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COMPARATIVE STUDY OF FRONT MILLING OF PEEK AND PEEK-CF30

Carlos Alfredo Gracioli Aita
Émerson dos Santos Passari
André João de Souza
Federal University of Rio Grande do Sul (UFRGS), Laboratory of Automation in Machining (LAUS), R. Sarmento Leite, nº 425, 90050-170, Porto Alegre, RS, Brazil.
carlosgracioliaita@gmail.com, emerson.passari@gmail.com, ajsouza@ufrgs.br

Abstract. *The thermoplastic poly-ether-ether-ketone (PEEK) is a low-density polymer with high durability, excellent stiffness, good toughness, and high chemical, thermal and mechanical resistances. The addition of carbon fiber enhances the properties of the matrix, resulting in PEEK-CF composites with great potential for industrial applications. Since studies on the milling of PEEK-CF are relatively new, it is necessary to thoroughly understand its machinability, as the properties of this composite vary according to the carbon fiber loading. Therefore, this work aims to perform a preliminary comparative study regarding machining force and surface roughness generated during dry face milling of PEEK and PEEK-CF30 (30% carbon fiber reinforcement). A Box-Behnken experimental design was used to create combinations of cutting parameters (cutting speed, feed per tooth, and depth of cut), and the analysis of variance was employed to investigate the influence of these parameters on the machining of both materials. The results showed that, within the analyzed parameter range, milling of PEEK-CF30 generated average roughness values 34.8% lower and machining force values 34.9% higher than PEEK due to the carbon fiber reinforcement. In PEEK, the feed per tooth was the parameter that most contributed to the roughness and force magnitudes, while in PEEK-CF30, depth of cut and cutting speed were more significant for surface roughness, and feed per tooth for machining force.*

Keywords: *PEEK, Carbon fiber, Front milling, Average surface roughness, Machining force*

1. INTRODUCTION

The organic thermoplastic poly-ether-ether-ketone (PEEK) is a semi-crystalline polyaromatic polymer with low density, high durability, excellent stiffness, good toughness, and high chemical, thermal, and mechanical resistance. These characteristics make PEEK an attractive material for replacing metals. Its applications span various sectors, including electrical, electronic, automotive, aerospace, and maritime industries (Hanifi et al., 2012a). In the aerospace industry, PEEK is often used as a substitute for aluminum alloys, mainly due to its performance in service at high temperatures (Mata et al., 2009a). PEEK has a melting point of 335 °C, a glass transition temperature of 143 °C, and it can be used continuously up to 250 °C without binding its characteristics. Moreover, its structure has high solubility and molecular weight, and presents mechanical properties like bronze. It also offers radiation resistance and low flammability (Davim et al., 2003).

Researchers have been engaged in developing PEEK-based composites for the past two decades. The addition of carbon fibers (CF), glass fibers (GF), or aramid fibers (AF) into thermoplastics has led to improvements in properties such as stiffness, strength, and hardness compared to unreinforced polymers while also increasing the service temperature (Zhu et al., 2020). Carbon fibers (CF) provide PEEK with improved matrix properties, resulting in composites with significant potential for industrial applications, particularly in producing high-quality medical implants (Xu et al., 2020). CF are usually used as reinforcements in thermoplastics due to their low deformation rate and high flexural modulus. These fibers are commonly applied in structural components operating above 150 °C due to their high mechanical strength and rigidity, good creep and corrosion resistance, and low thermal expansion (Ji et al., 2015).

As a result of these properties and potential industrial applications, it is necessary to understand the mechanisms involved in machining PEEK reinforced or not with carbon fiber (Mata et al., 2009b). Machining is an efficient manufacturing process that can produce specific mechanical components from PEEK-CF composites. This process can ensure dimensional accuracy and surface finish for the expected performance in service and increased component lifespan. As studies on the machining of PEEK-CF are relatively new, it is necessary to deeply understand its machinability, as the properties of this composite vary according to the carbon fiber loading composition (Hanifi et al., 2012b).

Ji et al. (2015) evaluated the mechanical properties and machinability of turning PEEK and PEEK-CF30. The results showed that PEEK-CF30 generated higher cutting force fluctuations and modified the fracture and deformation properties of the removed chip, leading to higher form deviation and roughness values than PEEK. Mata et al. (2009a) investigated the turning process of PEEK, PEEK-CF30, and PEEK-GF30. They concluded that the machinabilities of PEEK with carbon fiber (CF) and glass fiber (GF) reinforcements were lower than PEEK because of higher specific cutting pressures.

