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Evaluation of Peripheral Milling and Abrasive Water Jet Cutting in CFRP Manufacturing: Analysis of Defects and Surface Quality

Alejandro Sambruno , Álvaro Gómez-Parra , Pablo Márquez , Iñaki Tellaeche-Herrera 
and Moisés Batista 

School of Engineering, Mechanical Engineering and Industrial Design Department, University of Cadiz, Av. Universidad de Cadiz 10, 11519 Puerto Real, Cadiz, Spain; alvaro.gomez@uca.es (Á.G.-P.); pablo.marquezleal@alum.uca.es (P.M.); i.tellaecheherrera@alum.uca.es (I.T.-H.)

* Correspondence: alejandro.sambruno@uca.es (A.S.); moises.batista@uca.es (M.B.)

Abstract: The use of carbon fiber reinforced polymers (CFRP) is crucial in industries, such as aerospace, automotive, and marine, due to their excellent strength-to-weight ratio and corrosion resistance. However, machining CFRP is challenging due to its abrasive nature, which can cause premature tool wear. Some of the commonly used processes for machining these materials are dry milling and abrasive water jet machining (AWJM), which offer the best alternatives from an environmental point of view. This article presents an analysis of the defects and surface quality obtained in CFRP after machining by AWJM and milling. For this purpose, combinations of relevant parameters have been chosen for each process: cutting speed and tool wear in milling and traverse feed rate and hydraulic pressure in AWJM. The results obtained have been evaluated from two points of view: macroscopically, through the evaluation of delamination, and microscopically, through the study of the roughness in terms of Ra. Furthermore, a discussion on functional, environmental, economic, and social terms has been made between both processes. In summary, each machining process generates a specific type of delamination: Type II in milling and Type I in AWJM. In addition, the best Ra results are obtained for pressures of 1200 bar in AWJM.

Keywords: CFRP; AWJM; milling; delamination; surface quality



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1. Introduction

In the current industry, the use of composite materials has become crucially important due to their numerous advantages over traditional materials. Among these, carbon fiber reinforced polymers (CFRP) stand out for their exceptional strength-to-weight ratio, corrosion resistance, and dimensional stability. These characteristics make CFRPs particularly suitable for demanding industries such as aerospace, automotive, and marine, where weight reduction and increased efficiency are key objectives [1].

The machining of CFRP is a critical phase in the production of high-precision components. Peripheral milling, or profile contouring milling, is an essential process that ensures that final parts meet the exact specifications required for optimum performance [2]. This process not only affects surface quality and dimensional accuracy but also has a direct impact on the structural integrity of the component, so CNC (Computer Numerical Control) techniques are commonly used. However, CFRP composites are difficult to machine due to their low thermal conductivity and abrasive nature, which causes premature tool wear [3].

On the other hand, machining CFRP requires specific tools due to the unique properties of these materials, which combine high strength and stiffness with low weight. The tools must be able to handle the abrasiveness of the carbon fibers and the bonding characteristics of the polymer matrix [4]. The use of tungsten carbide tools is popular due to their combination of hardness and wear resistance, which makes them convenient for cutting abrasive materials such as CFRP [2,5]. However, on certain occasions, cutting

conditions require that these tools be improved, and for this reason, materials and coatings are used that offer greater hardness, allowing this material to be machined with better performance [6]. In this context, polycrystalline diamond (PCD) tools offer higher hardness and wear resistance than tungsten carbide, providing longer tool life and better surface finish quality, although they are more expensive and require specific cutting conditions to avoid damage [7–9]. However, this coating is not the only option. Other coatings, such as AlCrN or TiAlN, significantly improve machining quality and reduce tool wear [10]. In addition, they have a lower cost compared to PCD.

However, the material is not the only important aspect. The geometrical design of the tools is also crucial. Thus, selecting a suitable rake angle is essential to reducing cutting forces and minimizing the risk of delamination [11,12].

Tool material and tool geometry are two key aspects that affect tool behavior as well as tool life [13]. Excessive tool wear not only affects machining accuracy but also increases operating costs due to the need for frequent replacements. The mechanism that appears when machining CFRP is abrasive wear due to the abrasive nature of the carbon fiber reinforcement. This abrasion causes flank wear, from friction between the tool and the abrasive material, and crater wear, which happens on the rake face of the tool due to high temperatures and friction. This type of wear can reduce tool life and cutting quality [14]. However, this is not the only problem since the polymer that comprises this material can generate secondary adhesion and important defects on the tool [15].

