



Study of milling of low thickness thermoplastic carbon fiber composites in function of tool geometry and cutting conditions

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Abstract

The application of carbon fiber reinforced thermoplastic matrix composites (CFRTP) is constantly increasing in various industrial sectors due to their mechanical properties and advantages compared to thermoset matrix composite. Nevertheless, CFRTP machining generates a current problem due to the anisotropy of these materials, the difficulty of impregnation of the reinforcement in the matrix, and its low melting temperature. For this reason, the study of conventional operations such as milling to achieve geometries with a good surface quality and reduced cosmetic defects is a line of research of great interest. In this article, a comparison of five cutting tools with different geometries has been made in CFRTP milling. The surface quality and the formation of visual defects such as fiber pull-out have been evaluated for each tool and combination of cutting parameters. In this sense, 16.42 μm in terms of Rz is the minimum average value for the complete experiment obtained for a conventional tool (tool A). However, surface qualities in terms of Rz close to 20 μm and minimum cosmetic defects have been obtained with a hybrid tool (tool C) with -10° helix angle and 8 teeth with a combination of cutting parameters of 0.07 mm/tooth and 3000 rpm, being the most complete tool of the experiment.

Keywords Milling · CFRTP · Surface quality · Rz · Fiber pull-out · C/TPU

1 Introduction

The advantages and applications of thermoset matrix composite materials in various sectors are well known, especially in the aeronautical sector [3, 11, 15].

Alongside these materials, the use of composite materials reinforced with carbon fiber and thermoplastic matrix (CFRTP) is beginning to generate interest [20]. These maintain the excellent weight to mechanical properties ratio of thermosets. In addition, they can achieve higher impact resistance and faster processing times [10, 37].

These characteristics make them strategic materials in various sectors, especially in the automotive industry, due to the fact that they are materials that can be manufactured in mass [14]. Sectors such as the sports and marine industries are also beginning to apply these materials to various components [2]. In addition, this composite is stacked with metal alloys such as steel, in order to improve their functional performance [4].

Nevertheless, in order to achieve their purpose, these materials must be machined to adopt a specific geometry in the shortest possible production time to reduce costs [20].

Due to the abrasive nature of the reinforcement and the low cohesion between filaments and matrix due to the low viscosity of the thermoplastic material can generate great difficulties in the machining of these materials [1].

Also, the characteristic anisotropy of these materials means that each orientation of the material behaves differently when using cutting geometries, which can lead to defects such as

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delamination or low surface quality [29]. This in combination with the temperatures generated in the machining of these materials makes it necessary to study in detail machining operations that can correctly machine these materials [16].

An operation widely used in the machining of composite materials and of great interest is milling [12, 22]. It is a fast and flexible operation, which allows the reduction of operation times and the possibility of using many cutting geometries according to the needs, even machining several materials in the form of a stack at the same time [30, 31].

However, due to the characteristics of CFRTP, the milling of these materials can generate a poor surface finish due to possible losses of thermoplastic matrix or that the cutting edges do not completely cut the filaments depending on the cutting orientation [20]. Turki et al. [28] have studied the mechanisms that control the drilling of carbon and epoxy composites using orthogonal cutting. The results of their paper indicate that the orientation of carbon fibers plays an important role in the machining results and the mechanisms of shearing, bending, and matrix detachment. Furthermore, the correct selection of parameters has a direct influence on the surface quality obtained, resulting in scrapped parts [29].

For this reason, the search for specific cutting geometries for thermoset and thermoplastic composites is a line of great interest in current research. A comparison of tools for CFRTP milling was made by Masek et al. [19] in which they modified the feed rate per tooth, the cutting speed, and the machining depth. In their study, they indicate the need to use cutting tools with positive inclination angles in combination with a compression helix to obtain the best results. This is in line with the results obtained for Voss et al. [29] in milling CFRP, where positive rake angles allow easier chip evacuation producing smoother surfaces. Xu et al. [33] in their article point out how the machining of CFRP in the form of drilling produces thermal and mechanical damage to the machined wall surfaces in the form of delamination of the interface, cracks, cavities, and chip adhesion.

On the other hand, there is a direct relationship between the surface quality obtained and the parameters established in the machining of composite materials. The increase in feed rate produces an increase in the cutting forces which indicates greater abrasive wear on the cutting edges [27]. This, depending on the orientation of the carbon fibers and the cutting geometry, reduces the cutting capacity of the tools producing rougher surfaces and an increase in delaminations [29].

In milling, high cutting speed values increase the cutting capacity of the cutting edges allowing the cutting geometries to minimize delaminations that occur at angles of 135° and 45° [9, 17].

Nevertheless, there seems to be little information about the influence of cutting parameters and the selection of suitable cutting geometries for the milling of thermoplastic composites. The anisotropy of these materials and the possible loss of

matrix due to the temperatures reached as a function of the established parameters can generate a poor surface quality. Xu et al. [34] in their article specify how a decrease in cutting speed implies a lower process temperature, resulting in more consistent machining. In addition, Xu et al. [35] in other research suggest that low feed rates for machining polymer composites with thermoset resin mean lower process temperature and lower internal delaminations.

Another factor to take into account in machining processes such as milling is the effect of temperature on the matrix used in the composite. Xu et al. [36] explain how the thermoplastic resin used in their machining (PEEK) has a high degree of ductility and tends to deform plastically during the process, as the machining temperature exceeds the glass transition temperature of the material. In addition, Khanna et al. [18] in their article specify how the inclusion of cryogenic cooling in the machining of CFRP can lower the temperature and thus lead to better results. In this sense, Khanna et al. obtain better surface qualities as well as a lower number of delaminations on the surface of the material.