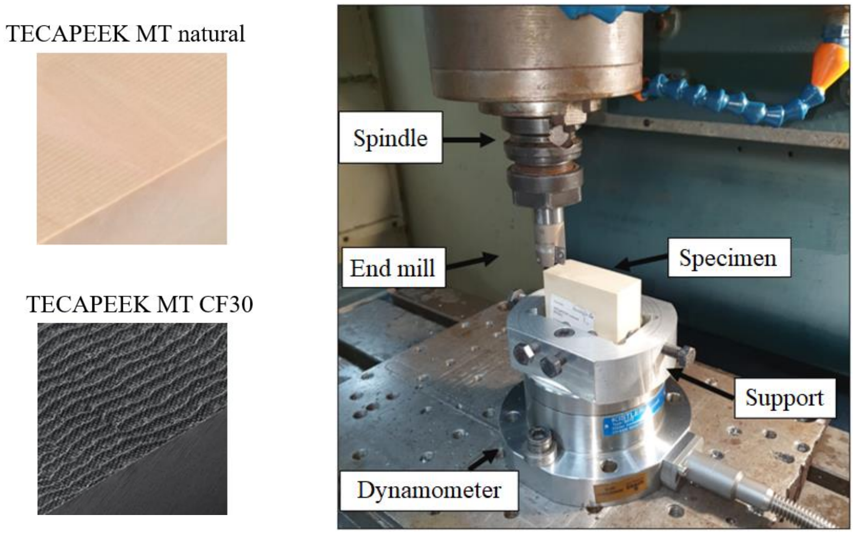
Davim and Mata (2008) conducted a study to analyze the performance of three different insert materials in turning PEEK and PEEK-CF30. Among other response variables, the authors evaluated the cutting force and surface roughness as a function of feed rate and cutting tool. They concluded that the best results were obtained with the PCD-coated carbide tool compared to the K10 uncoated carbide and polycrystalline diamond tools.

Few studies on the face milling of PEEK (reinforced or unreinforced) can be found in the scientific literature. A group of researchers worked on high-speed milling (HSM) for PEEK reinforced with 55-60% carbon fiber. A machining force (F_u) prediction model was developed by Cao et al. (2021), considering fiber distribution characteristics. The authors concluded that increasing the width of cut (a_e) and feed per tooth (f_z) decreased F_u within the analyzed range of input values. Furthermore, the highest machining force occurred at a cutting speed (v_c) of 1400 m/min, and v_c had a quadratic effect over F_u. Song et al. (2022a) proposed a mathematical model (composite light ropes) to estimate F_u. Considering the size effect between carbon fibers and cutting edge, the model showed excellent agreement with experimental data, with a maximum error of 8.3%. Song et al. (2022b) optimized the machined surface integrity based on specific cutting energy (SCE). A mathematical model was developed to predict SCE, closely approximating the practical results (maximum relative error of 7.6%). Liu et al. (2022) developed an efficient and low-surface-defect optimization method to analyze the thermal effect of cutting temperature during dry HSM. The authors concluded that temperature is mainly affected by v_c and carbon fibers' orientation.

Therefore, the present study aims to analyze comparatively the machining force (F_u) and average surface roughness (R_a) resulting from the front milling of PEEK and PEEK-CF30, which are relatively new and high-cost materials, aiming to generate data for future industrial/medical applications.

2. MATERIALS AND METHODS

The specimens used in this research were blocks with 61.5 x 41.0 x 26.6 mm in TECAPEEK MT natural and 46.5 x 46.6 x 31.4 mm in TECAPEEK MT CF30 (reinforced with 30% carbon fiber), both manufactured by Ensinger® Co. (Figure 1a). Dry front milling was performed in the ROMI® Discovery 308 machining center (maximum power of 5.5 kW and maximum spindle speed of 4000 rpm) using a Walter Tools® end mill cutter with a 20 mm diameter and 35 mm maximum projection length for two Walter Tools® PVD-TiAlN/Al_2O_3 coated carbide inserts with 0.8 mm tool-tip radius. Fig. 1b illustrates the experimental setup.



(a) (b)

Figure 1. (a) Images of specimens; (b) Experimental setup

Table 1 presents the variables and levels considered in this study, which were selected based on data found in the literature. The width of cut was kept constant (a_e = 11.5 mm). The Response Surface Methodology (RSM) with a 3-factor, 3-level Box-Behnken Design (BBD) was adopted to evaluate the effects of controllable input factors (cutting parameters) and their relationships with output response variables (machining force and average roughness). Table 2 shows the randomized combinations of parameters, highlighting the control runs.

The force signals in the three orthogonal directions (F_x, F_y, F_z) were acquired using the stationary piezoelectric dynamometer Kistler® 9272. The signal acquisition rate was set at 1.0 kS/s. Subsequently, the machining force (F_u) was calculated using Eq. (1). A sampling of 2.0 kS was considered within the stable machining region, excluding the entry and exit regions of the machined samples.

