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Milling Performance of Selective Laser Melted Ti6Al4V: A Taguchi Approach for Surface Roughness Optimization

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Selective Laser Melting (SLM) of Ti6Al4V titanium alloy offers enhanced mechanical properties and design flexibility, making it attractive for biomedical and aerospace applications. However, its poor machinability, especially during milling, presents a significant challenge. Despite previous efforts, limited studies have addressed process optimization for improved surface quality in SLM-manufactured Ti6Al4V. This study aims to enhance machinability by optimizing surface roughness using the Taguchi method. An L9 orthogonal array was implemented to assess the effects of spindle speed, feed rate, and depth of cut. Analysis using Signal-to-Noise (S/N) ratios and ANOVA identified spindle speed as the most influential factor, accounting for 83.67% of the surface roughness variation. The optimized parameters led to a significant reduction in surface roughness. This research provides a systematic approach for improving the milling of additively manufactured Ti6Al4V and contributes novel insights into machining strategies for SLM components.

Keywords: Selective Laser Melting, Milling, Taguchi, Surface Roughness, Ti6Al4V

1 Introduction

Titanium alloy Ti6Al4V is widely used in aerospace, biomedical, and automotive industries due to its excellent strength-to-weight ratio, corrosion resistance, and biocompatibility. With advancements in additive manufacturing (AM) [1,2], Selective Laser Melting (SLM) has emerged as a promising technique for fabricating complex Ti6Al4V components with high precision and material efficiency. However, the unique microstructural characteristics of SLM-produced Ti6Al4V, such as residual stress, porosity, and anisotropic grain structures, significantly influence its machinability compared to conventionally manufactured (casting) Ti6Al4V [3,4,5].

In conventional Ti6Al4V, the material typically exhibits a more homogeneous microstructure with better ductility and lower internal stress [6,7]. In contrast, SLM-fabricated Ti6Al4V often presents a finer microstructure with columnar grains, high hardness, and tensile residual stresses due to rapid solidification and layer-wise fabrication. These factors contribute to different cutting responses, affecting tool wear, cutting forces, and surface integrity during machining [8,9,10]. Studies have shown that SLM-Ti6Al4V tends to generate higher cutting temperatures and tool wear rates due to its higher strength and lower thermal conductivity, making post-processing more challenging.

Milling of Ti6Al4V – whether conventionally or additively manufactured – is inherently difficult due to its [11]:

- Low Thermal Conductivity – Heat generated during milling is concentrated on the cutting tool, leading to excessive wear and reduced tool life.
- High Chemical Reactivity – Ti6Al4V tends to adhere to cutting tools, accelerating tool wear and affecting surface quality.
- Work Hardening Tendencies – The material hardens as it is cut, increasing cutting forces and surface roughness.
- Residual Stresses in SLM Parts – Unlike conventionally processed Ti6Al4V, SLM parts contain higher residual stresses, which may lead to dimensional instability and unexpected material behavior during milling.
- Porosity and Anisotropic Properties – The presence of micro-voids and directional grain growth in SLM-Ti6Al4V alters chip formation, affecting machinability and increasing the likelihood of surface defects.

To address these challenges, optimization of milling parameters is crucial to achieving a high-quality surface finish while minimizing tool wear and machining time [12,13,14,15]. The Taguchi method, a robust statistical optimization technique, is widely used to enhance machining performance by systematically analyzing the influence of process parameters. By employing an L9 orthogonal array, this study aims to optimize milling parameters–spindle speed, feed rate, and depth of cut–to minimize surface roughness in SLM-fabricated Ti6Al4V. Signal-to-noise (S/N) ratio analysis and Analysis of Variance (ANOVA) are utilized to determine the most influential factors affecting surface quality.

This research provides valuable insights into the milling behavior of additively manufactured Ti6Al4V compared to its conventionally processed counterpart and contributes to the development of efficient machining strategies for industrial applications [16,17]. The findings will aid manufacturers in selecting optimal milling conditions for SLM-Ti6Al4V, ensuring better surface integrity, improved performance, and enhanced reliability in biomedical and aerospace components.

2 Methodology

2.1 Material Preparation

The material utilized in this study is Ti6Al4V alloy, a widely used titanium alloy known for its excellent biocompatibility, corrosion resistance, and high strength-to-weight ratio—making it particularly suitable for biomedical applications. The samples were fabricated through Selective Laser Melting (SLM), an advanced additive manufacturing (AM) technique capable of producing complex geometries with high precision and minimal post-processing.

