents or employing of textured base platform leads to a stable 3D printing process.
4. Light intensity: characterize the wavelength of the DLP's light source. It must compete with the curing wavelength of the printed resin. Furthermore, it ranges from 365 to 405 um. Consistent light intensity guarantees uniform curing of the resin around the printing area.

All the used parameters of the DLP 3D printing process are illustrated in Table 1. Furthermore, the geometry of the sample is shown in Figure 1.

Table 1: Parameters of the DLP 3d printing process

Printing parameters	**Value**	**Units**
Layer thickness	(50, 100, 150)	µm
Raster angle	(0°, 45°, 90°)	degree
Infill density	100%	
Light-off (Delay)	2	(s)
Bottom Layers Count	5	Layers
Lift Distance	5	(mm)
Lift Speed	150	(mm/min)
Retract Speed	250	(mm/min)

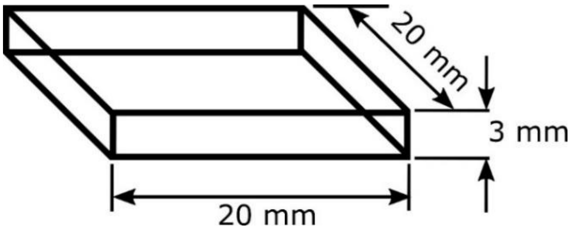

Figure 1. Representation of sample geometry

The Arma Risan is characterized by: Fast printing, Perfect topographies, Scratch Resistance, Color Stability, Excellent Endurance for Autoclave, High Surface Hardness, Carvable like gypsum, High flexural strength, Excellent Dimensional Stability, Works with 385 / 405 nm, Compatible with DLP / LCD, Shape Stability After Curing, Eliminated Phase Separation During Storage / Long Shelf Life.

Asiga Ultra 3D printer was utilized to print the acrylic resin at different printing parameters. Air bubbles were effectively avoided because the Arma Risan acrylic resin used in the DLP 3D printing process was in a liquid state during printing. The liquid resin naturally self-levels, minimizing the risk of air bubbles. Table 2 shows the mechanical properties of the acrylic resin. Figure 2 shows the utilized printer that was used for DLP process.

Table 2: Mechanical properties and viscosity of the acrylic resin

Property	**Standard**	**Value**
Flexural Strength (MPa)	ISO 4049	118,88
Elasticity Modulus (MPa)	ISO 4049	2047,05
Elongation at Break (mm)	ISO 4049	3,12
Viscosity (m.Pa.s 23 °C)		470

Layer height (µm) and printing orientation angle (°) were applied as two printing parameters and have been changed on three levels to examine their influence on the surface hardness and roughness of the printed specimens. Nine experimental runs were generated based on L9 orthogonal array of Taguchi design of experiment as depicted in Table 3. It is shown that the layer height and orientations were set on: 50, 100, 150 mm; 0, 45, 90°.

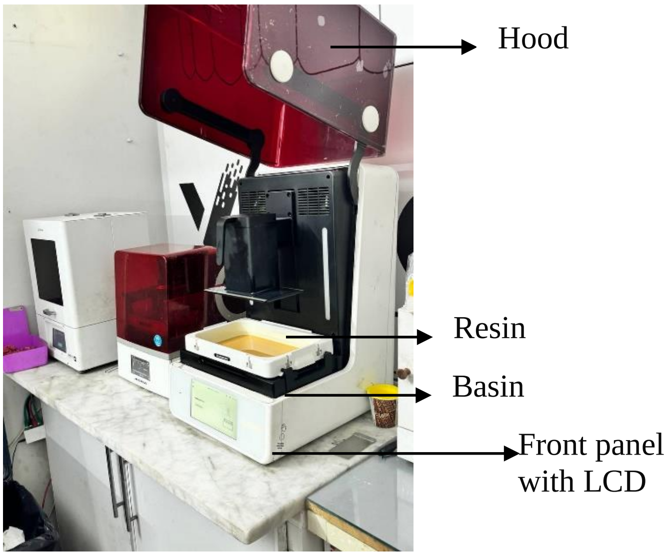

Figure 2. Asiga Ultra 3D printer

Table 3: Experimental Matrix

Experiment No.	Layer Height (µm)	Printing Orientation (°)
1	50	0°
2		45°
3		90°
4	100	0°
5		45°
6		90°
7	150	0°
8		45°
9		90°