All this, together with the heterogeneous and anisotropic nature of the material, can lead to the appearance of defects in the machined part [16]. Delamination is one of the most critical problems and occurs when the fiber layers separate due to excessive or inadequate cutting forces. This defect compromises the structural integrity of the machined component, which may result in premature failure in service [6,17]. Delamination can be minimized by using appropriate tools and optimized cutting parameters. But in addition to delamination, other common defects include surface cracks and uncut fibers. These defects result in poor surface quality and occur when the tool does not cut the fibers cleanly, leaving irregular edges and loose fibers on the surface of the material [2].

Therefore, in many cases, cutting fluids are used to lubricate and cool the tool, protecting it and achieving higher-quality machining. However, the use of these cutting fluids presents significant environmental challenges. The intensive use of cutting fluids, which are necessary to cool and lubricate the tools during machining, as well as the generation of waste contaminated with these fluids, has a large environmental impact [11]. These cutting fluids can be harmful to the environment, if not properly managed, and to people as they can cause general health damage. Their disposal and treatment represent an additional cost and a considerable environmental impact [13].

To mitigate these effects, techniques such as minimum quantity lubrication (MQL) have emerged. MQL uses a very small amount of cutting fluid, which is applied directly to the cutting zone in the form of an aerosol. This technique significantly reduces the volume of fluid required and thus reduces the environmental impact [18]. However, despite these improvements, MQL does not completely eliminate the problems associated with cutting fluids. The management of the waste generated and possible contamination are still issues to be considered [19]. In addition, MQL is not always applicable to all milling operations or to all materials, limiting its effectiveness as a universal solution to the environmental problems of peripheral milling [20]. Thus, despite its advantages, MQL cannot fully address the need for more sustainable and environmentally responsible production.

Another alternative is cold air cooling during CFRP milling, and this improves tool life and reduces surface roughness compared to dry milling. Cold air cooling also reduces abrasive wear and improves overall milling performance [21,22]. Thus, the tool life of cutting tools, even uncoated tungsten carbide tools, is improved compared to dry cutting conditions [23]. This minimizes the environmental impact of using cutting fluids but worsens the process performance.

In this context, abrasive water jet cutting (AWJM) has emerged as a promising and more sustainable alternative for CFRP machining. The AWJM process uses a mixture of high-pressure water and abrasive particles to cut materials. This technique offers several environmental and operational advantages over traditional milling. One of the main advantages is the elimination of cutting fluids, which significantly reduces the generation of dangerous waste and environmental pollution [24]. In addition, water jet cutting produces less heat during the cutting process, which minimizes adverse thermal effects on the material [12].

AWJM also allows for more accurate and cleaner cutting of the composite materials, reducing the possibility of defects such as delamination and surface tears. This is particularly important for maintaining the structural integrity of CFRP components, which are widely used in high-tech industries such as aerospace, automotive, and marine [5]. The ability to perform high-precision cutting without adversely affecting the material properties makes water jet cutting an attractive option for critical applications where quality and reliability are essential.

Abrasive water jet cutting uses a high-pressure stream of water mixed with abrasive particles to remove material. This process involves erosion of the material surface due to the impact of the abrasive particles accelerated by the water jet. The main material removal mechanisms in AWJM include micro-erosion and brittle fracture of the fibers and polymer matrix. These mechanisms allow for obtaining a precise and clean cut, minimizing thermal damage to the material due to the low heat generation during the process [25].

The key parameters that influence the effectiveness of AWJM are hydraulic pressure, traverse feed rate, and abrasive mass flow rate [26]. The water pressure must be high enough to provide the necessary kinetic energy for the abrasive particles. The traverse feed rate must be controlled to balance the material removal rate and cut quality. The abrasive mass flow rate is also critical to ensure uniform abrasive distribution and effective penetration into the material. These parameters must be optimized for each type of material and thickness to achieve the best results [27]. However, there are others, such as clearance distance, that have a significant impact on surface roughness when interacting with other controlling factors [28,29], causing considerable influence on the cut quality and the resulting taper geometry [30]. Using high pressure, low standoff distance, and high traverse feed rate allows for obtaining straighter cuts and better quality surfaces without a great influence on the type of lamination used [31].

However, despite the advantages offered by this technique, such as reduced thermal shock and cutting accuracy, there are several defects that can compromise the quality of the finish and the structural integrity of the material.