The SLM process was conducted using a RenAM 500E system (as illustrated in Figure 1), a high-performance metal 3D printer equipped with a fiber laser system and a controlled build environment designed to minimize oxygen content and ensure consistent material quality. The printing was carried out under a controlled argon atmosphere to prevent oxidation, with the baseplate preheated to 200 °C to reduce thermal gradients and minimize residual stresses during the build process.

Key laser parameters for the build included a laser power of 200 W, a scan speed ranging from 300 mm/s to 800 mm/s, and layer thicknesses of 0.03 mm and 0.06 mm. A constant hatch spacing of 0.12 mm was maintained throughout the fabrication process to ensure uniform energy distribution and proper melting between adjacent scan tracks.

The titanium powder used had a particle size distribution between 20–63 μm, a range specifically chosen to balance powder flowability and packing density while ensuring high-quality layer deposition and consistent melting behavior. This combination of process parameters was optimized to produce dense and homogenous Ti6Al4V samples with mechanical and surface properties appropriate for subsequent milling experiments and performance evaluation.

Fig. 1 *SLM Machine Type RenAM 500E*

To ensure consistency and reliability during the machining experiments, the SLM-fabricated Ti6Al4V samples were prepared in the form of rectangular blocks with dimensions of 150 mm × 50 mm × 10 mm. These standardized dimensions were selected to provide sufficient surface area and material volume for slot milling operations, while also enabling repeatable positioning and clamping during machining.

Prior to machining, a comprehensive material characterization of the SLM-produced Ti6Al4V alloy was conducted to establish baseline properties and confirm the quality of the fabricated samples. Key properties assessed included density, hardness, and microstructural features, as these characteristics directly influence the material's machinability and cutting behavior.

The density of the samples was measured using the Archimedes principle to evaluate the build quality and assess the presence of internal porosity. High relative density, typically above 99%, indicates successful fusion of powder layers and minimal defect formation during the SLM process. Hardness measurements were performed using a Vickers microhardness tester, providing insight into the mechanical resistance of the material and serving as an indirect indicator of the thermal history and cooling rates associated with the layer-wise fabrication process.

In addition, microstructural analysis was carried out using optical microscopy and scanning electron microscopy (SEM) to observe the morphology of the α and β phases, assess grain structure, and identify any unmelted particles or defects. The microstructure of the SLM Ti6Al4V typically exhibits fine acicular α' martensitic structures due to rapid solidification, which can affect both the hardness and the cutting forces experienced during milling.

By characterizing these fundamental material properties prior to machining, the study ensured that any variations in surface roughness or tool wear could be attributed primarily to machining parameters rather than inconsistencies in the workpiece material itself.

2.2 Milling Experiment

The milling experiments were conducted using a Hass VF 1 3axis is the subject of research (Fig. 2), equipped with a s created to explore the impact of cutting speed Vc, feedrate f, and depth of cut, d on the cutting force when milling the slot full immersion (0.5mm width). This model commonly uses cutting tools in the market.

Fig. 2 *T Hass VF 1 CNC Machine Used in The Experiment*

The study employed three key machining parameters[18]:

- Spindle Speed (rpm): [2000], [5000], [7000]
- Depth of Cut (mm): [0.1], [0.3], [0.5]
- Feed Rate ($mm.min^{-1}$): [600], [900], [1200]

In this study, a commercially available carbide cutting tool was employed to investigate the influence of key machining parameters – namely cutting speed (Vc), feed rate (f), and depth of cut (d) – on cutting forces during slot milling operations. The milling was conducted under full immersion conditions, wherein the entire width of the cutter engaged with the workpiece material. The slot width was precisely maintained at 0.5 mm, reflecting typical dimensional requirements for precision applications, particularly in the biomedical manufacturing sector.

The selection of the cutting tool was guided by its compatibility with standard industrial practices and its proven performance in high-accuracy machining tasks. The tool used features a 4-flute geometry, with a cutter diameter of 4 mm, a cutting edge length (L1) of 12 mm, an overall length (L) of 50 mm, and a shank diameter (d2) of 6 mm, as detailed in Figure 3. These dimensions make it suitable for micro- to medium-scale milling applications where precision, repeatability, and surface integrity are critical.

Utilizing a standardized, off-the-shelf tool allows the findings of this research to be more readily translated to real-world industrial settings, where cost-effective and scalable solutions are necessary. Moreover, the tool's design supports stable machining performance and consistent chip evacuation, which are essential when milling additively manufactured materials like Ti6Al4V, known for their anisotropic properties and challenging machinability.