Table 1. Natural and coded levels of the BBD input parameters

Controllable Factors	Levels		
	Low (-1)	Medium (0)	High (+1)
v_c (m/min)	150	200	250
f_z (mm/tooth)	0.05	0.075	0.1
a_p (mm)	0.5	0.8	1.1

Table 2. Combinations of cutting parameters randomized by BBD

Run	v_c (m/min)	f_z (mm/tooth)	a_p (mm)
1	150	0.05	0.8
2	250	0.05	0.8
3	150	0.1	0.8
4	250	0.1	0.8
5*	200	0.075	0.8
6	250	0.075	0.5
7	150	0.075	1.1
8	250	0.075	1.1
9	200	0.05	0.5
10*	200	0.075	0.8
11	200	0.05	1.1
12	200	0.1	1.1
13	150	0.075	0.5
14	200	0.1	0.5
15*	200	0.075	0.8

*Central level runs defined by BBD from middle points

$$F_u = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

To assess the machined surface finish, the portable roughness tester Mitutoyo® SJ-201 was used to acquire the average surface roughness (R_a) values and roughness profile in triplicate. After machining, the samples' textures were examined through images captured by the Zeiss® Stemi 508 optical stereo microscope.

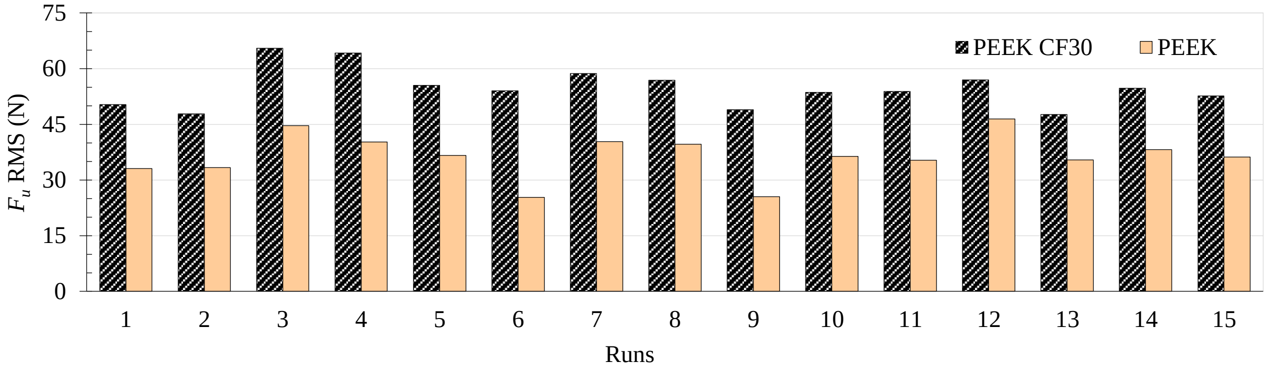
After the machining of samples, the collected machining force and average roughness values were statistically analyzed using empirical mathematical models and analysis of variance (ANOVA).

3. RESULTS AND DISCUSSIONS

3.1. Machining Force

Figure 2 shows the RMS values of machining force for each run from Tab. 2. During the milling of PEEK, runs 6 and 9 resulted in the lowest RMS values of F_u (about 25 N). In contrast, in the machining of PEEK-CF30, runs 2 and 13 generated the lowest values (approximately 48 N). It became evident that PEEK-CF30 exhibited higher machining forces than PEEK in all runs. The values were 34.9% higher on average because of the carbon reinforcement, which increases the material's hardness and strength (Zhu et al., 2020). It is worth noting that the highest value found was 65 N (run 3). This result is consistent with the studies conducted by Cao et al. (2021) and Song et al. (2022a), where similar force values were observed in the milling of PEEK-CF50. Besides, the repeatability of the process is evident when comparing the machining forces in the central level runs (5*, 10*, 15*), which exhibit minimal variations, indicating that the experimental procedure is appropriately adjusted and free from random errors.

To quantify the contribution of each controllable factor to the machining force result, Table 3 shows the reduced ANOVA for both materials, considering only significant values ($\alpha < 0.1$). The linear effects of feed per tooth (f_z) and depth of cut (a_p) contributed the most to the machining force. In PEEK, the cutting speed (v_c) and combined effect $v_c \times a_p$ influence the magnitude of F_u with a confidence interval above 98%. In PEEK-CF30, $v_c \times a_p$ affects F_u with a confidence interval of 93.3%. The contour plots (Fig. 3), with fixed values v_c = 200 m/min, f_z = 0.075 mm/tooth, a_p = 0.8 mm, confirm that higher values of f_z and a_p result in higher F_u. Additionally, higher v_c tends to reduce machining forces in the milling of PEEK while increasing F_u in the machining of PEEK-CF30.