The printing process consists of steps that must be performed sequentially to ensure smooth printing and good quality product as illustrated in the following steps:

- First and mix the resin well to achieve uniform viscosity, then heat the printer to the recommended temperature range of 23°C to improve the viscosity of the resin.
- Then fill the resin tank with resin and remove air bubbles to prevent print defects. Use Asiga's slicing software to position and slice 3D models to efficiently use build space and create appropriate support structures.
- Once the setup is complete, printing will begin. Layer cure times are set 2.5 seconds for standard layers and 10 seconds for base layers, depending on resin requirements and the environmental conditions. Print speed is set to 20mm/h based on layer thickness and resin type to balance accuracy and efficiency.

After printing, the post-curing stage involves carefully drying the printing plate to remove excess liquid resin. The printed object is removed from the plate and then carefully cleaned to remove any remaining resin residue. Finally, the object undergoes a curing process to harden and stabilize the resin. This involves a 1.99% alcohol cleaning and 10 light curing. This provides the mechanical properties and surface finish necessary for high-quality results.

The shore hardness tester Scale D (type THT180) was employed to measure the hardness due to its suitability to for polymeric materials. The surface roughness was measured by using the styles roughness tester. Three readings were taken for each test and averages are recorded and tabulated to make sure uniform distribution is obtained. For more clarification of the experimental work, flow charts with sequential steps are presented in Figure 3.

To test the hardness of the Arma resin (acrylic resin) used in Asiga 3D printed denture bases, the model underwent a post-curing process that included UV light and optional heat treatment at 75° to harden the surface and improve mechanical properties. After post-curing, the model was thoroughly cleaned to remove any remaining uncured resin, leaving only the cured material. This prepared surface was then tested using hard testing equipment such as the TH180, which is typically used for hard surfaces.

The TH180 operates using the Leeb repulsion method, which measures hardness based on the material's ability to withstand and repel a test object, providing a reliable measurement of the hardness of a resin surface under consistent conditions.