For these reasons, this article proposes a parametric and comparative study of five cutting tools of different geometry. For this purpose, for each tool, the feed rate per tooth and the cutting speed will be modified in order to establish a relationship between the surface quality in terms of Rz, the cutting parameters, and the selected geometry. Finally, the most suitable cutting geometry will be identified, as well as the range of cutting parameters that optimize the surface quality in the machining of thermoplastic composite materials.

2 Materials and methods

To carry out the experiments, carbon fiber has been used as a reinforcement and thermoplastic resin as a matrix to make the CFRTP composite. The composite material has been manufactured to achieve a final thickness of 2.08 mm. Table 1 shows the main characteristics of the material, as well

Table 1 Fiber, matrix, and CFRTP characteristics

Reinforcement	Fiber type	Twill 200 g/m ²
	Fiber thickness	0.25 mm
Matrix	Resin type	TPU (polyurethane)
	Melting temperature	145 °C
CFRTP	Ply orientation	(0°/90°)s
	Number of plies	7
	Composite thickness (t)	2.08 mm
	Fiber/matrix (%)	74.2/25.8
	Tensile strength (Mpa)	754
	Young modulus (Gpa)	23.4
	ILSS (Mpa)	8.1

as some interesting properties of the reinforcement and the matrix, respectively.

For the development of this research, different tool geometries have been considered according to the material to be machined, its thickness, and the cutting conditions. In addition, these tools have been recommended by the manufacturer for machining thermoplastic composites.

In this way, five tools of 6 mm diameter each with different number of teeth have been used to evaluate the effect of cutting geometry on the tests performed. Table 2 shows the main characteristics of each of the tools used. For convenience, and in order to identify them more easily, they have been designated with the letters A–E. In addition, images of the tools will be placed throughout the manuscript to make the reading easier. Figure 1 shows a macrograph of each tool together with its designation.

A 5-axis CNC machine (Kondia Five 400, Elgoibar, Guipúzcoa, Spain) has been used to perform the tests. In this experiment, it has been necessary to use only 3 of the 5 axes of the machine: *X*, *Y*, and *Z* axis. Three spindle speeds (*S*, rpm) and two feed rates per tooth (*fz*, mm/tooth) have been combined to obtain a combination of six trials. The set values for the cutting parameters have been defined on the basis of other studies and real application cases, and are indicated in Table 3. Each test is performed in the absence of lubricant due to the improved cutting conditions of composites.

Each trial will have a machining length of 50 mm. On the other hand, only the central 30 mm will be analyzed, in order to eliminate the input and output of tool in composite. To ensure a homogeneous cut, each tool is placed 3 mm below the lower face of material. A clamp applies pressure to the material to keep it fixed, leaving a gap of 10 mm between sides (Fig. 2).

After machining the slots, a rugosimeter (Mahr Perthometer, PGK 120, Göttingen, Germany) has been used to measure the final surface quality. For this purpose, the average of the absolute values of the five highest peaks and the five lowest valleys has been measured in terms of *Rz*. The measurements have been taken on both sides of the slot, i.e., in the direction of machining, up-milling (left side of slot, in accordance with cutting direction), and against, down-milling (right side of slot, in opposition of cutting direction). In order to verify the values calculated, 6 measurements have been taken on each side of the slot at different points on its surface (Fig. 3).

A typical defect in the machining of composite materials is the generation of fiber pull-out. In this article, it has been carried out an analysis of the fiber pull-out generated in the cuts according to each tool. For this purpose, a stereoscopic microscope (Nikon, SMZ 800, Tokyo, Japan) has been employed in order to obtain macrographies of the sections where a major fiber pull-out appears.

3 Results

3.1 Machining strategy analysis

Table 4 shows the average values of *Rz* together with their deviations. It can be seen how the *Rz* values obtained for up-milling and down-milling appear in different columns. In general, it can be noted that the values achieved with down-milling strategy are much higher than those of up-milling. This makes sense because in opposition, there is a minor force when the tool tooth hits the material. This phenomenon in metal

Table 2 Properties of tools employed in this experiment

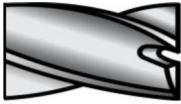
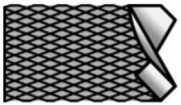



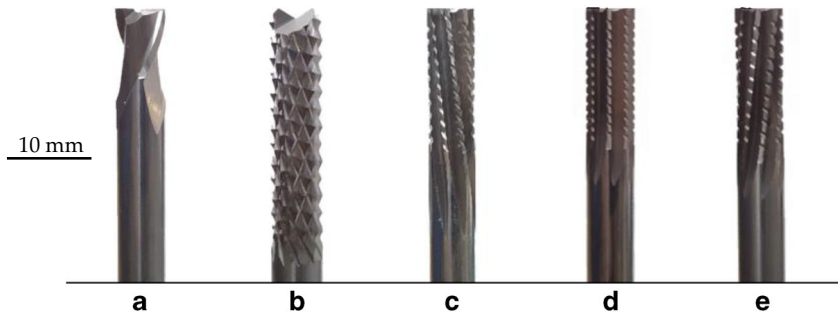
Designation	Material	Diameter	N° of teeth (<i>z</i>)	Geometry	
A	Tungsten Carbide Cobalt (WC-Co), non-coated	6 mm	2	Helix angle 30°	
B	Tungsten Carbide Cobalt (WC-Co), non-coated	6 mm	11	-	
C	Tungsten Carbide Cobalt (WC-Co), diamond coated	6 mm	8	Helix angle -10°	
D	Tungsten Carbide Cobalt (WC-Co), diamond coated	6 mm	8	Helix angle 0°	
E	Tungsten Carbide Cobalt (WC-Co), diamond coated	6 mm	8	Helix angle 10°	

Fig. 1 Image and designation of the tools employed in the experimental study



alloys can be favorable, but for composites, a lower cutting force can cause the fibers to deform but not break.

