EFFECTS OF VORTEX-COOLED COMPRESSED AIR ON SURFACE QUALITY IN END-MILLING CFRP

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Abstract. *The use of CFRP (carbon fiber reinforced plastics) has grown in the aeronautical and automotive industry due to its excellent properties. As a new relative material, it still lacks information regarding its behavior in machining, particularly milling. Thus, this work presents the evaluation of cutting parameters in end-milling CFRP with a carbide end-mill tool aiming to generate a better surface finish. The experiments were designed using three-factor, three-level Box-Behnken Design considering feed rate (f), axial depth of cut (a_p), and cooling conditions (cc) as controllable variables, whereas roughness parameter R_a as a response variable. The results showed that the most significant parameters on the R_a values were the quadratic effect of axial depth of cut (a_p^2) and its effect combined with feed rate (a_p x f) and with the cooling condition (a_p x cc). Therefore, the optimized levels of input parameters were f = 0.21 mm/rev and a_p = 0.8 mm with vortex-cooled compressed air end-milling.*

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) is a composite material often used in several areas such as aerospace, military, automotive, construction, wind turbines, motorcycles, bicycles, sports, and home appliances due to its valuable properties as low density, high resistance, high rigidity, and high corrosion resistance [1]. Components of CFRP are generally manufactured close to their liquid form by the molding method. However, it is common to apply a second machining process such as milling or drilling to reach the desired dimensions and tolerances [2].

Despite the recent increase in its application, milling CFRP continues to be a manufacturing process that generates various defects on the material surface, which delamination being the critical failure mechanism occurring in the process [3, 4]. Furthermore, fiber pull-out and the matrix loss can also be highlighted as surface defects generated in the process that cause, in some cases, a component rejection [2, 5]. Moreover, another problem caused is the high tool wear rate due to the low thermal conductivity and the material's abrasive nature. Chips and fibers of CFRP act like abrasive particles during the cutting process. Thus, the continuous friction with the cutting tool generates abrasive wear [6]. These phenomena deteriorate the material's surface quality during milling and decrease productivity due to cutting tool change times, thereby increasing production costs. Reducing tool wear and improving surface finish when machining CFRP are the main goals of diverse researchers [1].

Nor Khairusshima & Sharifah [7] concluded that the cooling method is a variable affecting the machining CFRP and the tool's life is longer with chilled air machining (9.29 min) compared with dry machining (6.54 min). Lower tool life was observed in high cutting speed (v_c) due to the high heat generated. High feed per tooth (f_z) influenced the cutting stability because of high vibration, causing more tool failures and a worse surface finish.

Yalçin et al. [8] and Nor Khairusshima et al. [9] concluded that roughness values generated in air-cooled milling are lower than in dry milling. Pecat et al. [10] evaluated the surface finish based on the CFRP micrograph's milled surface. A severe change in the subsurface region was observed at working temperatures of 120ºC, indicating cracks by the thermal damages. They concluded that 80ºC is the ideal temperature in milling CFRP (below the vitreous transition point of epoxy resin) when the best cutting force results are found. Wang et al. [11] concluded that the matrix resin support for the fibers is unsuitable when the cutting temperature exceeds the glass transition temperature, which causes a low surface quality in the CFRP. Consequently, the temperature significantly influences the surface quality.

Some studies showed the influence of axial depth of cut (a_p) on the surface roughness after machining fiber-reinforced plastics. Zhou et al. [12] found that a_p is the most significant factor in surface roughness, and its increase worsens the CFRP machined surface quality. According to the authors, the multiple layers of epoxy resin are hard to remove, which can adhere to the machined surface due to the combined effect of force and heat generated by the cutting tool's action. Gao et al. [13] also observed that the increase in a_p during the machining CFRP grows the cutting forces and negatively affects the surface roughness. Furthermore, the material's cutting occurs with the fiber's detachment and folding until it ruptures, forming a chip. The process repeats itself, generating a surface texture formed by exposed fibers and resin ridges, being able to have separations of the fibers and resin.

Thus, it is intended to analyze the influence of different axial cutting depths (0.6, 1.0, and 1.4 mm), feed rates (0.07, 0.14, and 0.21 mm/rev), and cooling conditions (dry, compressed air, and vortex-cooled compressed air) on surface finish generated by end-milling CFRP.