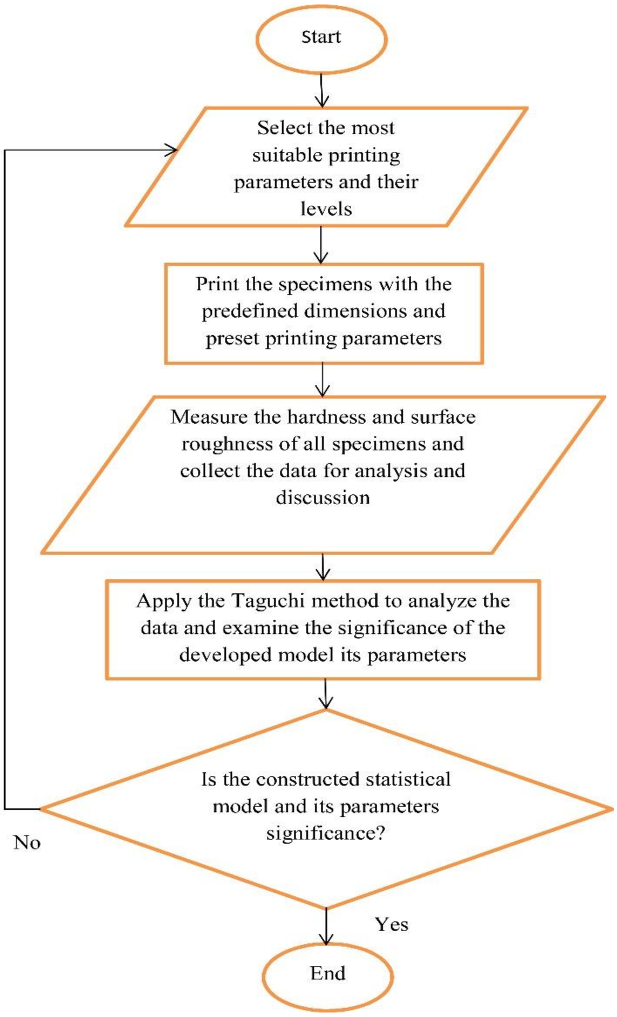

Figure 3. Flowchart of the experimental work.

The Stylus Tester SRT-6210 identifies surface irregularities by using a diamond-tipped stylus to move across the surface of the material and measure the vertical displacement. This makes it ideal for capturing the roughness of printed acrylic. The digital display displays real-time surface roughness data with parameters such as Ra, Rz, etc., giving operators a quick and easy understanding of the surface quality of the material.

3. Results and Discussion

The experimental work, which has been described in the preceding section, was carried out and the achieved findings will be analysed and discussed in this section. Nine specimens were printed at different printing parameters and Figure 4 shows these specimens with corresponding parameters and levels. The dimensions of each specimen are: 20×20 × 4 mm^3

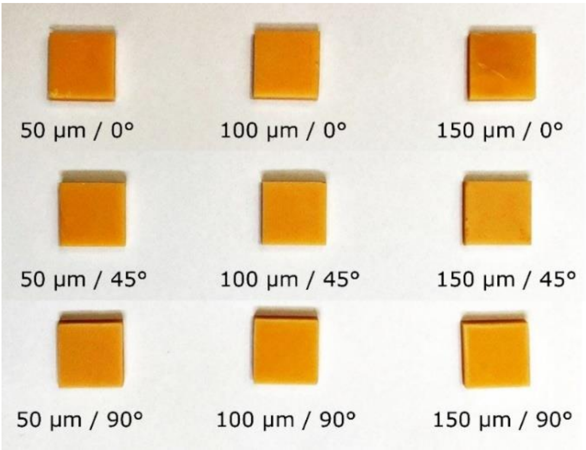

Figure 4. Printed specimens at different layer thicknesses and orientations

With respect to the hardness results, Shore hardness testing was used to measure the hardness of the DLP specimens due to suitability for polymeric materials. The hardness of each specimen was measured three times at arbitrary locations on the square area. Average values were listed in Table 4 for every printing set where each set of parameters produced different hardness as the Table depicts. Analysis of variance is a helpful tool in identifying the significance of the constructed model and its factors with percentage contribution. Therefore, ANOVA results were generated by Minitab statistical software as illustrated in Table 5. This confirms the significance of the developed model besides the layer thickness and printing orientation where all produced a p-value less than 0.05 at a 95% confidence level. In addition, 51% and 46% were recorded as contribution percentages for the layer height and printing orientation and the compliment is the error as shown in Table 5.

The R^2, adjusted R^2, predicted R^2 were also calculated the software and they were: 96.34%, 92.67%, and 81.45% respectively. Therefore, all these measures are statistically significant and enable us to navigate the model.

Table 4: Shore hardness of the DLP printed specimens

Experiment No.	Layer height (LH)	Printing orientation (PO)	Shore Hardness (D)
1	50	0°	85
2		45°	83
3		90°	80
4	100	0°	82
5		45°	79
6		90°	78
7	150	0°	81
8		45°	76
9		90°	75

Table 5: Analysis of Variance (ANOVA) results of hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	81.778	20.4444	26.29	0.004
LH	2	42.889	21.4444	27.57	0.005
PO	2	38.889	19.4444	25.00	0.005
Error	4	3.111	0.7778		
Total	8	84.889			

To support Table 4 and 5 results, a visualization of the finding trend would be more useful. Therefore, the main effect plot of the mean of hardness means was presented in Figure 5. In contrast, 3D surfaces plot of hardness vs. layer height and printing orientation was depicted in Figure 6, while corresponding contour plot was revealed in Figure 7.