This may result in a lower final surface quality obtained during machining, which is reflected in values of the table (Fig. 4a). These results are consistent with other studies, such as Nguyen et al. [21] and Ozkan et al. [23] in which they note a better machining in CFRP following the up-milling strategy. In addition, the fiber pull-out defect appears to a greater extent on the right side of the slot, i.e., with the down-milling strategy (Fig. 4b).

For example, in tool type A, values between 16.42 and 26.00 μm appear in up-milling. On the other hand, the Rz reaches values of up to 57.11 μm . The deterioration of the surface quality becomes double if the two machining strategies are compared. The same phenomenon occurs with the rest of the tools used in this experiment. Therefore, it seems that for the performance of CFRTP contourmilling maintaining an up-milling strategy provides a higher surface quality.

The highest Rz value is generated by tool B in 1000 rpm and 0.05 mm/tooth test being 115.14 μm . Tool D also produces a very high value of 103.44 μm at 1000 rpm and 0.03 mm/tooth. The best surface quality is given to tool A with values such as 16.42–16.57 μm . This article focuses on getting good surface quality in conventional CFRTP machining. Therefore, after the previous discussion, it has been decided to analyze in detail only the Rz values that are in accordance with machining (up-milling), since they are the smallest.

3.2 An overview of Rz values measured

Figure 5 shows the Rz values for machining the thermoplastic composite following the up-milling strategy. Each color

Table 3 Combination of cutting parameters used for each test

Trial	S (rpm)	Fz (mm/tooth)
1	1000	0.03
2	1000	0.05
3	1000	0.07
4	3000	0.03
5	3000	0.05
6	3000	0.07

represents the 6 corresponding trials for each tool. The aim of this subsection is to analyze the results obtained and to define a description of the defects in the tools employed.

In this way, it can be seen how, as discussed in previous section, the lower values of Rz are acquired by tool A. This tool has the biggest evacuation channel of all the tools employed. Chip evacuation is one of the most relevant aspects in composite machining. As mentioned in other studies, such as those carried out by Pereira et al. [25] and Wang et al. [32], a smaller chip channel could cause the chip to get stuck in the tool, causing an increase in the cutting forces generated during machining. The CFRTP used in this article has a low glass transition temperature and is therefore quite influenced by the temperature caused by the machining process. The matrix of composite melts and joins the carbon fiber particles that are removed during machining. This means that the chip generated needs enough space to be evacuated and does not interfere in the final surface quality of composite.

Tools C, D, and E have 8 teeth arranged along the diameter; therefore, they have a smaller evacuation channel than tool A. This makes it difficult to remove the chips, which can get stuck in the tool itself. Figure 6 shows the chip stuck in the tool channel at the end of one of the tests. For this reason, these three tools take a higher Rz value than tool A. Tool B is the most particular of 5 tools employed. It contains 11 teeth distributed in a helical way along the tool diameter. This means that the evacuation channels generated between teeth are very small. This is the reason for the randomness of results shown in Fig. 4. Some of the Rz values obtained with tool B are similar to those obtained with the other 4. However, two of them are the highest values of the experimental set.

3.3 Analysis of the surface quality obtained per tool

In this subsection, the analysis of the surface quality obtained for each trial is developed. In each graph, the average Rz values together with their deviations are represented. For each combination of parameters, a macrograph of the fiber pull-out generated in that trial has also been included. Above the set of macrographies, there are two yellow-dashed lines that indicate the point from which the fiber pull-out is generated and the upper limit of this defect.

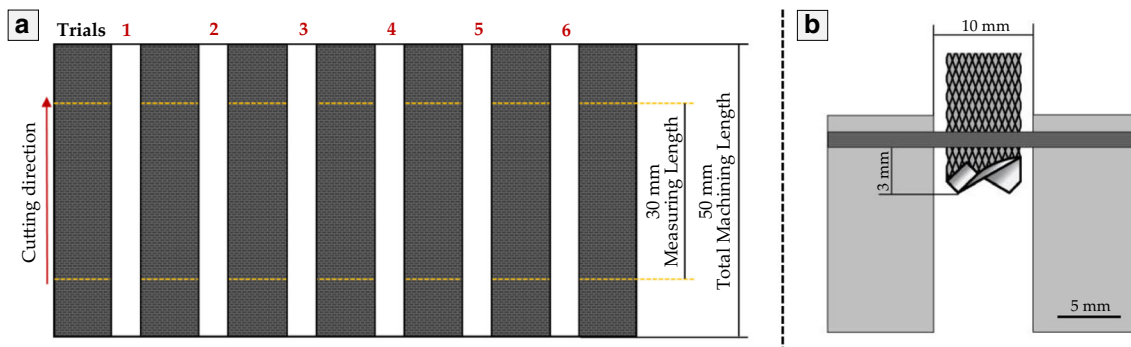


Fig. 2 a Machining layout on the composite. b Tool positioning in machining

Figure 7 shows the values obtained for tool A. It can be seen how the highest points of Rz occur with 0.05 mm/tooth for both cutting speeds. In addition, the deviations generated for 1000 rpm are smaller than those for 3000 rpm. Higher cutting speed means higher temperature during the machining process [7]. The temperature causes the adhesion defect to increase, making both the tool and the material susceptible to this defect. This may justify a wider range of values for a cutting speed of 3000 rpm. However, it should be noted that tool A is the one that has obtained the best results from Rz. In particular, a cutting speed of 3000 rpm and a feed rate of 0.03 and 0.07 mm/tooth generate values of 16.42 and 16.54 μm, respectively.