Run	1	2	3	4	5*	6	7	8	9	10*	11	12	13	14	15*
v_c (m/min)	150	250	150	250	200	250	150	250	200	200	200	200	150	200	200
f_z (mm/tooth)	0.05	0.05	0.1	0.1	0.075	0.075	0.075	0.075	0.05	0.075	0.05	0.1	0.075	0.1	0.075
a_p (mm)	0.8	0.8	0.8	0.8	0.8	0.5	1.1	1.1	0.5	0.8	1.1	1.1	0.5	0.5	0.8

Figure 2. RMS machining force values produced by milling

Table 3. Reduced ANOVA for F_u ($\alpha < 0.1$)

Specimens	Variable	P-value	Contribution
PEEK	f_z	< 0.001	47.0%
	a_p	< 0.001	36.5%
	v_c	0.012	5.80%
	v_c x a_p	0.018	4.56%
PEEK-CF30	f_z	0.012	31.9%
	a_p	0.034	19.5%
	v_c x a_p	0.067	13.5%

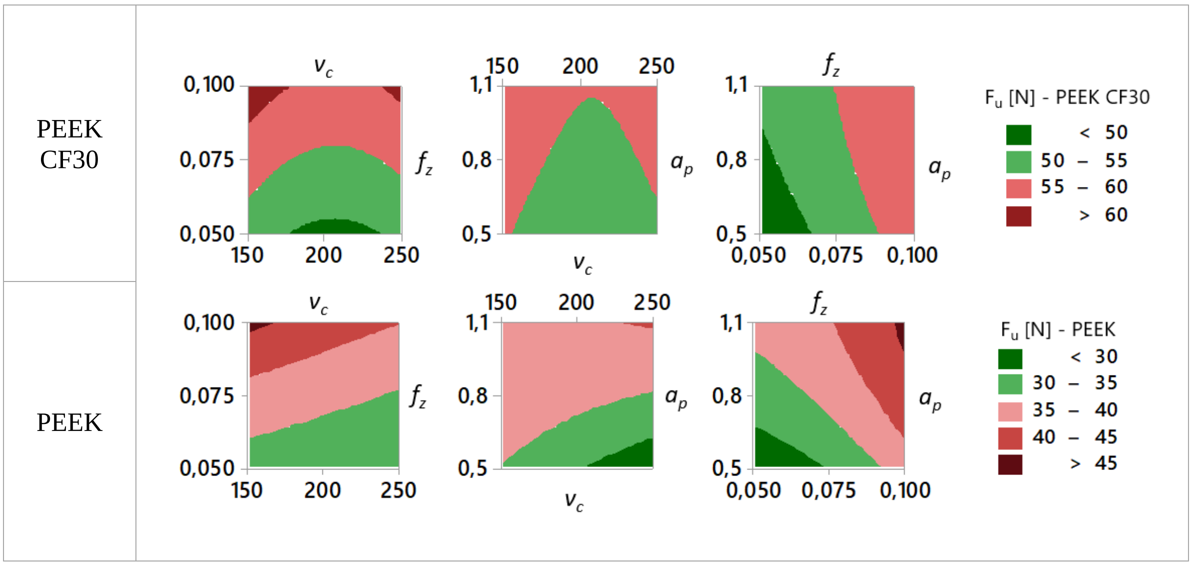


Figure 3. Contour plots for F_u

The complete second-order polynomial regression model of the machining force (F_u) resulted in a strong curve fit, with a coefficient of determination R^2 = 98% for PEEK (Eq. 2). In the case of PEEK-CF30, the best fit was achieved with a simplified second-order model, resulting in R^2 = 76% (Eq. 3).

$$F_u = 27.7 - 0.113\,v_c + 121\,f + 12.4\,a_p + 0.000051\,v_c^2 + 2102\,f^2 - 15.09\,a_p^2 - 0.921\,v_c{\cdot}f + 0.1555\,v_c{\cdot}a_p - 50.8\,f{\cdot}a_p \quad (2)$$

$$F_u = -\,24.3 + 0.275\,v_c - 386\,f + 124.7\,a_p + 3917\,f^2 - 31.1\,a_p^2 - 0.309\,v_c{\cdot}a_p \quad (3)$$