2. MATERIALS AND METHODS

The CFRP workpiece is a carbon fiber reinforced polymer matrix plate formed by 38 layers of pre-impregnated carbon epoxy bidirectional sheets of about 0.2 mm thick each, with 0/90º fiber orientations. The final plate's thickness is 8.7 ± 0.3 mm (variation due to the manufacturing process). This variation caused changes in the axial depth of cut (a_p). Thus, the $a_{p\text{-}T}$ (intended theoric value) and the $a_{p\text{-}R}$ (measured real value) were defined. The experimental procedure was performed at a CNC ROMI Discovery 308 machining center, according to Fig. 1, using a 10 mm diameter Kennametal uncoated solid carbide end mill with four teeth and a 30º helix angle. The cutting speed (v_c) was kept constant (120 m/min) due to spindle speed limitation (4000 rpm maximum). The cooling conditions (*cc*) used were dry cutting (DRY), regular compressed air (AIR) at 17°C, and vortex-cooled compressed air (VCCA) at 6°C. The compressed-air line pressure was 300 kPa for both conditions.

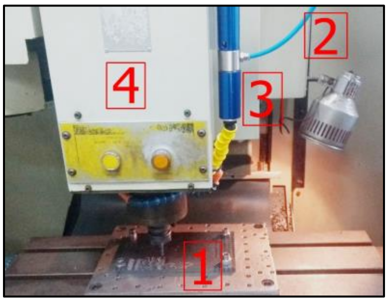


Figure 1 – Experimental setup: [1] CFRP's plate; [2] Compressed-air line; [3] Vortex tube; [4] Machining center.

The Box-Behnken design of experiments (BBD) was carried out to understand the influence of control factors (input machining parameters) on the response variable (surface roughness) generated by end-milling CFRP. BBD is a statistical optimization method that aims to work simultaneously in obtaining the best levels in a set of factors that exert influence on a specific process. Then, three factors were varied in three levels according to Tab. 1.

Table 1 – Controllable factors and levels used in BBD.

Controllable Factors	Notation	Unit	Levels		
			Low (–1)	Medium (0)	High (+1)
Axial depth of cut (theoric)	$a_{p\text{-}T}$	mm	0.6	1.0	1.4
Feed rate	f	mm/rev.	0.07	0.14	0.21
Cooling conditions	cc	–	DRY	AIR	VCCA

Surface roughness parameter R_a (average roughness generated by end-milling CFRP was acquired through the Mitutoyo SJ-201P stylus profilometer with a resolution of 0.01 µm. A sampling length of 2.5 mm and an evaluation length of 12.5 mm were considered in these measurements, according to DIN EN ISO 4288. Each machined surface was measured at least in three points of the sample. Lastly, the arithmetic means of these acquired values were calculated. Furthermore, images by a scanning electron microscope (SEM) Zeiss Evo Ma10 were collected to analyze the machined surface.

The combinations of control variables (f, a_p, and cc) used in the BBD experimental design were defined in Tab. 2. A reduced variance analysis (r-ANOVA) model was carried out using the Minitab®19 software to quantify each factor's linear and quadratic effects and their interactions on the response variable (R_a). A 95% confidence interval was considered (p-value ≤ 0.05). So, the factor with a higher p-value was eliminated to perform the r-ANOVA. After eliminating it, a new analysis and a new elimination of the factor with a higher p-value were made, repeating the process until all were below 5% (to ensure a 95% confidence interval) or until it reaches the coefficient of determination R^2 > 70%.

After the statistical processing of all information, the input parameters optimization was also performed by BBD via Minitab®19.

3. RESULTS AND DISCUSSIONS

Table 2 shows the arithmetic means of R_a values. When comparing samples 1 and 8 (f = 0.21 mm/rev; AIR condition), the R_a values grew up about 600% with the $a_{p\text{-}R}$ (the real value of a_p) increases from 0.28 to 1.65 µm, confirming the influence of axial depth of cut (a_p) to raise roughness values for high feed rates (f). Other authors had similar results [11-13].

Table 2 – Mean R_a and R_z values obtained after end-milling CFRP.

Run	f (mm/rev)	$a_{p\text{-}T}$ (mm)	$a_{p\text{-}R}$ (mm)	cc	R_a (µm)
1	0.21	0.6	0.28	AIR	0.96
2	0.14	1.0	0.74	AIR	2.52
3	0.07	1.0	0.86	VCCA	1.68
4	0.14	0.6	0.52	VCCA	1.93
5	0.21	1.0	1.01	VCCA	1.83
6	0.07	0.6	0.70	AIR	2.20
7	0.14	0.6	0.77	DRY	1.75
8	0.21	1.4	1.65	AIR	4.50
9	0.07	1.4	1.72	AIR	2.27
10	0.21	1.0	1.44	DRY	2.05
11	0.14	1.4	1.73	VCCA	3.37
12	0.14	1.4	1.80	DRY	1.75
13	0.07	1.0	0.80	DRY	1.49
14	0.14	1.0	0.90	AIR	2.39
15	0.14	1.0	0.95	AIR	1.85

Table 3 presents the r-ANOVA of R_a values for a 95% confidence interval. The results show that the quadratic effect of axial depth of cut (a_p^2) and its combined effect with feed rate ($f \times a_p$) are the most significant factors for R_a (contributions close to 30%). The combined effect $a_p \times cc$ also stands out, making a significant factor on R_a (19.2% of the contribution). The linear effect of feed rate and the quadratic effect of cooling conditions (cc^2) are also significant factors, but with a minor contribution.