On the other hand, it can be seen that the geometry of tool A is not optimal for achieving a good cosmetic finish. The fiber pull-out defect appears in all the combinations of parameters used, being 1.58 mm the highest value obtained. The top layer of carbon fiber in composite is deformed in the direction of tool rotation but does not break. This tool is not completely designed for machining composite materials. The number of teeth of a tool for composite machining is one of the most influential variables in the process.

Hintze W. et al. [13] in their study agree that an increase in the number of teeth generates poorer results in terms of surface quality, but can improve the pull-out defect or delaminations of composite materials. This discussion matches the results obtained in this experiment. As seen above, tool A is the one that shows the lowest values of Rz.

As mentioned above, tool B has 11 cutting edges distributed in a helical pattern along the tool diameter. This tool geometry is designed to perform the final finish of a contourmilling process on composite materials. The high number of teeth makes the carbon fibers break more easily. This is reflected in the macrographs shown in Fig. 8. Compared to tool A, the fiber pull-out defect generated is much lower and in some cases is even close to 0. In contrast, in the combination of 1000 rpm and 0.05 mm/tooth parameters, this defect can be seen significantly. It should be noted that the fiber pull-out coincides with the highest Rz value obtained in this set of trials.

With such small and even insignificant evacuation channels, tool blockage can occur during machining. Fiber particles next to the temperature affected adhesive could consolidate and get stuck between the tool and the material. This can lead to particle adhesion on the machined surface and even to the tool losing its cutting ability.

However, very striking Rz values appear when machining CFRTP with this type of tool. In particular, there are several combinations of parameters that achieve average values between 19.82 and 24.91 μm with small deviations, similar to those obtained by tool A. On the other hand, this tool contains the highest values of Rz, reaching 70.34 μm. Authors such as Geier N. et al. [9] obtain similar results. With this tool geometry, they achieve higher Rz values compared to other tool types.

Tools C, D, and E are a hybrid between type A and B. A greater number of cutting edges are known to benefit the

Fig. 3 Setting of roughness parameter Rz measurements in the material section

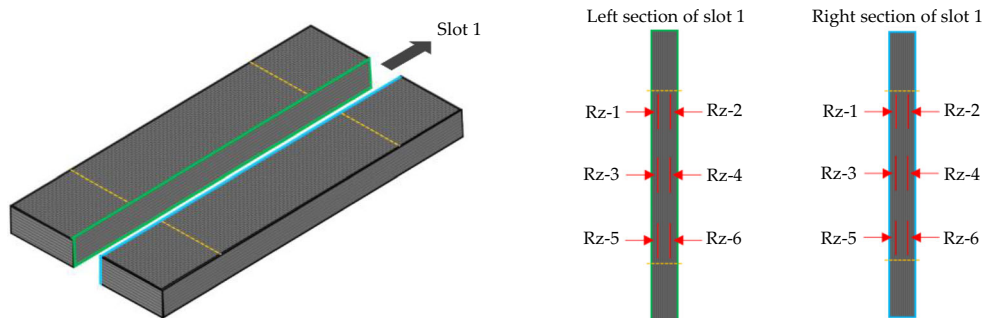
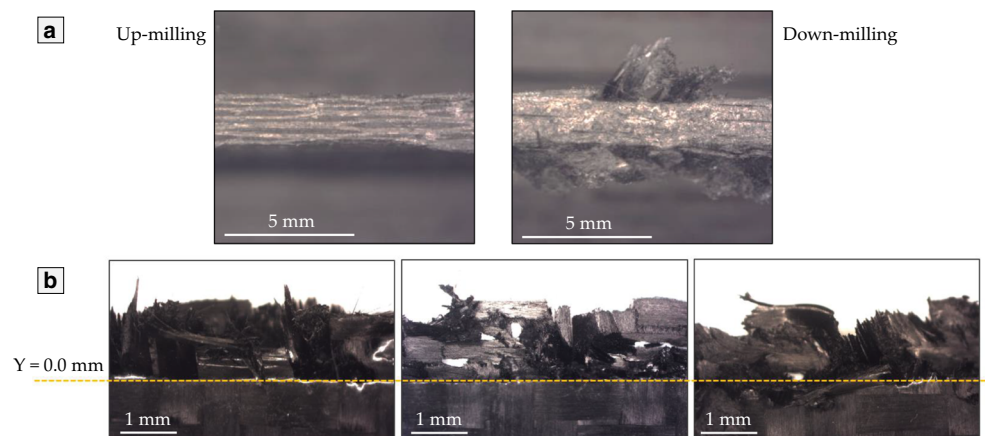


