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INFLUENCE OF CUTTING CONDITIONS ON SURFACE ROUGHNESS OF PA AND PA15

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Abstract: *Engineering polymers, particularly polyamides, are increasingly used due to their favorable properties; however, their machinability—especially in the case of glass fiber-reinforced composites—remains a challenge. Conflicting findings in the literature regarding the effect of fillers on surface finish, particularly for composites with lower fiber content, highlight the need for further investigation. In this context, the present study focuses on the experimental examination of the influence of milling parameters on the surface roughness of two materials: pure polyamide (PA) and a composite containing 15% glass fibers (PA15). Milling was executed on a HAAS Tool Room Mill CNC system, employing a 4 mm standard end milling cutter. For each material, various machining regimes were applied, combining three spindle speeds and three feed rates. Surface roughness was evaluated using Ra and Rmax parameters in accordance with ISO 4287, and measurements were conducted with an ISR-C002 profilometer. The obtained results show that PA exhibits lower Ra and Rmax values compared to PA15, along with more stable behavior across all machining regimes. PA15 demonstrated higher roughness and variability. The most favorable results for both materials were achieved at higher spindle speeds and moderate feed rates. This study contributes to a better understanding of the relationship between material composition and machining parameters, providing valuable insights for optimizing surface quality in polymer composites.*

Keywords: *Polyamide, Glass-Fiber Reinforced Polyamide, CNC machining, Milling, Surface roughness*

1. INTRODUCTION

With the growing application of engineering polymers in modern industrial manufacturing, a more comprehensive understanding of their behavior during machining processes is essential. Polyamides (PA), including PA15 and its modified variants, are distinguished by their mechanical strength, chemical resistance, and favorable tribological properties. Their benefits-such as wear and abrasion resistance, mechanical stability at elevated temperatures, low gas permeability, and dimensional stability-are primarily attributed to the presence of strong intermolecular hydrogen bonds between amide groups [1]. However, their susceptibility to moisture, which leads to plasticization and a consequent reduction in mechanical performance, remains a limiting factor [2,3].

To enhance mechanical properties—particularly strength and stability under variable loading conditions—polyamides are increasingly reinforced with glass fibers, resulting in composite materials such as Glass-Fiber Reinforced Polyamide (PA-GF) [2]. However, the addition of glass fibers introduces material anisotropy, which directly affects both mechanical performance and fatigue behavior. Unlike isotropic materials such as metals, short fiber-reinforced composites exhibit complex damage mechanisms, including interfacial debonding, matrix cracking, fiber breakage, and other failure modes. Studies indicate that PA15 demonstrates moderate anisotropy, whereas PA30 exhibits a pronounced anisotropic response, complicating the prediction of mechanical behavior under load. The mechanical performance also depends on the fiber length, orientation, and the degree of fiber-matrix interaction [2,4].

Despite their advanced mechanical properties, these materials continue to present challenges in terms of machining and accurate characterization—particularly regarding surface finishing and the prediction of long-term performance under sustained loading. Numerous studies have indicated that the presence of glass fibers significantly affects surface roughness parameters during machining. For instance, N.M. Vaxevanidis et al. demonstrated that PA66-GF30 composites, compared to pure PA66, exhibit higher Ra and Rz values, especially at lower cutting speeds [5]. Similar conclusions were reported by F. Quadrini et al., emphasizing that composite machining behavior is further influenced by fiber distribution, concentration, and prior manufacturing processes [6].

On the other hand, some studies suggest that composite polyamides may exhibit improved surface finish under certain conditions. For example, G. Vasile et al. reported that PA66–GF30, when machined with optimized milling parameters, can achieve lower surface roughness compared to pure PA66 [7]. Such conflicting findings in the literature highlight the need for further experimental research, particularly in the context of composites with lower filler content and under controlled machining regimes.

Considering these divergent findings and the limited data available for composites with lower filler content, this study focuses on comparing the surface roughness of pure polyamide (PA) and a composite containing 15% glass fibers (PA15) under various milling conditions. The Ra and Rmax parameters were analyzed to assess the influence of filler content on machinability and surface quality. The experiment aims to evaluate the advantages and limitations of both materials under realistic machining conditions, and the results are compared with literature data to provide a deeper understanding of the relationship between material composition, cutting parameters, and surface finish.