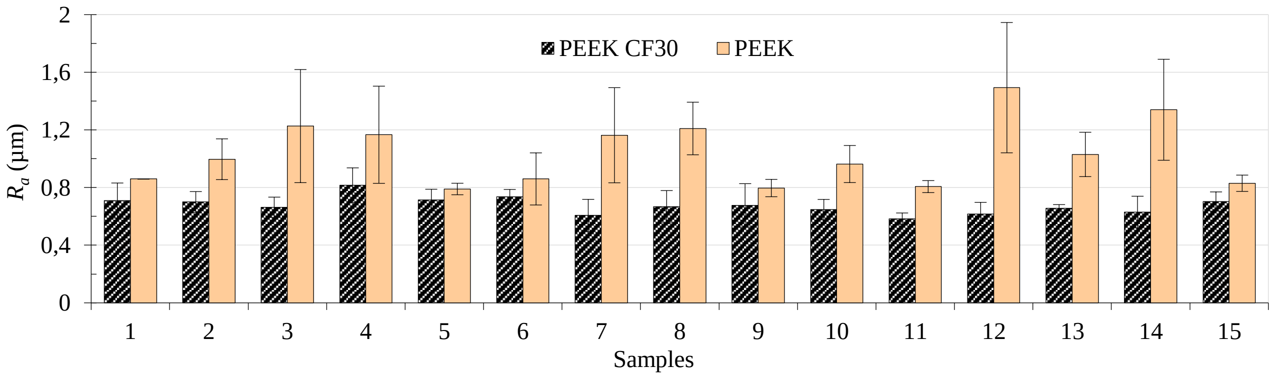
The optimized cutting parameters, aiming to minimize the machining force values (F_u), are shown in Table 4. For PEEK, the optimized combination with high v_c, low f_z and low a_p was not predicted in Tab. 2. However, run 6 (high v_c, medium f_z and low a_p) resulted in a F_u value close to the estimated one. In the case of PEEK-CF30, the optimization of F_u occurred at a set of levels very similar to run 9 (medium v_c, low f_z and low a_p); consequently, this similarity was confirmed in the estimated and measured results.

Table 4. Optimized results for F_u

Specimens	v_c (m/min)	f (mm/tooth)	a_p (mm)	F_u estimated (N)	F_u measured (N)
PEEK	250	0.05	0.5	23.1	25.3 (run 6)
PEEK CF30	209	0.05	0.5	46.2	47.7 (run 9)

3.2. Surface Roughness

Figure 4 shows the average surface roughness (R_a) values generated by different runs from Table 2. Contrary to what has been reported in the literature, the addition of CF to PEEK, under the employed machining conditions, resulted in decreased mean and standard deviation of the Ra values. The CF reinforcement increases the hardness and strength of PEEK, leading to greater material brittleness, which may have facilitated chip formation and its evacuation from the cutting zone. This behavior could have contributed to the generation of a better surface finish. For PEEK-CF30 milling, sample 11 exhibited the lowest R_a value (0.58 ± 0.04 µm). In PEEK machining, samples 9 and 11 showed the lowest R_a values (0.80 ± 0.06 µm and 0.81 ± 0.04 µm, respectively). Zhang et al. (2020) reported similar values to this study for PEEK-CF30 milling (R_a = 0.25 to 0.83 µm). The highest values were observed in sample 12 (R_a = 1.49 ± 0.45 µm) for PEEK and sample 4 (R_a = 0.82 ± 0.12 µm) for PEEK-CF30.



Sample	1	2	3	4	5*	6	7	8	9	10*	11	12	13	14	15*
v_c (m/min)	150	250	150	250	200	250	150	250	200	200	200	200	150	200	200
f_z (mm/tooth)	0.05	0.05	0.1	0.1	0.075	0.075	0.075	0.075	0.05	0.075	0.05	0.1	0.075	0.1	0.075
a_p (mm)	0.8	0.8	0.8	0.8	0.8	0.5	1.1	1.1	0.5	0.8	1.1	1.1	0.5	0.5	0.8

Figure 4. Average roughness measured after milling

Analyzing PEEK, samples machined with higher f_z (3, 4, 12, 14) produced higher R_a values. Samples 7 and 8 also resulted in high Ra values, indicating that a high a_p also affects the surface finish. Furthermore, run 7 (low v_c, medium f_z, high a_p) generated a sample with a higher deviation than run 8 (high v_c, medium f_z, high a_p), demonstrating that low v_c reduces the machined surface quality. Guo et al. (2021) found that an increase in a_p tends to cause an increase in R_a for PEEK; however, this trend did not apply to PEEK-CF10. In the present study, this was also observed since it was challenging to identify the best and worst surface finishes for PEEK-CF30. There were no difficulties in generating low roughness values (considering the parameter variations within the studied ranges), as all measured R_a values remained below 1.0 µm. Zhang et al. (2020) noted that feed rate (v_f) was the most influential factor on roughness in PEEK-CF30 milling, followed by rotation speed (n); in this case, a_p did not significantly modify R_a.