Table 4 Rz values obtained in all tests

Tool	Test	Spindle speed S (rpm)	Feed rate per tooth F_z (mm/tooth)	Average Rz ¹ (up-milling) ($\mu\text{m} \pm \mu\text{m}$)	Average Rz ¹ (down-milling) ($\mu\text{m} \pm \mu\text{m}$)
A	1	1000	0.03	17.71 \pm 4.10	45.31 \pm 23.70
	2	1000	0.05	24.53 \pm 3.85	51.38 \pm 21.25
	3	1000	0.07	16.57 \pm 4.71	33.51 \pm 16.15
	4	3000	0.03	16.42 \pm 6.52	57.11 \pm 38.54
	5	3000	0.05	26.00 \pm 8.21	46.59 \pm 16.64
	6	3000	0.07	16.54 \pm 6.55	32.10 \pm 4.62
B	1	1000	0.03	24.91 \pm 4.26	77.74 \pm 31.10
	2	1000	0.05	58.32 \pm 12.02	115.14 \pm 29.08
	3	1000	0.07	19.82 \pm 2.77	35.36 \pm 12.65
	4	3000	0.03	22.00 \pm 5.35	31.88 \pm 25.80
	5	3000	0.05	35.54 \pm 6.85	42.69 \pm 11.73
	6	3000	0.07	54.78 \pm 8.98	30.03 \pm 6.65
C	1	1000	0.03	36.53 \pm 17.53	59.90 \pm 13.09
	2	1000	0.05	30.24 \pm 8.89	58.12 \pm 18.65
	3	1000	0.07	23.72 \pm 9.69	49.25 \pm 28.37
	4	3000	0.03	40.91 \pm 13.98	27.29 \pm 6.96
	5	3000	0.05	31.12 \pm 9.22	36.34 \pm 10.53
	6	3000	0.07	24.03 \pm 6.50	24.09 \pm 4.45
D	1	1000	0.03	21.73 \pm 13.30	103.44 \pm 46.53
	2	1000	0.05	21.17 \pm 5.62	63.77 \pm 10.69
	3	1000	0.07	34.03 \pm 5.48	62.83 \pm 17.54
	4	3000	0.03	37.29 \pm 5.84	53.71 \pm 18.39
	5	3000	0.05	44.44 \pm 7.92	62.62 \pm 14.52
	6	3000	0.07	47.53 \pm 14.61	54.23 \pm 21.08
E	1	1000	0.03	28.25 \pm 17.18	66.03 \pm 18.84
	2	1000	0.05	25.26 \pm 8.71	62.38 \pm 13.43
	3	1000	0.07	39.20 \pm 10.87	82.89 \pm 15.53
	4	3000	0.03	35.64 \pm 18.09	53.52 \pm 13.18
	5	3000	0.05	31.83 \pm 6.21	37.15 \pm 7.96
	6	3000	0.07	38.44 \pm 6.85	54.45 \pm 6.69

¹ Average values are based on 6 different measurements

Fig. 4 a Visual inspection of a slot section: left up-milling, right down-milling. **b** Fiber pull-out defect in down-milling parts (2 \times)



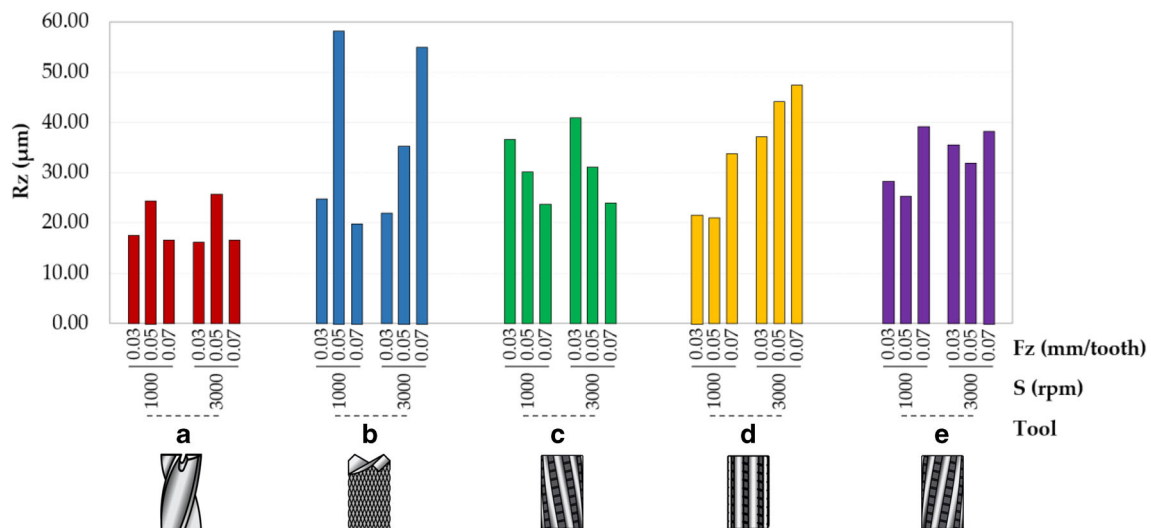


Fig. 5 Graphical representation of Rz values achieved by each tool

machining of composite materials. For this reason, these tools have 8 cutting edges. In addition, an evacuation channel is a positive element that allows the chip not to affect the final machined surface.

Figure 9a shows the values measured for tool C with a -10° helix angle. It can be seen that for the same cutting speed, Rz values decrease as the feed rate increases. In the same way, the deviations shown follow the same trend as the average values; i.e., they become smaller as feed rate increases. This causes that the final quality obtained is more homogeneous with a greater removal of material. In general, tool D (Fig. 9b) and tool E (Fig. 9c) show similar trends.

There is a higher accuracy of the measured values as the feed rate increases. In addition, in all 3 tools, as the cutting speed increases, the Rz values increase. This effect also occurs with the previous tools. An increase in the cutting speed implies an increase in the process temperature, which can lead to a less clean cut due to the adhesion defect.

The 3 tools are in a similar range of average values. However, it is worth noting the results obtained for tool D (Fig. 9b) with a combination of 1000 rpm and 0.07 mm/tooth. This combination is the one that generates a lower average value together with a small deviation. The negative helix angle produces the highest Rz values. However, the Rz values obtained for a positive helix angle are smaller. In an up-milling strategy, a positive helix angle makes the cutting edge of the tool to machine in the same direction as the helix angle, which could result in better material removal.

On the other hand, tool C, with a negative helix angle (-10°), generates a decreasing trend as the feed rate increases. On the contrary, the trend in tool E (positive helix angle, 10°) increases as the feed rate also increases.