The trend of hardness means is that it decreases downwards with increasing the layer height and printing orientation, as visualized with red arrows. Each point in Figure 5 is the average of three hardness values for the same parameter level regardless of the level of other parameter. The dashed line stands for the average hardness of nine runs, which is slightly less than 80.

The experimental results in Table 4 were plotted in three dimensions where layer height is placed on the X-axis printing orientation is located on the Y-axis and Hardness is put on the Z-axis. The high hardness zone was pointed out by the red arrow.

The projection of the 3D plot yielded contour plots of Figure 7. It shows multiple zones starting with lighter green (minimum hardness zone) and ending with darker one (maximum zone) as arrows in red.

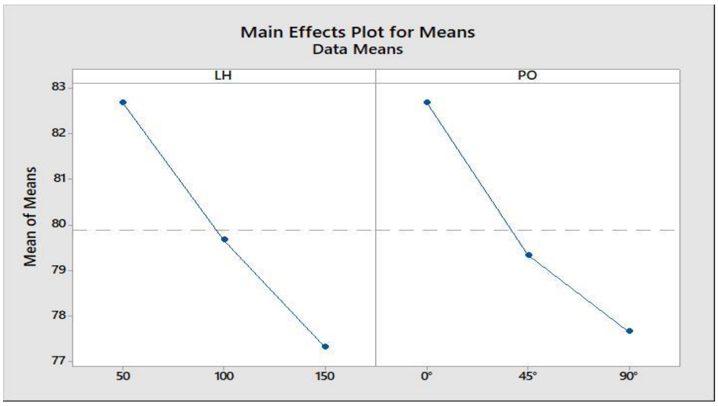

Figure 5. Main effect Plot of Hardness

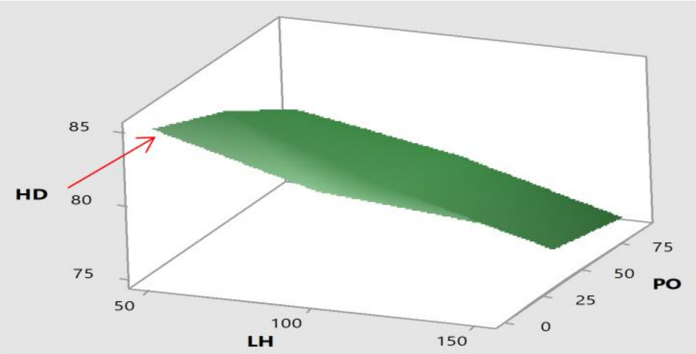

Figure 6. 3D surface Plot of Hardness (HD) vs. layer thickness (LH) and printing orientation (PO)

The boundary that maintains maximum hardness ranges from zero-degree printing orientation up to slightly greater than 50° and from 50 µm layer height up to 87 µm. Therefore, both plots (3D and contour) have given helpful views in illustrating the data pattern, parameters interaction, and maximum zone with corresponding range. Maximum hardness is observed at lower LH (50 µm) and horizontal PO (0°), where optimal layer bonding and stress alignment are achieved, as depicted in Figures 7 and 8.