The study's focus on cutting force measurement under defined immersion and engagement conditions provides valuable insights into tool-material interaction and helps optimize cutting parameters to reduce tool wear, improve dimensional accuracy, and achieve superior surface finishes–especially critical for biomedical implants and structural components where tolerance and integrity are paramount. The cutting tool used in this research is a standard 4-flute end mill, widely recognized for its stability and efficiency in high-speed milling operations. The geometrical and dimensional properties of the tool, which are critical for modeling and analysis, are detailed in Figure 3, with specifications sourced directly from the manufacturer's catalog to ensure accuracy and reproducibility.

The tool has a diameter of 4 mm, which is well-suited for small and precise machining operations. It features a cutting length (L1) of 12 mm, allowing sufficient engagement with the workpiece material during full slotting operations. The overall length (L) of the tool is 50 mm, providing the necessary reach and rigidity, especially important in minimizing deflection and vibration during high-speed machining. The shank diameter (d2) is 6 mm, offering enhanced stability when clamped into the tool holder, thereby improving cutting precision and surface finish.

The 4-flute configuration allows for a balanced combination of material removal rate and surface quality, while also supporting efficient chip evacuation during slot milling. The tool's design and material properties make it suitable for the cutting of titanium alloys such as Ti6Al4V, which present challenges due to their low thermal conductivity and high strength [19]. By using this tool in the study, the resulting data and analyses reflect realistic machining conditions, thus improving the applicability and relevance of the findings to industrial practices.

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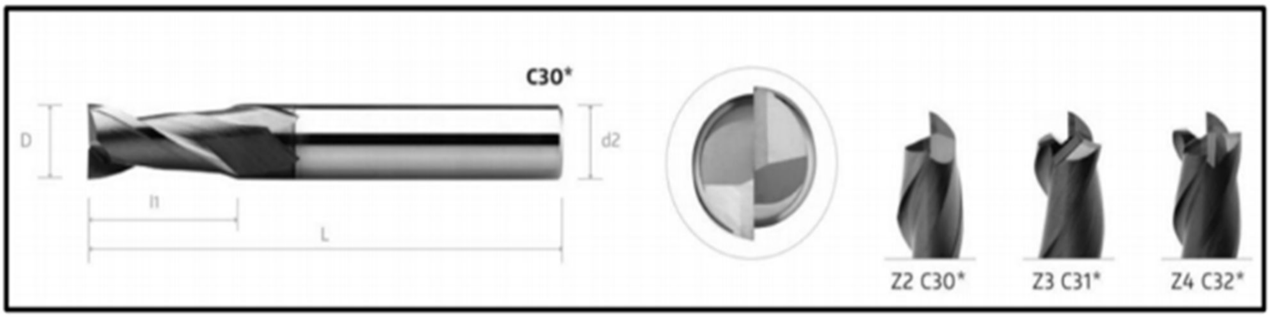

Fig. 3 *Cutting Tool Used for The Experiments*

Tab. 1 *Parameter Cutting Tool*

Parameter	Description
Flute	4
Corner Form	Sharp corner edge
Tool Material	Solid carbide
Rake Angle	10°
Helix Angle	40°
Coating	Uncoated

Cutting Tools parater shown on Tab. 1.

To systematically investigate the effects of key milling parameters on surface roughness and other machining outcomes, this study employed the Taguchi method for experimental design. Specifically, an L9 orthogonal array was selected, which is well-suited for evaluating three parameters, each at three distinct levels, while minimizing the number of required experimental trials. This approach provides an efficient and statistically robust framework for identifying optimal machining conditions and understanding parameter interactions.

The use of the L9 (3^3) array enabled the study to explore the influence of spindle speed, depth of cut, and feed rate under nine unique milling conditions. Each row of the array represents a different combination of parameter levels, ensuring a balanced distribution of factors across the experimental space. This design not only reduces experimental time and cost compared to a full factorial design but also facilitates the computation of Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA) for determining the significance and contribution of each parameter to the response variables.

By applying this structured approach, the study was able to effectively identify the parameter settings that lead to improved surface quality, while also providing insights into the relative importance of each factor in the machining of additively manufactured Ti6Al4V components.

2.3 Surface Roughness Measurement

Following the milling process, the surface roughness (Ra) of each machined sample was quantitatively evaluated to assess the quality of the resulting surface finish. Measurements were conducted using an Infinite Focus Alicona optical 3D surface measurement system, known for its high precision and non-contact capabilities, making it particularly suitable for detailed surface characterization in biomedical and precision engineering applications [20].