As regard to the fiber pull-out defect, it can be seen how, in general, the high number of cutting edges performs its function. This defect appears in a minor way in the tools that have

Fig. 6 a Carbon fiber particles consolidating with the composite matrix blocking the evacuation channels of tool D. b Plan view of the stuck tool

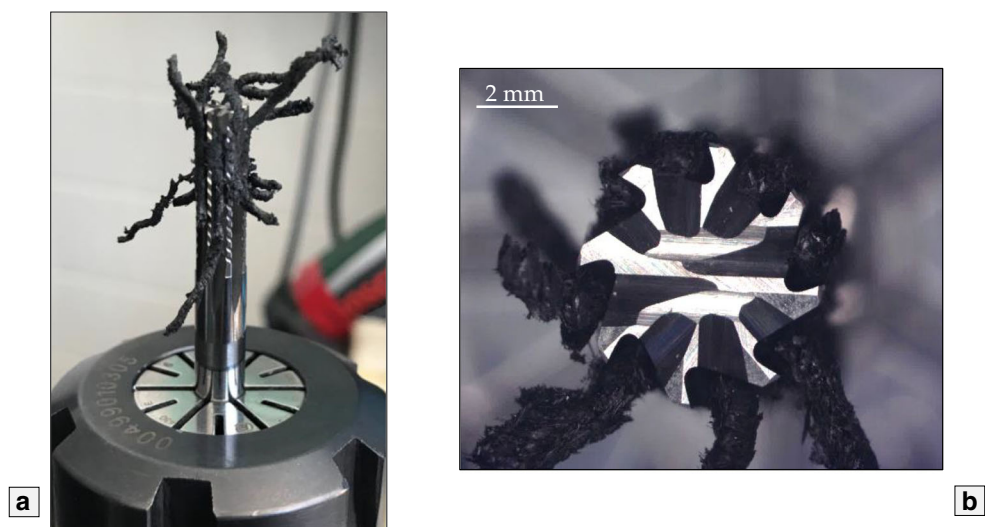
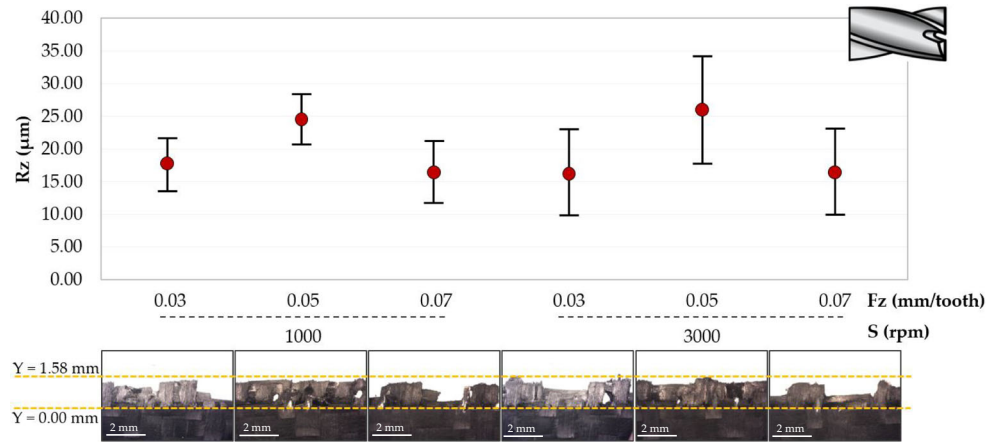


Fig. 7 Graphical representation of average Rz values, their deviations, and the fiber pull-out occasioned by tool A



a helix angle: C and E. In tool C, an increase in cutting speed leads to a decrease in carbon fiber pull-out. As for tool E, it can be seen that at low feed rates, the results obtained are the best of the set of trials carried out. On the other hand, from a feed rate of 0.07 mm/tooth, it seems that the geometry of the tool makes it difficult to cut these wires.

Tool D, with a helix angle of 0°, has generated fiber pull-out defect in all trials. The helix angle of a tool gives the chip channel a curved shape, in which the detached chips can be evacuated easier. In this case, as could be seen in Fig. 6, the absence of a helix angle has made chip removal difficult during machining. This has caused a blockage of the tool with fiber particles consolidated to the composite matrix.

Shengchao H. et al. [26] study the wear of this type of tools in CFRP machining. They conclude that using this type of tool decreases the cutting force required in the process. Lower cutting force allows higher surface qualities to be achieved. In this article, tool D generates a surface quality similar to the one obtained by tool A when machining at low feed rates. However, tool E, with a positive helix angle (+10°) generates less fiber pull-out when the composite is machined at low feed rates.

3.4 Discussion of CFRTP milling

The milling of thermoplastic matrix compounds with different types of tool geometries has led to significant results. In terms of surface quality, the conventional tool with 2 teeth (tool A) has generated the lowest Rz values obtained in this experiment. Tool B has produced quite different results. It should be noted that this tool geometry is designed to perform the surface finishing of previously machined materials. Therefore, when a complete slot is made with this kind of tool, there may be an unpredictable behavior. Tools C, D, and E show slightly higher Rz values than those caused by the conventional tool (A). However, these values have a fairly clear trend.