Figure 5 shows the roughness profiles for the samples with the highest and lowest roughness for both materials. For PEEK, there is a significant difference in the roughness profiles produced by run 12 (higher f_z) and run 11 (lower f_z). Sample 12 exhibits numerous peaks and valleys ranging from 2 to 6 µm, while sample 11 has only a few peaks and valleys exceeding 2 µm, resulting in a more uniform and stable profile. According to the images, sample 12 shows machining marks and small portions of material being torn from the surface, whereas sample 11 exhibits a visible improvement in the machined surface.

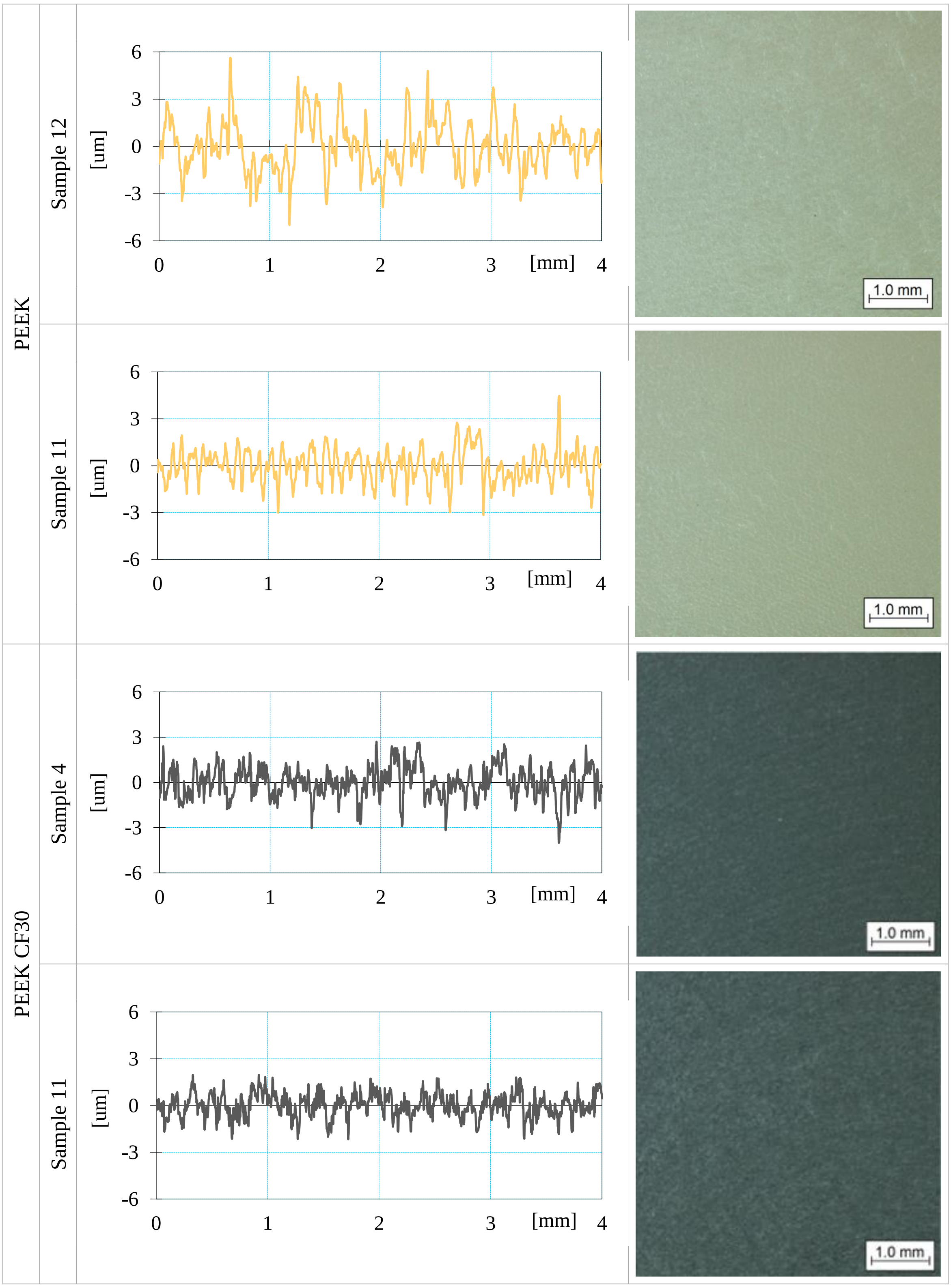


Figure 5. Roughness profiles and images of textures for samples with the best and the worst surface qualities.