The system was configured with a cut-off length of 150 mm and an evaluation length of 10 mm, in accordance with ISO surface roughness measurement standards. To ensure the reliability and representativeness of the data, surface roughness was measured at three distinct locations on each machined sample. These locations were strategically chosen along the tool path to account for possible variability due to tool engagement and wear effects.

The mean Ra value from these three measurements was calculated and recorded as the representative surface roughness for each experimental run. This averaging approach minimized the influence of localized irregularities and enhanced the consistency of the dataset, thereby ensuring a robust basis for subsequent statistical analysis and optimization of the milling parameters.

Fig. 4 *Infinite Focus Alicona Imaging*

2.4 Data Analysis

To evaluate the experimental results systematically and ensure the reliability of the findings, the following analytical methods were employed.

2.4.1 Signal-to-Noise (S/N) Ratio Analysis

The Taguchi method was utilized to identify the optimal milling parameters for minimizing surface roughness. Specifically, the "smaller-the-better" quality characteristic was selected, as lower surface roughness is desirable in biomedical applications for improved implant performance. The S/N ratio provides a quantitative measure of variation and robustness by converting the trial results into a logarithmic scale, allowing for a more stable evaluation of factor influence despite experimental noise. This approach facilitated the identification of parameter settings that consistently yield minimal surface roughness.

2.4.2 Analysis of Variance (ANOVA)

ANOVA was conducted to statistically determine the significance and relative contribution of each milling parameter—namely spindle speed, feed rate, and depth of cut–on surface roughness. This analysis quantified the percentage contribution of each factor, enabling the identification of the most influential parameter. The results of ANOVA not only validate the findings from the S/N ratio analysis but also provide insights into the sensitivity of surface roughness to each input factor, which is crucial for process optimization and control.

2.4.3 Confirmation Test

To validate the optimal parameter settings identified through the Taguchi method, a confirmation test was performed under the suggested optimal conditions. The experimentally obtained surface roughness values were then compared with the predicted values derived from the Taguchi model. This comparison served to verify the accuracy of the optimization process and assess the predictive capability of the model. A close agreement between the predicted and actual values would confirm the robustness and reliability of the proposed milling parameters.

3 Result and Discussion

This research focuses on the analysis of surface roughness (Ra) following milling operations on additively manufactured Ti6Al4V samples. The evaluation was conducted through a series of nine experimental trials, which were systematically designed using the Taguchi method as previously described. The Taguchi approach, utilizing an L9 orthogonal array, enabled efficient experimentation while ensuring comprehensive coverage of the parameter space defined by three key milling variables: spindle speed, depth of cut, and feed rate.

The results of the surface roughness measurements for each trial are summarized in Table 2, which presents the Surface Roughness Analysis outcomes. For each experiment, the surface roughness was measured at three locations along the machined slot–specifically at the starting point, midpoint, and endpoint—to account for any variation along the cutting path. The average of these three readings was calculated to represent the surface roughness value corresponding to each set of machining parameters.

These results provide the basis for further statistical analysis, including the calculation of Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA), which are used to identify the most influential factors affecting surface finish. The data in Table 2 serve as a foundational element in determining the optimal combination of milling parameters that lead to the lowest possible surface roughness, ultimately contributing to improved machining performance and product quality in biomedical applications.

Tab. 2 *Surface Roughness Analysis Result*

Exp	Spindle Speed (rpm)	DoC (mm)	Feed Rate (mm.min^{-1})	Average Ra (μm)
1	2000	0.1	600	3.45
2	2000	0.3	900	3.56
3	2000	0.5	1200	3.87
4	5000	0.1	900	2.26
5	5000	0.3	1200	2.80
6	5000	0.5	600	3.00
7	7000	0.1	1200	2.2
8	7000	0.3	600	2.11
9	7000	0.5	900	2.52

This study focused on evaluating the influence of milling parameters on the resulting surface roughness (Ra) of Ti6Al4V samples produced through additive manufacturing. Surface roughness is a critical quality indicator, especially in biomedical applications where implant surfaces require high precision and smooth finishes to enhance biocompatibility and reduce bacterial adhesion.