As for the fiber pull-out defect, it is observed that the conventional tool (A) obtains the worst results. In all the tests carried out with tool A, this defect has been generated in a homogeneous way. As it has been commented along the document, this tool is not designed to perform the machining of composite materials. Therefore, although it generates good surface qualities, it is not able to eliminate the fibers that are found in the upper layer of the material. Something similar has happened with tool D; however, the defect in this tool is caused by the absence of a helix angle. Tool B has generally

Fig. 8 Graphical representation of average Rz values, their deviations, and the fiber pull-out occasioned by tool B

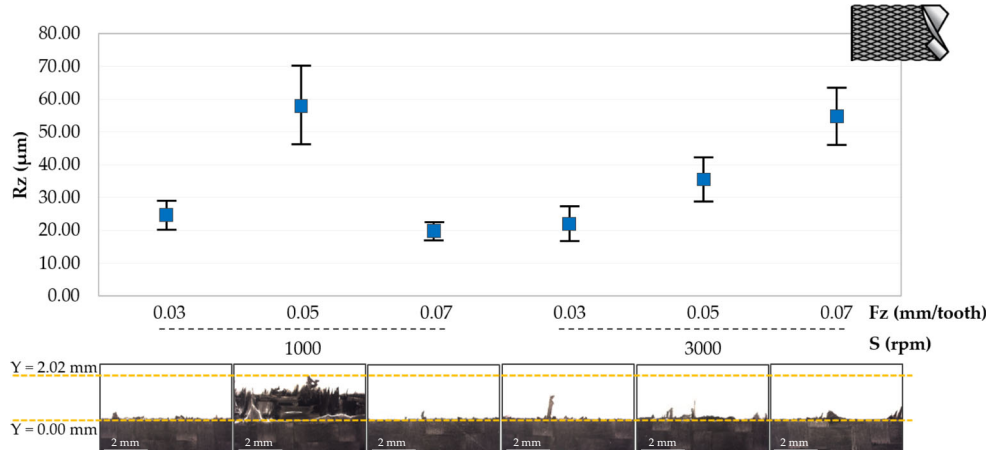
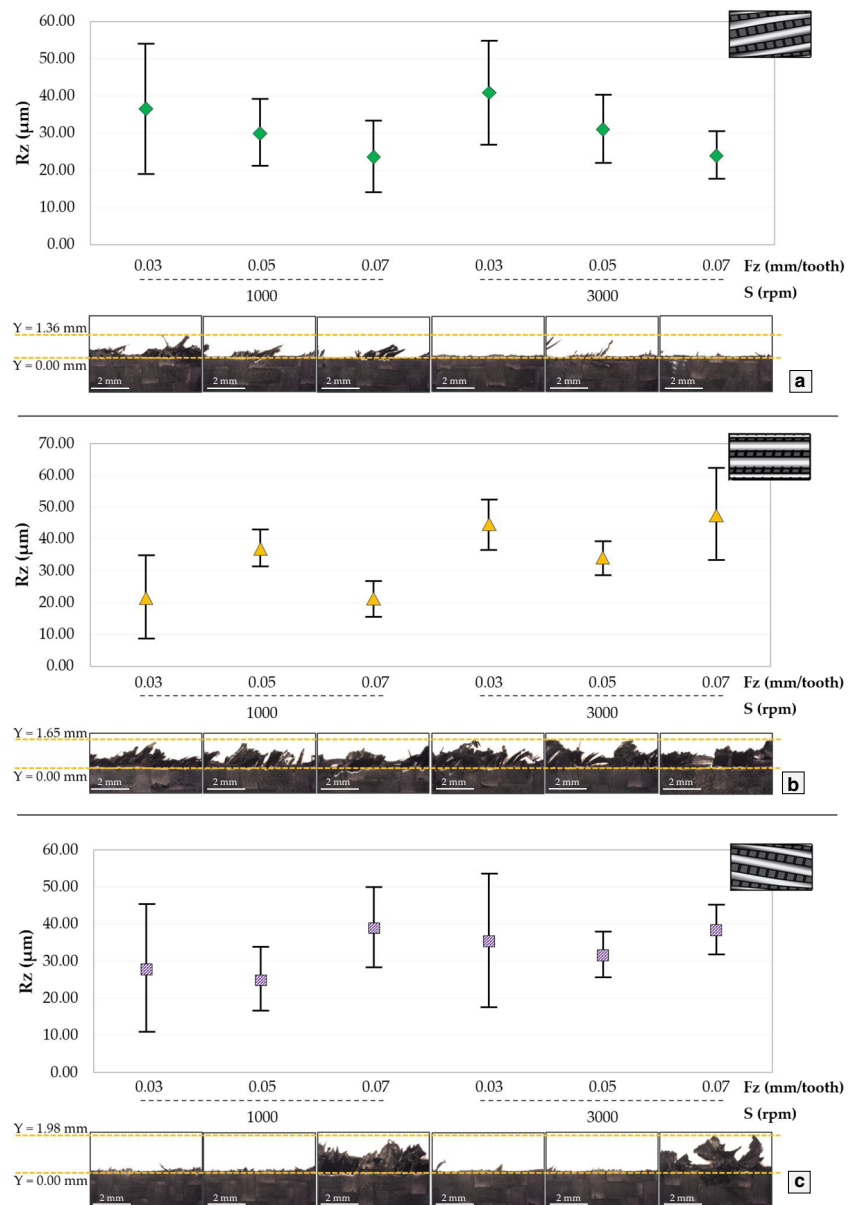


Fig. 9 Graphical representation of average Rz values, their deviations, and the fiber pull-out occasioned by (a) tool C, (b) tool D, and (c) tool E



offered the best results in terms of fiber pull-out. The height of the loose fibers found in the material is very close to 0. Tool C, with a negative helix angle (-10°), provides better results when machining the CFRTP at a high cutting speed. By contrast, tool E, with a positive helix angle ($+10^\circ$), has been affected by the feed rate.