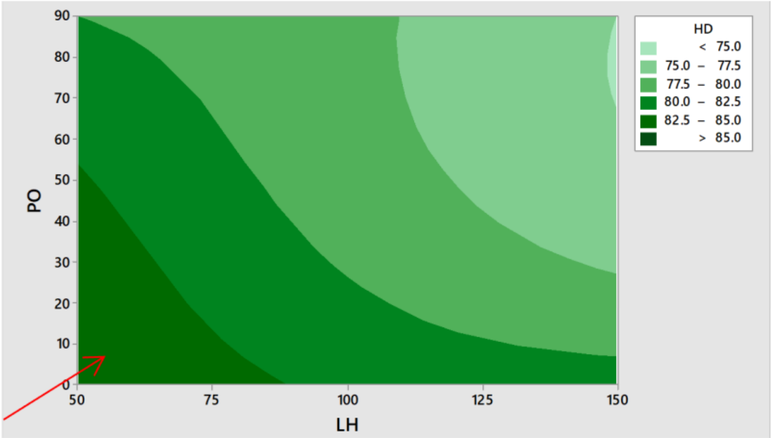

Figure 7. Contour Plot of Hardness (HD) vs. layer thickness (LH) and printing orientation (PO)

The interpretation of why the same DLP acrylic resin shows different hardness is that it has been processed (digitally light printed) at different parameters and levels. Consequently, different surface structures have been produced that are reflected in the hardness of each specimen. In other words, different responses for resistance to hardness indenter, and therefore, printing in zero direction with light layer thickness resulted in a harder surface layer.

Pertaining the surface roughness of the DLP specimens, they were also measured and evaluated as what was done in the hardness to provide insight into the two selected attributes and how they have been affected by the two input parameters.

The surface roughness was measured triply, averaged, and listed in Table 6 ahead of each printing set. Different averaged values were obtained at each set that reflect the influence of the selected parameters on the printed specimens. To examine their degree of significance, ANOVA Table 7 is generated from the experimental data by using Minitab software. It is clearly seen that developed model beside layer height and printing orientation are significant where all recorded very small p-value that approaches to zero. Therefore, this model is ready to discuss and analyse its results.

Similarly to hardness results visualization, Figure 8 shows the main effect plot roughness mean, while Figure 9 illustrates the 3D surface plot of surface roughness against layer height and printing orientation, and finally the contour plot for the same inputs and response was presented in Figure 10.

Table 6: Surface roughness of DLP printed specimens

Experiment No.	Layer height (µm)	Printing orientation (°)	Surface Roughness (µm)
1	50	0°	0.1156
2		45°	0.1872
3		90°	0.2589
4	100	0°	0.2372
5		45°	0.3089
6		90°	0.3806
7	150	0°	0.3589
8		45°	0.4306
9		90°	0.5022

Table 7: Analysis of variance (ANOVA) results of Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.119633	0.029908	17945000.00	0.000
LH	2	0.088817	0.044408	26645000.00	0.000
PO	2	0.030817	0.015408	9245000.00	0.000
Error	4	0.000000	0.000000		
Total	8	0.119633			

It is noticed that the average roughness decreases with increasing both layer height and printing orientation. In other words, the surface becomes coarser. However, the slope and length of each pattern are different due to differences in degree of significance and contribution. The layer height line slope and length are steeper and longer than the corresponding one of printing orientation. This interprets why layer height contributed by 74.25% to produce the output roughness compared with 25.75% for printing orientation. The difference between contributions is around triple times unlike their effects on hardness which were close to each other. This explanation is consistent with what was obtained from the ANOVA results.

A 3D surface plot of the surface roughness against layer height and printing orientation is depicted in Figure 9. It looks like a rhombic shape and finer surface roughness is located at the low levels of layer height and printing orientation as the red arrow reveals where less than 0.2 µm is achieved. At the opposite corner, a coarser surface is recorded with greater than 0.5 µm at higher layer height and printing orientation.

Figure 8. Main effect Plot of Surface roughness

The projection of a 3D surface plot on the XY plane produced a contour plot having different distinguished zones ranging from finer to coarser at various levels of layer height and printing orientation. From the surface roughness point of view, getting a smoother surface is an important goal of any product processed by any manufacturing process. Therefore, the fine surface area is located here at the left bottom corner. Exactly, the same zone that produced the maximum hardness area with the same boundary (0°-≤50, 50-87 µm) has generated the minimum surface as red arrows pointed out the lighter green triangle.