Following the experimental procedure, the surface roughness data for each trial were compiled and are presented in Table 2, which summarizes the average Ra values obtained under different parameter combinations. For each slot, surface roughness was measured at three distinct positions along the tool path: the starting point, midpoint, and endpoint of the machined slot. These locations were selected to capture potential variations in tool engagement, thermal effects, and wear progression along the cutting direction. The mean of these three measurements was then calculated to represent the surface roughness value for each experimental condition.

Based on a detailed analysis of the experimental results derived from the Taguchi L9 orthogonal array, the optimal combination of milling parameters that achieved the lowest average surface roughness (Ra) was determined to be a spindle speed of 7000 rpm, a depth of cut (DoC) of 0.1 mm, and a feed rate of 900 mm.min^{-1}. This particular set of parameters was found to produce the most favorable surface finish among all tested combinations, demonstrating a strong alignment with the "smaller-the-better" criterion employed in the Signal-to-Noise (S/N) ratio analysis. This criterion prioritizes conditions that minimize the response variable–in this case, surface roughness–while also reducing variability and enhancing process robustness.

The superior surface quality achieved with this parameter combination underscores the critical role of high spindle speed in achieving smoother finishes. A higher spindle speed contributes to increased tool engagement frequency, reduced chip load per tooth, and improved heat dissipation at the cutting zone, all of which lead to reduced tool-workpiece interaction irregularities and improved surface uniformity. Meanwhile, the lower depth of cut (0.1 mm) minimizes the cutting force and material deformation during machining, thereby lowering the risk of surface damage, vibration, and tool deflection–factors commonly associated with rougher finishes.

Although the feed rate was set at a moderate level (900 mm.min^{-1}), it proved to be optimal in maintaining a balance between machining efficiency and surface finish quality. Excessively low feed rates can lead to tool rubbing and increased heat generation, while excessively high feed rates may compromise surface integrity by introducing chatter and uneven material removal. The selected feed rate in this study appears to mitigate these risks effectively.

Overall, this optimal parameter set reflects a harmonized interaction between cutting variables, leading to minimized surface roughness. The findings serve as a valuable guideline for machining additively manufactured Ti6Al4V components, particularly in precision-critical industries such as biomedical and aerospace engineering, where surface finish plays a vital role in mechanical performance, fatigue resistance, and functional integration of the final product.

The identified parameter set demonstrates the critical role of spindle speed and feed rate in controlling surface roughness during the milling of SLM-produced Ti6Al4V alloy. A higher spindle speed contributes to increased cutting frequency and more efficient chip removal, which reduces the chances of built-up edge formation and tool chatter–both of which can degrade surface quality. Similarly, an optimized feed rate (in this case, 900 mm.min^{-1}) supports steady tool engagement and promotes uniform material removal, which enhances the consistency of the machined finish without causing excessive vibration or tool loading.

Although the depth of cut was set at a relatively low value (0.1 mm), this contributed to reduced cutting forces and minimized thermal and mechanical stress on the workpiece. This is especially important for Ti6Al4V, a material known for its low thermal conductivity and high strength, which makes it susceptible to surface damage and tool wear under aggressive cutting conditions.

Overall, the results highlight the importance of fine-tuning machining parameters to achieve high-quality surfaces, particularly when working with additively manufactured titanium alloys, where surface finish plays a crucial role in the mechanical performance and functional integration of the final component–especially in biomedical and aerospace applications. This result is illustrated in the Fig. 5.

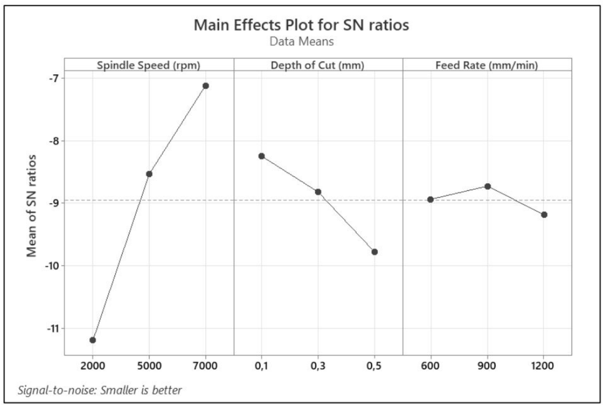

Fig. 5 *Optimum Parameter with Surface Roughness*

In this study, Analysis of Variance (ANOVA) was performed to quantify the influence of spindle speed on surface roughness during the milling of additively manufactured Ti6Al4V. The results of the analysis are graphically represented in Figure 6, which illustrates the relationship between spindle speed and the average surface roughness (Ra) values obtained across the experimental trials.