In contrast, the differences in the roughness profiles on the PEEK-CF30 samples generated by run 4 (higher v_c, higher f_z, and medium a_p) and run 11 (medium v_c, lower f_z, and higher a_p) are very slight. In sample 4, only a few peaks and valleys exceeded 2 µm, while in sample 11, the profile remained within the range of ±2 µm. The images of sample 4 show visible tool marks, different from sample 11, where these marks are not as clearly observable. As aforementioned, the samples generated in PEEK-CF30 had low roughness values for all combinations (R_a < 1.0 µm), which is evident when comparing the roughness profiles. These results obtained for PEEK-CF30 align with Zhang et al. (2020), where similar roughness profiles and values were found.

Aiming to quantify the contribution of each controllable factor on the average roughness (R_a), Table 5 presents the reduced ANOVA for both materials, considering only the significant values ($\alpha < 0.1$). The feed per tooth (f_z) was the only significant variable in the analysis of R_a for PEEK (57% of contribution over R_a). On the other hand, f_z significantly affected the surface roughness obtained by milling PEEK-CF30 only when combined with cutting speed (v_c). Besides, the addition of carbon fiber resulted in significant linear and quadratic effects from the cutting speed (v_c) and depth of cut (a_p), with high contributions from a_p^2 (26.4%) and v_c (21%) in R_a values.

Table 5. Reduced ANOVA for R_a

Specimens	Variable	P-value	Contribution
PEEK	f_z	0.006	57.1%
PEEK-CF30	v_c	0.013	21.0%
	a_p	0.029	13.4%
	v_c^2	0.042	13.6%
	a_p^2	0.008	26.4%
	v_c x f_z	0.027	13.9%

Figure 6 shows the contour plots for the average roughness in both specimens. The best results (low Ra) tend to be generated in the milling of PEEK with medium v_c, low f_z, and medium a_p. In PEEK-CF30, it is suggested to apply medium v_c, low f_z, and high a_p. In both cases, the recommended feed per tooth is the lowest value, whereas this is the main cutting parameter affecting the surface roughness. The variation in a_p did not generate significant changes in the R_a values on PEEK samples; however, for machining PEEK-CF30, higher a_p values lead to a better surface finish. Medium v_c (200 m/min) is recommended, like Zhang et al. (2020), where the optimal value was v_c = 150 m/min.

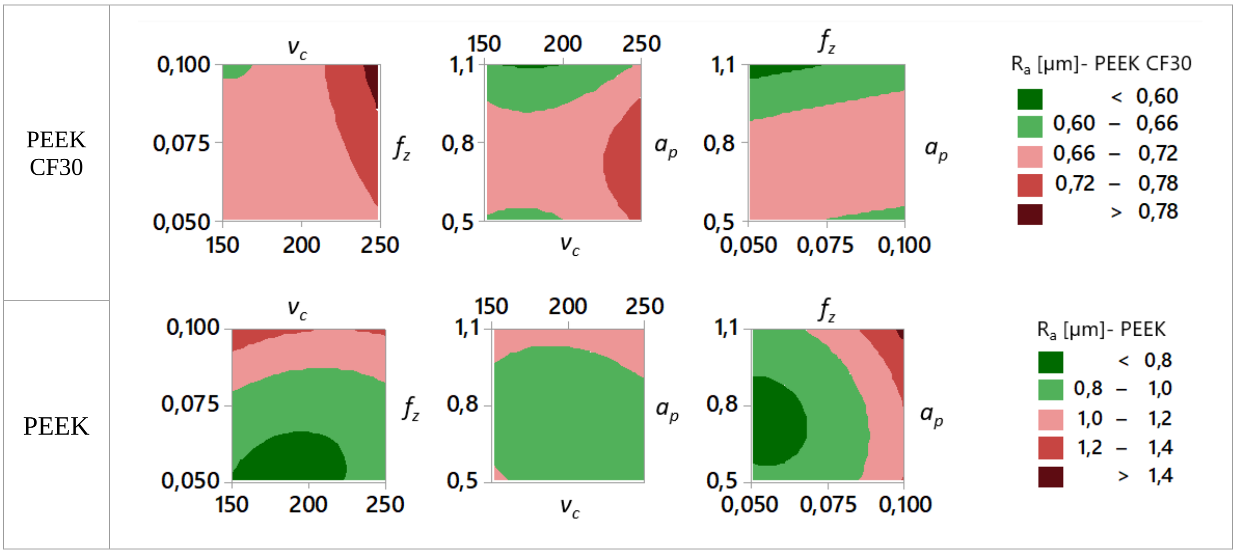


Figure 6. Contour plots for R_a

The polynomial regression model of the average roughness (R_a) indicates that a complete second-order model resulted in a suitable curve fit, with a coefficient of determination R^2 = 86.2% for PEEK (Eq. 4). Considering PEEK-CF30, the best fit was also achieved with a complete second-order model, resulting in R^2 = 92.7% (Eq. 5).