The surface texture of DLP specimens that have been evolved at different layer height and printing orientation provided different roughness values when styles surface tester probe passed along it. This can be ascribed to the surface irregularities, valleys, and peaks may were at the minimum level when the DLP printed in zero direction at low layer height.

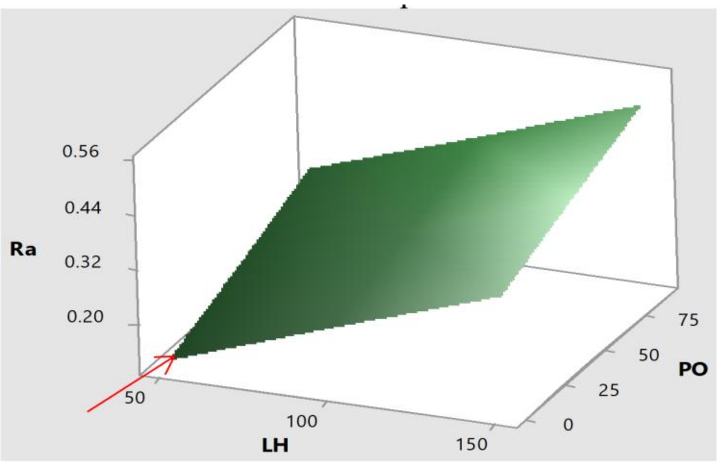

Figure 9. 3D surface Plot of Surface roughness (Ra) vs. layer thickness (LH) and printing orientation (PO)

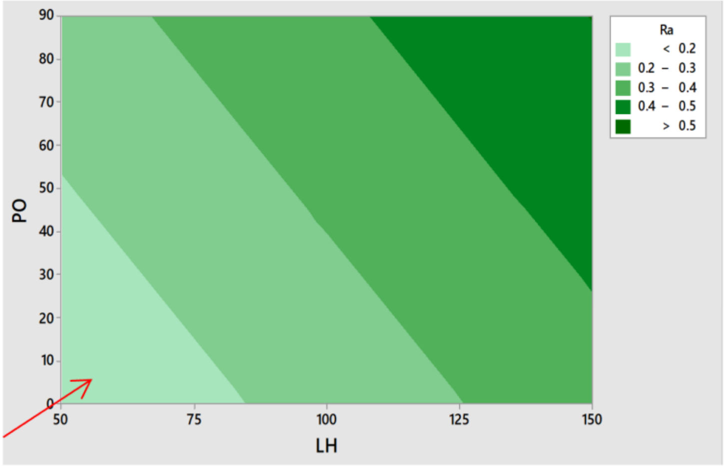

Figure 10. Contour Plot of Surface roughness (Ra) vs. layer thickness (LH) and printing orientation (PO)

To sum up, both the hardness and surface roughness of 3D printed dental materials are significantly affected by input parameters such as layer height and printing orientation. Investigation of these parameters is critical to improving the hardness, surface roughness, and overall durability of the final product.

It was noticed that hardness decreases with increasing layer height (LH) and printing orientation (PO) due to weaker inter-layer bonding, higher surface roughness, and incomplete polymerization at larger layer heights, which reduce the material's resistance to indentation. Additionally, steeper printing orientations (e.g., 45° or 90°) cause layer misalignment, lower load-bearing capacity, and increased void formation, further compromising hardness. The combination of these effects at higher LH and PO results in reduced structural integrity and mechanical performance.

Lower layer heights enhance interlayer adhesion, increase hardness, and improve surface roughness. A layer height of 50 µm produces the highest hardness, while a layer height of 150 µm reduces hardness due to weaker bonding. This is consistent with [6], who found that lower layer height improves aggregation and mechanical properties. With respect to the surface roughness, the lower layer heights (50 µm) produce smoother surfaces (roughness 0.115 µm), whereas higher layer heights of 150 µm degrades the roughness (>0.5 µm) due to the step effect.