One of the main defects associated with AWJM is the surface finish. The cut surface may show striations or linear marks resulting from the instability of the water jet and variations in feed rate. These striations not only affect the aesthetics of the part but can also influence its functional performance. The quality of the surface finish depends to a large extent on the correct calibration of operating parameters, such as water pressure and traverse feed rate, as well as appropriate maintenance of the equipment to prevent irregular wear of the nozzle [32].

Another significant defect is delamination, which is especially critical in the machining of composite materials. Delamination occurs when layers of material separate due to high water jet pressure. This defect compromises the structural integrity of the part and can result in premature failure during use. To minimize delamination, it is essential to properly adjust the water pressure and traverse feed rate and to consider the use of appropriate supports during the cutting process [33].

The taper angle is another common problem in AWJM. It refers to the variation in the width of the cut from the inlet to the outlet of the jet, creating a tapered cut instead of a straight cut. This angle can affect the dimensional accuracy of the part and its ability to be assembled. The taper angle is influenced by factors such as water pressure, traverse feed rate, and nozzle-to-material distance. Optimizing these parameters can help reduce this defect and improve cut quality [34].

Delay of the jet or lagging is another notable defect. It occurs when the water jet does not cut the material uniformly due to the inertia of the abrasive and the water flow, resulting in an

uneven cut surface. This defect is particularly problematic in thicker materials, where the jet can deflect and cause an inaccurate cut. To mitigate jet lag, it is crucial to maintain proper feed rate and constant water pressure and to ensure that the abrasive is well distributed in the jet [35].

In summary, abrasive water jet machining offers several advantages over traditional techniques but also presents significant challenges in terms of defects such as surface finish, delamination, taper angle, and jet lag. Understanding and properly managing these defects by optimizing operating parameters and equipment maintenance is essential to maximizing the benefits of AWJM and ensuring the quality and integrity of machined parts.

Thus, conventional milling and abrasive water jet cutting (AWJM) affect the properties of CFRP parts differently, particularly the interlaminar Shear Strength (ILSS). In general, parts processed with AWJM are subjected to higher shear and compressive stresses due to machining-induced damage, especially at the entry and exit points of the jet. Conventional milling shows less surface and subsurface damage compared to AWJM [36] because, mainly, tangential stress is performed.

For all the reasons explained above, a comparative study of the machining of CFRP specimens by milling and abrasive water jet is carried out in this article. As regards milling, we propose to carry it out under nonlubricated conditions, such as dry machining, since this type of machining is the most environmentally friendly. For this purpose, different combinations of cutting parameters will be carried out, where the cutting speed and the tool wear will be the most relevant parameters in milling, while the hydraulic pressure and the traverse feed rate will be the most influential in AWJM. A visual analysis of defects obtained after the various machining operations will be carried out. In addition, an analysis of the surface finish obtained by both processes in terms of R_a will be carried out. A statistical analysis will be carried out to determine the significance of the parameters used during the process. Finally, a discussion on environmental, functional, economic, and social terms between the milling and AWJM processes will be carried out.

2. Materials and Methods

For the development of this study, a CFRP composite material made by a thermosetting resin of the epoxy type reinforced with carbon fiber has been used. In this sense, the material used was of the pre-preg type. This pre-preg form facilitates the lamination process and ensures the uniformity of the resin and fiber supply throughout the part. In this case, the top face designation is considered as the face in contact with vacuum bagging film and the bottom face as the face in contact with the tooling. Specifically, the material used is called Hex-Ply® M21/34%/UD194/IMA-12K [37], manufactured by Hexcel Composites (Hexcel Composites, Parla, Madrid, Spain). From its designation, it is clear:

- M21: designation of the resin used.
- 34%: reference to the percentage of resin in the composite material.
- UD: fiber architecture, “UD” indicates unidirectional.
- 194: fiber mass (g/m^2).
- IMA-12K: name of the fiber used.

The material properties can be seen in Table 1. In addition, for the development of this study, a 250×215 mm plate of 4.05 mm thickness with a layer orientation of $0^\circ/30^\circ/-30^\circ$ was fabricated. A series of peripheral milling and abrasive water jet cutting (AWJM) tests was performed on this plate under industrial conditions.