$$R_a = 3.54 - 0.0127\,v_c - 16.5\,f - 3.05\,a_p + 0.000032\,v_c^2 + 196\,f^2 + 1.397\,a_p^2 - 0.0393\,v_c \cdot f + 0.00361\,v_c \cdot a_p + 4.78\,f \cdot a_p \qquad (4)$$

$$R_a = 1.355 - 0.00745\,v_c - 7.75\,f + 0.812\,a_p + 0.000015\,v_c^2 - 4.2\,f^2 - 0.650\,a_p^2 + 0.0327\,v_c \cdot f - 0.000333\,v_c \cdot a_p + 2.67\,f \cdot a_p \qquad (5)$$

Table 6 shows the optimized cutting parameters that minimize the average roughness values. The estimated parameters for the milling of PEEK are very close to those of run 9 (medium v_c, low f_z and medium a_p), whose sample presented a similar R_a value to sample 11 (best surface finish). Regarding PEEK-CF30, the optimized values essentially configure run 11 (medium v_c, low f_z and high a_p), which generated the best result in the experimentation. Abdullah et al. (2014) estimated, using a regression model (R^2 = 89.84%), the lowest value of average roughness (R_a = 0.81 µm) using high spindle speed (n = 5754 rpm), low feed per tooth (f_z = 0.026 mm/tooth), and high depth of cut (a_p = 5.11 mm) in the face milling of TECAPEEK MT natural.

Table 6. Optimized results for R_a

Specimens	v_c (m/min)	f (mm/tooth)	a_p (mm)	R_a estimated (µm)	R_a measured (µm)
PEEK	199	0.05	0.7	0.78	0.80 ± 0.06 (sample 9)
PEEK CF30	195	0.05	1.1	0.58	0.58 ± 0.04 (sample 11)

Given the proximity of the input parameter levels suggested by the model and the combinations tested aiming for lower R_a, validation tests were not performed, as the adequacy of the model to the experimental values was proven since the experimental roughness values were very close to those indicated by the optimization model.

4. CONCLUSIONS

A preliminary study evaluating the cutting force (F_u) and average roughness (R_a) in dry front milling of Ensinger® TECAPEEK MT natural and TECAPEEK MT CF30 was conducted by varying cutting speed (v_c), feed per tooth (f_z) and depth of cut (a_p). Based on the results obtained, the following conclusions can be defined:

- In all machined samples, the RMS values of cutting force (F_u) generated in the milling of PEEK-CF30 were higher than 47.8 N. In comparison, the values produced by machining of PEEK were lower than 46.5 N due to the presence of carbon fiber (CF) reinforcements. For both specimens, considering a confidence interval higher than 96.5%, the variables that contributed the most to the magnitude of F_u were f_z and a_p, with 47.0% and 36.5% for PEEK, and 31.9% and 19.5% for PEEK-CF30, respectively. Additionally, the combination of $v_c \times a_p$ contributed 13.5% to PEEK-CF30 within a confidence interval of 93.3%.
- The coefficients of determination (R^2) for the second-order polynomial regression models of cutting force (F_u) were 98% for PEEK and 76% for PEEK-CF30. The optimized parameters for PEEK (v_c = 250 m/min, f_z = 0.05 mm/tooth, a_p = 0.5 mm) resulted in F_u = 23.1 N, while for PEEK-CF30 (v_c = 209 m/min, f_z = 0.05 mm/tooth, a_p = 0.5 mm), F_u = 46.2 N.
- Unlike verified in the literature, in all machined samples, the mean values of R_a were lower than 0.8 µm with low standard deviations for the PEEK-CF30 surfaces and higher than 0.8 µm with high standard deviations for the PEEK surfaces. The only significant variable for PEEK was f_z, with a contribution of 57.1%. For PEEK-CF30, a_p^2 (26.4%), v_c (21.0%), $v_c \times f_z$ (13.9%), v_c^2 (13.6%), and a_p (13.4%) were the most influential factors over R_a.
- The polynomial regression models for R_a had R^2 = 86.2% for PEEK and R^2 = 92.7% for PEEK-CF30. The optimized parameters for PEEK (v_c = 199 m/min, f_z = 0.05 mm/tooth, a_p = 0.7 mm) resulted in R_a = 0.78 µm, while for PEEK-CF30 (v_c = 195 m/min, f_z = 0.05 mm/tooth, a_p = 1.1 mm), R_a = 0.58 µm.

Finally, within the range of analyzed cutting parameters, the results indicated that adding CF to PEEK increased machining force during dry face milling because the reinforcement increases the PEEK's hardness and strength. In contrast, the CF added in PEEK promoted a decrease in surface roughness values. This reinforcement can have grown the composite brittleness, facilitating chip formation and its evacuation from the cutting zone, and enhancing the surface quality.

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