Printing direction affects inter-layer bonding, stress distribution and surface quality. A 0° orientation (horizontal) produces maximum hardness, while a 90° orientation (vertical) results in a weaker bond and reduced strength. Horizontal printing reportedly enhances breakage resistance.

Higher printing orientations amplify the "staircase effect," reduce precision in layer alignment, and introduce gravitational and toolpath inconsistencies, all of which contribute to increased surface roughness. Lower orientations minimize these effects, resulting in smoother surfaces. Printing in the 0° orientation yields the smoothest surface (roughness of 0.115 µm), while printing at 90° increases the roughness (>0.5 µm) due to layer misalignment. Therefore, horizontal direction minimizes the surface irregularities.

The obtained results confirm that hardness and surface roughness make this method suitable for the mass production of customized denture bases, temporary crowns, and orthodontic appliances. Additionally, these parametric investigations can reduce production costs and improve efficiency in dental laboratories and prosthetic manufacturing.

These two responses are key indexes that impact the clinical conduct, useful life, and performance of the denture base. For dental applications, smoother surfaces are generally preferable as they enhance patient comfort, hygiene, and overall product quality. Increased roughness's negatively affects mechanical properties like strength, hardness, and wear resistance but can offer benefits in niche applications requiring strong bonding. Therefore, improving surface roughness is crucial for balancing performance and functional requirements. Therefore, understanding their variation can help in choosing the most appropriate materials for patient [20].

To sum up, the findings confirm that a 50 µm layer height and 0° orientation were better levels to produce hard and fine surface that would support the denture durability and surface quality. Table 8 summarizes the results of the current study with what have been achieved of some selected studies in terms of the effect of layer height and printing orientation on the hardness and surface roughness.

Table 8: comparison the results of the current study with other related published works

No.	Study	Effect of Layer Height	Effect of Printing Orientation
1	Zhang et al., 2022 [6]	Thinner layers improve interlayer bonding, enhancing hardness	Vertical orientations weaken mechanical strength
2	Wu et al., 2023 [16]	Layer height and post-curing influence surface smoothness	Orientation affects light exposure and polymerization quality
3	Lucas et al., 2021 [19]	Smoother surfaces achieved with thinner layers	Horizontal printing provides better wear resistance
4	Falahchai et al., 2023 [22]	3D-printed resins show lower hardness but better surface smoothness than traditional acrylics	Optimized orientation improves mechanical properties and aesthetics
5	Santos et al., 2024 [23]	3D-printed resins outperform conventional acrylics when layer height is optimized	Optimal printing orientation enhances durability and smoothness
6	Current study	Lower layer height improves hardness and surface roughness	0° orientation gives higher hardness and surface roughness

4. Conclusions

This study investigated the effects of layer height and printing direction on the hardness and surface roughness of DLP-printed denture base samples. Based on the achieved results, the following conclusions can be drawn:

1. Successfully produced DLP samples with different layer heights and printing directions, proving the feasibility of 3D printing for denture base applications.
2. Both the printing layer height and orientation have a significant impact on hardness and surface roughness, with the contributions 51% and 49% for hardness, and 74.25% and 25.75% for roughness respectively.
3. Lower layer height (50 µm) significantly improves interlayer adhesion and minimizes surface irregularities, resulting in significantly improved hardness and surface smoothness.

4. Printing in a 0° orientation resulted in the highest hardness and smoothest surface roughness, while printing in a 90° orientation resulted in weak adhesion and rough surface.
5. Better hardness and surface roughness was reached to 85 HD and 0.1156 µm at 50 µm layer height and 0° printing orientation.
6. These findings highlight the potential of DLP-printed denture bases as a strong alternative to traditional materials, offering superior mechanical properties and surface quality when optimal printing parameters are applied.

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