Table 3 – Reduced ANOVA (P critical value = 0.05).

Controllable Factors	R_a (R^2 = 87.74%)	
	P-value	Contribution
f	0.007	3.66%
a_p^2	0.001	25.98%
cc^2	0.007	8.82%
f x a_p	0.001	30.07%
a_p x cc	0.005	19.21%

Figure 2 presents the 3D surface plots of R_a. It is observed that the plots for both response variables follow the same growth pattern for all controllable factors (f, a_p, cc). Values of a_{p-R} low (0.3 to 0.8 mm), middle (0.8 to 1.4 mm), and high (1.4 to 1.8 mm) were considered. For low a_{p-R}, increasing f reduced the R_a values (samples 6 and 1) by about 55% (from 2.20 µm to 0.96 µm). The increase in f (samples 9 and 8) doubled the R_a value (from 2.27 to 4.5 µm) about high a_{p-R}. A similar result was found by Kiliçkap et al. [14].

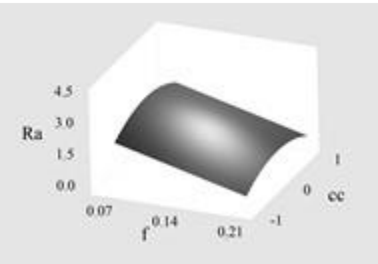
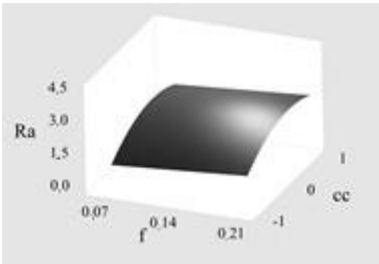
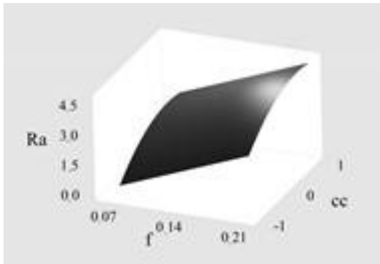
a_{p-R} = 0.4 mm	a_{p-R} = 1.1 mm	a_{p-R} = 1.8 mm
		

Figure 2 – Surface plots of R_a values according to a_{p-R}.

There is an inflection point for a_p at which the f value changes the average roughness values differently for each extremity. Below the a_p = 0.8 mm (Fig. 3), the increasing f reduces the R_a values; above this a_p, the growing f increases these R_a values. Otherwise, when used low feed rate (f = 0.07 mm/rev.) and AIR milling (samples 6 and 9), the increase of a_p affected the R_a values (from 2.20 to 2.27 µm) shallowly.

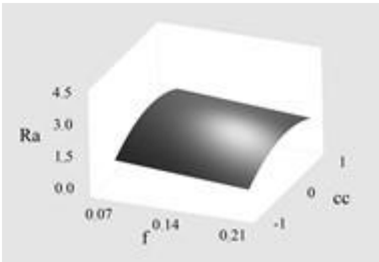


Figure 3 – Inflection point of R_a (a_p = 0.80 mm).

Analyzing samples 2 and 7 (f = 0.14 mm/rev and $a_{p\text{-}R} \cong 0.75$ mm) in which the cooling condition is changed from DRY to AIR, there is an increase in R_a values (from 1.75 to 2.52 µm). However, the R_a on samples 11 and 12 (f = 0.14 mm/rev and $a_{p\text{-}R} \cong 1.75$ mm) growth when changing from DRY to VCCA (R_a from 1.75 to 3.37 µm). Therefore, the cooling by compressed air (AIR and VCCA) was insufficient in extracting the heat generated from the cutting zone when a_p rises, growing R_a. This effect increases the temperatures, the tool wear and reduces the matrix resin's support for the fibers [6, 8, 9, 12, 13].