2. MATERIALS AND METHODS

This study involved the use of two types of polymer materials: pure PA and the composite PA15. These materials were selected due to their widespread industrial applications, as well as their distinct differences in structure and mechanical properties. The experimental part of the study included milling of the selected materials, which was performed on a HAAS Tool Room Mill CNC machine (Fig. 1). Milling was chosen because it allows precise control of cutting parameters and provides insight into material behavior under realistic machining conditions.

The machining was performed using a 4 mm diameter end mill (2MLE040200130, JJ Tools Co. Ltd.), specifically designed for polymer material processing. For each material, 9 samples were prepared, with variations in cutting conditions applied to each sample—specifically, spindle speed and feed rate:

- Spindle speeds: 2000 rpm, 3000 rpm, and 4000 rpm, and
- Feed rates: 200 mm/min, 400 mm/min i 600 mm/min.

The combination of the selected parameters resulted in a total of nine machining regimes per material, enabling the analysis of the individual effects of each factor on surface finish.

a)

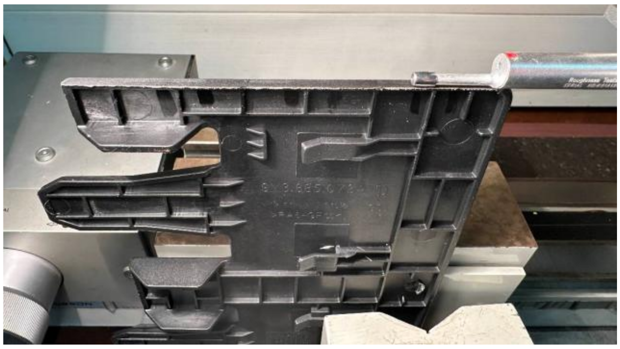
b)

Figure 1. Experimental milling setup: a) HAAS Tool Room Mill CNC milling machine, and b) Sample machining process

Following the milling process, the samples were prepared for surface roughness measurement. Preparation included the removal of residual particles and contaminants from the surface, as well as storage under controlled conditions to preserve dimensional stability prior to measurement. Measurements were conducted in accordance with ISO 4287 [8], using an ISR-C002 INSIZE Roughness Tester profilometer. Three measurements were taken on each surface, and the arithmetic mean was used as the representative value (Fig. 2).

Two fundamental parameters commonly used to quantify surface finish quality were measured: Ra – the arithmetic average roughness, and Rmax – the maximum profile height on the analyzed surface. These parameters are widely applied for surface condition evaluation, as they provide insight into the microgeometry of the machined zone, which is essential for subsequent functional requirements, including contact behavior, wear resistance, and assembly with other components [8].

a)



b)

Figure 2. Surface roughness measurement setup: a) INSIZE ISR-C002 surface roughness tester, and b) Surface roughness measurement procedure

3. RESULTS

To analyze the influence of glass fiber reinforcement on surface finish, Table 1 presents the measured values of Ra and Rmax parameters for PA and PA15 samples under various milling conditions.

In general, the PA material exhibited lower surface roughness values compared to PA15. The lowest recorded Ra value for the PA material was 0.597 µm, observed at a spindle speed of 4000 rpm and a feed rate of 400 mm/min. Under the same machining conditions, the corresponding Rmax value was 5.532 µm.

An increase in spindle speed from 2000 to 4000 rpm resulted in a decrease in both Ra and Rmax values. Similarly, a moderate increase in feed rate from 200 to 400 mm/min was also accompanied by a reduction in surface roughness. However, a further increase in feed rate to 600 mm/min led to a slight rise in both parameters.

Table 1. Measured surface roughness values of the samples after milling

Sample	Spindle speed, rpm	Feed Rate, mm/min	Ra (PA), µm	Rmax (PA), µm	Ra (PA15), µm	Rmax (PA15), µm
1	4000	200	1.46	10.224	2	15.361
2	4000	400	0.597	5.532	2.107	14.571
3	4000	600	0.653	5.038	1.579	13.928
4	3000	200	1.528	9.088	2.124	16.546
5	3000	400	0.626	6.767	2.259	14.867
6	3000	600	0.987	7.211	1.64	15.756
7	2000	200	1.334	9.681	2.575	18.275
8	2000	400	1.33	9.384	2.448	16.744
9	2000	600	1.614	11.656	2.411	19.559
Unmachined surface	**-**	**-**	**5.518**	**41.193**	**5.092**	**39.316**

The PA15 material, which contains glass fiber reinforcement, exhibited higher surface roughness values across all tested machining conditions. The lowest recorded Ra value for PA15 was 1.579 µm, observed at a spindle speed of 4000 rpm and a feed rate of 600 mm/min. Under the same conditions, the measured Rmax value was 13.928 µm.