The data reveal a clear inverse correlation between spindle speed and surface roughness: as the spindle speed increases, the measured surface roughness values consistently decrease. This trend indicates that higher spindle speeds contribute to improved surface quality, resulting in smoother machined surfaces. Conversely, at lower spindle speeds, higher surface roughness values are observed, reflecting a deterioration in surface finish.

This behavior can be attributed to the dynamics of the cutting process. At higher spindle speeds, the cutting tool engages the material more effectively, reducing cutting forces and minimizing built-up edge formation. Additionally, increased speed reduces tool–workpiece contact time per unit area, leading to lower heat accumulation and less tool wear, both of which contribute to finer surface finishes. On the other hand, lower spindle speeds may result in increased friction, higher cutting forces, and more pronounced tool marks on the machined surface, thereby degrading the surface quality.

The significant impact of spindle speed on surface roughness, as quantitatively confirmed through Analysis of Variance (ANOVA) –with a contribution percentage of 83.66%—highlights the dominant role this parameter plays in determining the surface quality of milled components. This high contribution value indicates that among all the investigated parameters (spindle speed, feed rate, and depth of cut), spindle speed exerts the strongest influence on the resulting surface finish, making it a critical factor in the optimization of milling operations.

This finding is especially relevant in the context of machining additively manufactured Ti6Al4V alloy, where maintaining a high-quality surface is paramount. Due to the inherent characteristics of AM-produced materials–such as anisotropy, microstructural inhomogeneity, and potential residual stresses—surface irregularities are more prone to occur if machining parameters are not properly controlled. The use of higher spindle speeds facilitates better chip formation and evacuation, reduces tool vibration, and enhances the stability of the cutting process, all of which contribute to smoother surfaces.

In high-performance applications such as biomedical implants, the implications of surface roughness are even more pronounced. A finely machined surface not only improves the aesthetic and dimensional precision of the implant but also plays a crucial role in biological performance, including osseointegration, cell adhesion, and wear resistance. Poor surface finish, on the other hand, may lead to stress concentrations, corrosion initiation sites, or impaired mechanical compatibility with biological tissues.

Therefore, the demonstrated significance of spindle speed in this study offers a clear direction for process parameter prioritization in precision manufacturing. By optimizing spindle speed, manufacturers can achieve superior surface finishes while reducing the likelihood of defects, ultimately contributing to the reliability, safety, and clinical success of biomedical components.

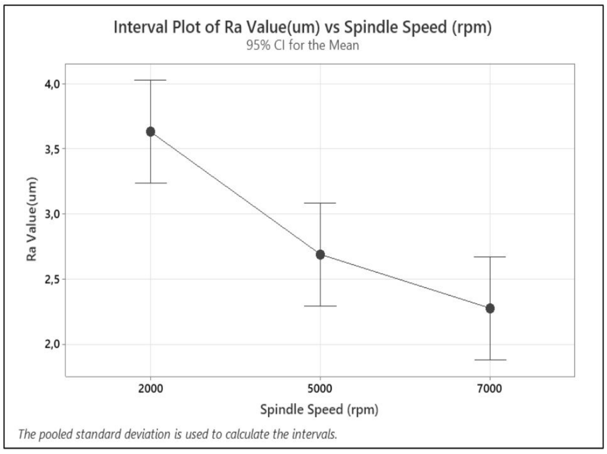

Fig. 6 *ANOVA Relationship Between Spindle Speed and Surface Roughness*

This research places a strong emphasis on the analysis of surface roughness, which serves as a critical performance metric in the machining of additively manufactured Ti6Al4V components for biomedical applications. The study employed a Taguchi design of experiments (DoE) approach using an L9 orthogonal array, which facilitated the systematic investigation of the effects of three key milling parameters–spindle speed, depth of cut, and feed rate–each evaluated at three distinct levels.

A total of nine experimental trials were conducted as defined by the Taguchi layout, and the resulting surface roughness values (Ra) for each trial are summarized in Table 3. These values represent the average of three measurements per slot (taken at the starting, middle, and end positions) to account for any variability along the cutting path. This averaging method enhances the accuracy and reliability of the surface quality data by mitigating local inconsistencies due to tool wear or thermal effects.

To better understand the influence of individual parameters on surface roughness, an Analysis of Variance (ANOVA) was performed on the Signal-to-Noise (S/N) ratios derived from the experimental results. The ANOVA results, also presented in Table 3, provide a quantitative assessment of each parameter's contribution to variations in surface roughness. The analysis clearly indicates that spindle speed is the most dominant factor, with a substantial contribution of 83.67% to the observed variation in surface roughness. This high percentage underscores the critical role spindle speed plays in determining surface finish quality, likely due to its influence on cutting dynamics, tool-workpiece interaction, and heat generation.