Figure 4 shows the machined surface profiles and images of samples 1 and 8 (f = 0.21 mm/rev and AIR) in which only $a_{p\text{-}R}$ was changed (0.28 mm and 1.65 mm, respectively). The roughness profile of sample 1 (Fig. 4a) is constant, with relatively low peaks and valleys (± 3 µm) and a low average value ($R_a \cong 1$ µm) precisely because the generated surface has homogeneous and non-fractures carbon fibers, without apparent fiber pull-outs. However, the roughness profile of sample 8 (Fig. 4b) is very irregular, with high peaks and valleys (± 18 µm), noted by Gao et al. [13] as well. High average value ($R_a \cong 4$ µm) was also observed, defined by the fracture of carbon fibers and the resin exposure after machining with $a_{p\text{-}R}$ = 1.65 mm. Nor Khairusshima [7] detected higher thermal stress when increasing a_p, obtaining worse surface quality.

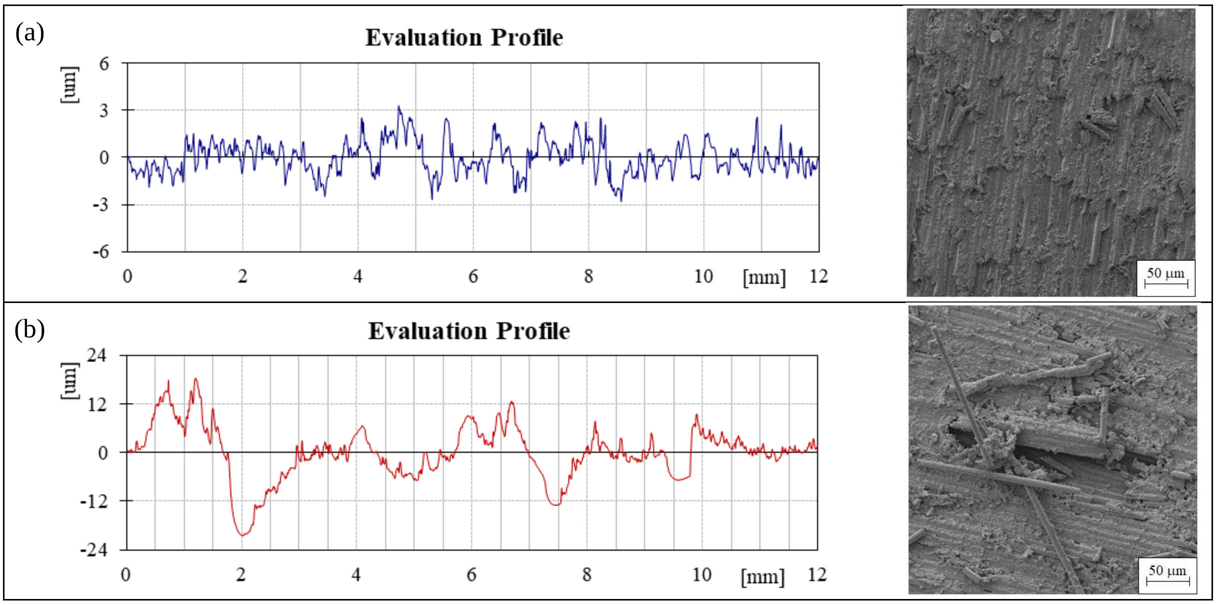


Figure 4 – Roughness profiles and SEM images (500x magnification): (a) sample 1; (b) sample 8.

Gao et al. [13] explain that the fiber and matrix separate from each other due to the interphasic disconnection caused by the tool when it enters the workpiece at the 0° angle. The separation is propagated with f that causes bending and compression stress in the fiber and matrix until the fiber reaches a critical length, and its rupture happens at an angle close to 90°, exposing the resin.

Finally, the BBD optimized the control variables from r-ANOVA, finding $a_{p\text{-}T}$ = 0.6 mm, f = 0.21 mm/rev, and VCCA condition.

4. CONCLUSIONS

Conclusions regarding the surface quality after end-milling CFRP were the following:

- The quadratic effect of axial depth of cut (a_p^2) and its combined effect with feed rate ($f \times a_p$) and cooling conditions ($a_p \times cc$) were the most significant factors on the surface roughness. Together, they had a contribution of 75% on R_a.
- There is an inflection point at a_p = 0.8 mm, which f does not influence the R_a values. When a_p < 0.8 mm, R_a decreases with increasing f; but, for a_p > 0.8 mm, R_a values grow with increasing f.
- Considering f = 0.07 mm/rev and AIR, a_p did not significantly affect the R_a values.

- High a_p in DRY milling resulted in lower roughness values than AIR and VCCA milling, while low a_p in AIR milling generated the highest R_a value.
- The strong influence of a_p in CFRP machined surface is related to the carbon fiber fracture and the resin exposure that generate irregularities, fiber pull-outs, cracks, and low quality.
- The controllable factors optimization via BBD found f = 0.21 mm/rev and a_p = 0.6 mm with VCCA.

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