Although this machining regime yielded the lowest roughness values for PA15, they were still higher compared to the corresponding values obtained for the PA material. In all cases, both Ra and Rmax values for PA15 were higher than those measured for PA under the same machining conditions.

The highest measured values of Ra and Rmax for both materials were recorded at the lowest spindle speed (2000 rpm) and the highest feed rate (600 mm/min). Under these conditions, the Ra value for PA15 was 2.575 µm, while the Rmax reached 19.559 µm.

Compared to PA15, the PA material exhibited lower roughness values across all machining regimes. The PA samples showed more uniform surfaces with consistently lower Ra and Rmax values, whereas the PA15 samples demonstrated higher roughness across all parameter combinations (Fig. 3).

4. DISCUSSION

The analyzed materials, PA and PA15, exhibit pronounced differences in behavior during milling, which is expected given their composition. PA, as a homogeneous thermoplastic material, is characterized by good machinability and lower surface roughness values, making it suitable for applications that require high precision and surface quality. In contrast, PA15 contains 15% glass fiber reinforcement, which contributes to increased stiffness and dimensional stability, but also results in higher Ra and Rmax values. This may limit its use in applications where surface finish is of critical importance [1].

The presented results indicate that the lowest surface roughness values for both materials were achieved at higher spindle speeds and moderate feed rates. PA demonstrated stable and consistent roughness values across all machining regimes, whereas PA15 showed greater variability, which can be attributed to the more complex microstructure of the composite.

The obtained results can be compared with findings from the literature. Studies by N.M. Vaxevanidis et al. and E. Kurama, which focus on PA66-GF30, show that the addition of glass fibers increases surface roughness, while higher cutting speeds and lower feed rates significantly contribute to its reduction [5,9]. These findings are consistent with the results presented in this study, particularly with respect to the behavior of the PA material.