In contrast, the depth of cut and feed rate contributed 11.64% and 4.69%, respectively. These relatively lower percentages suggest that while these parameters do influence surface roughness, their effects are significantly less pronounced compared to spindle speed within the selected parameter range. The low contribution of feed rate, in particular, may be attributed to the narrow range of values investigated or the inherent material properties of Ti6Al4V, which could render it less sensitive to changes in feed at the tested levels.

These findings highlight the importance of prioritizing spindle speed optimization in future machining strategies aimed at enhancing surface finish, especially in the context of biomedical implant manufacturing where surface integrity is paramount [14,18].

Tab. 3 *Analysis of Variance for SN Ratios of Surface Roughness*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Spindle Speed	2	25.58	25.58	12.79	22.85	0.04	83.67
DoC	2	3.56	3.56	1.78	3.18	0.23	11.64
Feed Rate	2	0.31	0.31	0.15	0.28	0.78	4.69
Residual Error	2	1.11	1.11	0.55			
Total	8	30.57					

4 Conclusion

Based on the conducted experiments and analytical findings, the following key conclusions can be drawn, highlighting the study's contributions, practical implications, and areas for further research.

- Spindle speed was identified as the dominant factor, contributing 83.66% to the variation in surface roughness. This confirms that higher cutting speeds significantly improve surface finish by reducing contact time and enhancing chip evacuation.
- A larger depth of cut increased surface roughness, contributing 11.64% to surface variation, due to higher cutting forces, tool deflection, and induced vibration – all leading to poor surface integrity.
- Feed rate, although generally associated with higher roughness in conventional machining, had a lesser impact (only 4.69% contribution), and within the tested range, showed a slight positive effect due to improved chip removal.
- The Taguchi optimization approach effectively guided the selection of milling parameters, and the model's prediction was experimentally validated, showcasing the reliability of statistical optimization in additive–subtractive manufacturing contexts.

This study offers new insight into machining of additively manufactured Ti6Al4V, showing that higher feed rates, when combined with high spindle speed and low depth of cut, may not always deteriorate surface finish, which contradicts some conventional assumptions. Industrial implication: The findings can directly assist precision manufacturing sectors, such as biomedical implant production, where surface smoothness is critical for biocompatibility, fatigue resistance, and long-term functionality. Limitation: The experiments were limited to dry milling conditions and a fixed tool type. Future studies may explore the effect of coolants, tool materials, or post-processing treatments on surface integrity. Knowledge contribution: This work deepens understanding of how AM-fabricated titanium alloys behave under subtractive operations, particularly in milling, bridging a crucial gap between additive design freedom and final surface quality requirements.

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References

[1] LIU, X., CHU, P. K., DING, C. (2004). *Surface Modification of Titanium, Titanium Alloys, and Related Materials For Biomedical Applications*. doi: 10.1016/j.mser.2004.11.001.

[2] DE VITERI, V. S., FUENTES, E. (2013). Titanium and Titanium Alloys as Biomaterials. Tribology - Fundamentals and Advancements, *InTech*. doi: 10.5772/55860.

[3] AL-RUBAIE, K. S., MELOTTI, S., RABELO, A., PAIVA, J. M., ELBESTAWI, M. A., VELDHUIS, S. C. (2020). Machinability of SLM-Produced Ti6Al4V Titanium Alloy Parts. *J. Manuf. Process*, Vol. 57, pp. 768–786. doi: 10.1016/j.jmapro.2020.07.035.

[4] MOHAMMED, M. T., SEMELOV, V. G. S., SOTOV, A. V. S. (2019). SLM-Built Titanium Materials: Great Potential of Developing Microstructure and Properties For Biomedical Applications: *A Review*. Institute of Physics Publishing. doi: 10.1088/2053-1591/ab624c.

[5] ZHANG, X., & LIOU, F. (2021). Introduction to additive manufacturing. In *Additive manufacturing* (pp. 1-31). Elsevier.

[6] EYLON, D., FROES, F. H., GARDINER, R. W. (2013). Developments in Titanium Alloy Casting Technology. *Physical & Mechanical Metallurgy,* Vol. 35, pp. 35-47.