In general, CFRTP milling results in a variety of defects. The use of a thermoplastic matrix makes the glass transition temperature of the material lower than that of a thermosetting resin. Therefore, the thermoplastic material can be more affected by the temperature of the milling process than the CFRP. This is reflected in the surface quality obtained in other experimental studies where the Rz values are much lower than those obtained in this experiment [5]. On the other hand, as in the case of CFRP [6, 24], the milling of this type of material

produces defects such as the elimination of the fiber yarns due to the efforts made by the cutting tool.

The machining of this type of material in other non-conventional technologies such as abrasive water jet machining, AWJM, could be interesting in terms of surface quality. In general, the temperature generated in the AWJM is lower than that caused by conventional milling [8]. This can cause the thermoplastic matrix of a composite material to be less affected by machining. However, the selection of an appropriate cutting tool geometry can achieve really good cosmetic defects that the waterjet may not get. Today, cutting tools are manufactured such as B, C, D, and E tools, designed to eliminate defects such as fiber pull-out, internal delaminations, or die loss during machining.

4 Conclusions

An experimental study on the influence of tool geometry and cutting conditions on the milling of thermoplastic carbon fiber composites has been carried out. The machining has been discussed by means of the surface quality obtained in material in terms of R_z and the cosmetic quality of material in terms of fiber pull-out. The literature review allowed to select cutting speed and feed rate as the most influential input parameters in the machining performed, keeping other parameters fixed, such as the machining depth at 3 mm. Cutting speeds have been 1000 and 3000 rpm; moreover, feed rates per tooth have been 0.03, 0.05, and 0.07 mm/tooth.

Three different types of tools, each with 6 mm diameter, have been selected for milling. Tool A has a conventional milling geometry with two cutting edges and a wide evacuation channel. Tool B has a tool geometry designed for finishing composite materials. It contains 11 teeth arranged helically along the flute. Tools C, D, and E have 8 cutting edges with teeth distributed along the surface. As there are more cutting edges, the chip channel of this tool is narrower than that of tool A. Each of them has a specific helix angle: C (-10°), D (0°), E (10°). In order to obtain a repeatability and reproducibility of the measured values, 6 measurements of R_z have been taken on each side of slot at different points on its surface. The most relevant conclusions of this research are as described below:

- The up-milling and down-milling strategies have been analyzed with the 5 tools used in this experiment. It has been seen how the down-milling strategy, in general, always obtains higher R_z values than those resulting from the up-milling strategy. In opposition machining, a lower cutting force is generated when the tool hits the material. In metal alloys, this cutting force can generate a better surface quality. On the other hand, in the machining of composites, a low cutting force can cause the fiber yarns to be deformed by the path of the tool but not to break off. This discussion has been contrasted with other studies of milling of thermostable composite materials, where they agree that the down-milling strategy generates a worse surface quality which is the machined surface. Since the objective of the article is to find the best results for CFRTP machining with different types of tools, it has been decided to analyze in detail only the R_z values and the fiber pull-out defect achieved for the up-milling strategy.
- CFRTP milling per tool has been analyzed in terms of R_z and fiber pull-out. The conventional tool (A) is the one that has obtained the best results of R_z , being $16.42 \mu\text{m}$ the minimum average value for the complete experiment. Tool B achieves rather low average values of R_z , such as $19.82 \mu\text{m}$, but at the same time gets the highest values of the whole experiment, $58.32 \mu\text{m}$ or $54.78 \mu\text{m}$. Tools C, D,

and E have a similar range of values, from roughly 21 to $47 \mu\text{m}$. However, they show different trends from each other. Tool C shows a decrease in R_z values as the feed rate increases. In tools D and E, the R_z values increase as the feed rate too.

- It has been discussed how these results can be related to the chip evacuation channel of each tool. A small chip channel can cause the chip to get stuck in the tool, causing an increase in the cutting forces generated during machining. In addition, the low glass transition temperature of the CFRTP used in this experiment may ease tool blockage. Tool A has the largest evacuation channel, so it is less likely to lose its cutting ability. Tools C, D, and E have 8 cutting edges, which makes the evacuation channels very small compared to tool A. Thus, it is understandable that the R_z values obtained for tools C, D, and E are higher than for tool A. Tool B has the smallest evacuation channel so it shows the highest R_z values of the whole experiment.
- An inspection of the fiber pull-out defect produced in the material after machining has been carried out. It has been possible to see how tool A does not have a cutting geometry suitable for machining composites. The fibers are deformed but not broken. This has occurred in all the tests of this tool. Tool C generates the minimum fiber pull-out at cutting speeds of 3000 rpm. Tool E also generates minimum fiber pull-out at low feed rates 0.03–0.05 mm/tooth.

Finally, the most complete tool geometry for machining thermoplastic composites is the C tool, with 8 cutting edges and a helix angle of -10° . This tool at 0.07 mm/tooth and a cutting speed of 3000 rpm has obtained average R_z values similar to the minimum values achieved by tool A. Furthermore, with this combination of parameters, it achieves a minimum fiber pull-out defect.

Nomenclature R_z , average of the absolute values of the five highest peaks and the five lowest valleys; TPU, thermoplastic polyurethane; C/TPU, carbon/thermoplastic polyurethane; AWJM, abrasive water jet machining; CFRP, carbon fiber reinforced plastics with thermoset matrix; CFRTP, carbon fiber reinforced thermoplastics; z , number of teeth; F_z , feed rate per tooth; S , spindle speed

Authors' contribution A.S. and F.B. developed machining tests. M.B. and J.S. developed data treatment. F.B., A.S., M.B., B.S., and J.S. analyzed the influence of the parameters involved. F.B. and A.S. collaborated in preparing figures and tables and F.B., A.S., M.B., B.S., and J.S. wrote the paper.

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Data availability All the data have been presented in the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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