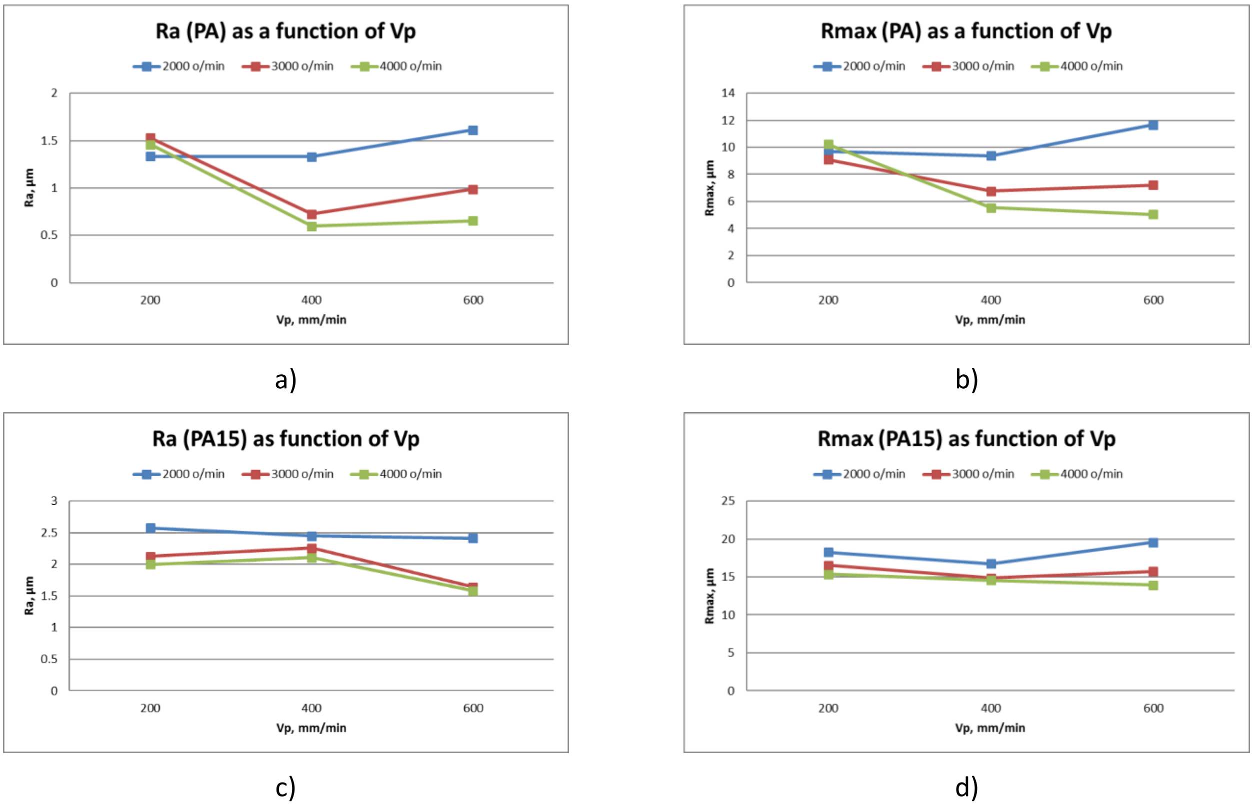


Figure 3. Surface roughness parameters as a function of feed rate: a) Effect of spindle speed and feed rate on Ra for PA, b) Effect of spindle speed and feed rate on Rmax for PA, c) Effect of spindle speed and feed rate on Ra for PA15, and d) Effect of spindle speed and feed rate on Rmax for PA15

In contrast to previous findings, G. Vasile et al. demonstrated that PA66-GF30 can exhibit lower surface roughness than pure PA66, particularly when optimal machining parameters are applied. This discrepancy may be attributed to differences in tooling, cutting geometry, the percentage of filler content (30% compared to 15%), as well as the type and distribution of the fibers and additives themselves [7].

Additional comparisons with other researchers confirm the significance of machining parameters on surface finish. For instance, A. Yardimeden reported a positive effect of increased cutting speed and larger tool radius on surface quality in GFRP materials. Although tool radius was not varied in the present study, a positive influence of increased spindle speed was observed—particularly in the case of PA [10].

The study by K. Palanikumar et al. indicates that feed rate has a dominant influence on Ra, while cutting speed plays a secondary role. The lowest Ra values in their results were achieved with a combination of high spindle speed (4000 rpm) and moderate feed rate (400 mm/min), confirming the synergistic effect of these two parameters. The authors also emphasize the importance of fiber orientation relative to the cutting direction, which may be relevant to the observed differences in PA15 behavior under certain machining regimes [11].

E. Kuram, in his study on micro-milling of polypropylene with and without fillers, reported increased surface roughness and tool wear in reinforced samples—findings that align with the observations related to PA15 [11]. In addition, the results of Y. Yan et al., which indicate that machining outside the viscoelastic range positively affects surface quality, are consistent with our findings for PA, where a more stable and uniform surface finish was recorded [12].

The Taguchi method has been widely used in several studies for the optimization of machining parameters, with increased cutting speed and reduced feed rate or depth of cut identified as the most effective strategies for minimizing Ra values [14,15].

In the study by Nikam et al., the lowest Ra value (~0.54 μm) was achieved under conditions similar to those that yielded the best results for PA in the present research, further confirming the relevance of the obtained findings [14].

Although the results presented in this study are largely consistent with those found in the literature, certain discrepancies exist regarding the significance of individual parameters, as confirmed by the study of S. Ghalme et al. [15]. The analyzed data clearly highlight the complexity of the interplay between material composition and machining parameters in determining surface quality, reinforcing the need to tailor machining regimes to the specific characteristics of each material type.

5. CONCLUSION

The obtained results indicate that both material composition and the selection of machining parameters have a significant influence on the surface finish quality of engineering polymers. A comparative analysis of PA and PA15 demonstrated that pure polyamide achieves lower surface roughness values and more consistent results, confirming its suitability for applications that require high precision and fine surface finish. On the other hand, the addition of glass fibers in PA15 contributes to increased strength and dimensional stability but also makes it more difficult to achieve smooth and uniform surfaces. A combination of higher spindle speeds and moderate feed rates proved to be optimal for improving surface quality in both materials, which aligns with current scientific findings. The results of this study may serve as a foundation for the optimization of machining regimes depending on the specific requirements of the intended application.

Future research will focus on examining the influence of additional factors such as tool geometry, fiber orientation, and filler type, in order to gain a more comprehensive understanding of the mechanisms that govern surface finish in composite polymer materials.

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