[7] NASTAC, L., GUNGOR, M. N., UCOK, I., KLUG, K. L., TACK, W. T. (2006). Advances in Investment Casting of Ti-6Al-4v Alloy: *A Review*. doi: 10.1179/136404605225023225.

[8] LIZZUL, L., SORGATO, M., BERTOLINI, R., GHIOTTI, A., BRUSCHI, S. (2020). Influence of Additive Manufacturing-Induced Anisotropy on Tool Wear in End Milling of Ti6Al4V. *Tribol. Int*., Vol. 146. doi: 10.1016/j.triboint.2020.106200.

[9] VIGNESH, M., RANJITH KUMAR, G., SATHISHKUMAR, M., MANIKANDAN, M., RAJYALAKSHMI, G., RAMANUJAM, R., ARIVAZHAGAN, N. (2021). Development of Biomedical Implants through Additive Manufacturing: *A Review*. Springer. doi: 10.1007/s11665-021-05578-7.

[10] GROVER, T., PANDEY, A., KUMARI, S. T., AWASTHI, A., SINGH, B., DIXIT, P., SINGHAL, P., SAXENA, K. K. (2019). Role of Titanium in Bio Implants and Additive Manufacturing: An Overview. Materials Today: *Proceedings*, Elsevier Ltd, pp. 3071–3080. doi: 10.1016/j.matpr.2020.02.636.

[11] ALIJANI, F., AMINI, R., GHAFFARI, M., ALIZADEH, M., OKYAY, A. K. (2014). Effect of Milling Time on The Structure, Micro-Hardness, and Thermal Behavior of Amorphous/Nanocrystalline Tinicu Shape Memory Alloys Developed By Mechanical Alloying. *Mater Des*, Vol. 55, pp. 373–380. doi: 10.1016/j.matdes.2013.09.009.

[12] ASLANTAS, K., EKICI, E., ÇIÇEK, A. (2018). Optimization of Process Parameters For Micro Milling of Ti-6Al-4V Alloy Using Taguchi-Based Gray Relational Analysis. *Measurement* (Lond), Vol. 128, pp. 419–427. doi: 10.1016/j.measurement.2018.06.066.

[13] PANSHETTY, S. S., BUTE, P. V. (2016). *Optimization of Process Parameters in Milling Operation by Taguchi's Technique using Regression Analysis.* Available: www.ijste.org

[14] GHANI, J. A., CHOUDHURY, I. A., HASSAN, H. H. (2004). Application of Taguchi Method in The Optimization of End Milling Parameters. *J Mater Process Technol*, Vol. 145, No. 1, pp. 84–92. doi: 10.1016/S0924-0136(03)00865-3.

[15] DANIYAN, I., TLHABADIRA, I., ADEODU, A., PHOKOBYE, S., MPOFU, K. (2020). Process Design and Modelling For Milling Operation of Titanium Alloy (Ti6Al4V) Using The Taguchi Method. *Procedia CIRP*, Elsevier B.V., pp. 348–355. doi: 10.1016/j.procir.2020.03.103.

[16] ZHANG, D., FENG, Z., WANG, C., WANG, W., LIU, Z., NIU, W. (2018). Comparison of Microstructures and Mechanical Properties of Inconel 718 Alloy Processed By Selective Laser Melting and Casting. *Materials Science and Engineering: A*, Vol. 724, pp. 357–367. doi: 10.1016/j.msea.2018.03.073.

[17] ZONG, X., JI, Z., ZHAO, Z., FENG, X., DING, X., NAN, H. (2023). Microstructure and Tensile Property of Hybrid Fabricated Ti-6Al-4V Alloy by Investment Casting and Laser Additive Manufacturing. *Metals* (Basel), Vol. 13, No. 4. doi: 10.3390/met13040668.

[18] VIPINDAS, K., KURIACHEN, B., MATHEW, J. (2019). Investigations Into The Effect of Process Parameters on Surface Roughness and Burr Formation During Micro End Milling of TI-6AL-4V. *International Journal of Advanced Manufacturing Technology*, Vol. 100, No. 5–8, pp. 1207–1222. doi: 10.1007/s00170-016-9210-3.

[19] ZEMAN, P., BACH, P., & TRMAL, G. (2017). Tool life of PM-HSS cutting tools when milling of titanium alloy. *Manufacturing Technology*, 17(1), 115-121.

[20] HRICOVA, J., & NAPRSTKOVA, N. (2015). Surface roughness optimization in milling aluminium alloy by using the Taguchis design of experiment. *Manufacturing Technology*, 15(4), 541-546.