The slotting milling tests were carried out on a Vurcon BR25 machining center (Vurcon, Elche, Alicante, Spain) with an 8 mm diameter milling tool with 10 teeth and a helix angle of 15° . The CFRP plate has been clamped at different points to the work table of the CNC milling machine in order to reduce the vibrations caused during machining. Three different high-carbon steel tools have been used, each one in a different state of life, with total accumulated machining times of 30 s (considered as a new tool), 3.5 h, and 7 h. The test consisted of making a slot 10 mm wide and 50 mm long. A constant cutting speed (S) of 100 m/min and a constant feed rate per tooth (f_z) of 0.005 mm/rev (also expressed as a traverse feed rate (TFR) of 200 mm/min) was used in all slots. The relationship between

the cutting parameters is determined by Equations (1) and (2), where D is the diameter of the tool, N is the revolution per minute, and z is the number of teeth of the tool.

Table 1. Reinforcement, matrix, and carbon fiber reinforced polymer (CFRP) properties.

Properties	Reinforcement	Matrix	CFRP
Volume (%)	59.2	34.0	-
Density (g/dm ³)	1790	1280	1580
Glass temperature (°C)	-	180	195
Tensile Strength (GPa)	6.1	-	3.1
Young Modulus (GPa)	298	-	178
Compression Strength (MPa)	-	-	1500

$$S = \frac{\pi \cdot D \cdot N}{1000} \text{ (m/min)} \quad (1)$$

$$TFR = f_z \cdot z \cdot N \text{ (mm/min)} \quad (2)$$

Three slots were made with each tool. Figure 1a shows a representation of the tests carried out by each milling tool. It should be remembered that the tool is of a diameter a little smaller than the machined slot. Therefore, as can be seen in Figure 1b, the tool machined each slot with 100% of diameter in one direction (climb milling) and with 25% of diameter in the other direction (conventional milling). In this way, the differences found on the different sides of the slot can be analyzed, which makes a difference between a slotting process (side of the slot with 100% of diameter) and an edging process (side of the slot with 25% of diameter).

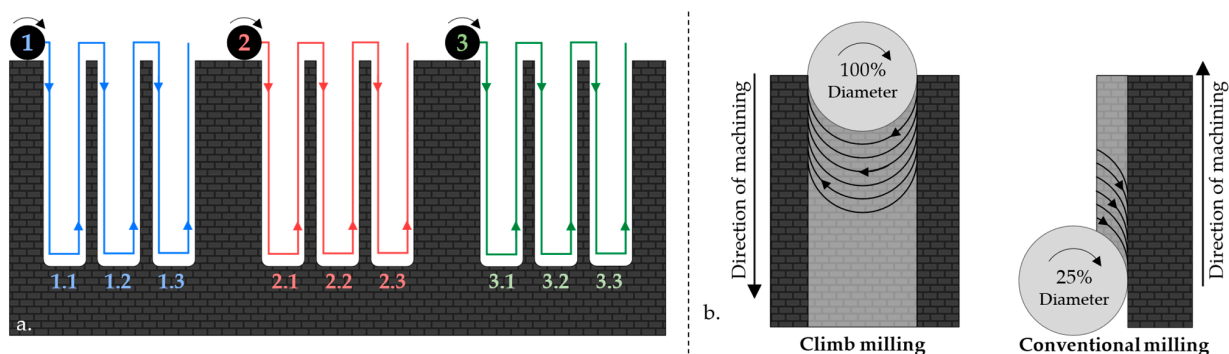


Figure 1. (a) Diagram of post-processing by peripheral milling tool followed by the CNC machine. (b) Visual representation of material removal according to machining direction.

AWJM machining was performed using a TCI Cutting BP-C 3020 machine (TCI Cutting, Valencia, Spain) fed with Mesh 120 Indian garnet abrasive and a 0.78 mm diameter and 380 mm length of the focusing tube, respectively. The AWJM machine was equipped with an ultra-high capacity pump (KMT, Streamline PRO-2 60, Bd Nauheim, Germany). On this occasion, given the small diameter of the tool, unidirectional slots of 50 mm in length were performed. The variable process parameters were traverse feed rate and hydraulic pressure. Some of the fixed process parameters were the abrasive mass flow rate and the clearance distance of nozzle material. The combination of selected parameters is shown in Table 2.

In all samples, a characterization of the elements involved in the tests was carried out using a Nikon SMZ 800 stereo optical microscope (Nikon, Tokyo, Japan) and a Mahr MarSurf PS 10 roughness tester (Mahr, Hannover, Germany). With the help of microscopy, the most important defects generated in each machining process were characterized, as well as the delamination generated on the surface of the material. On the other hand, the surface finish of the cut section was characterized in terms of R_a with the help of the roughness meter. In the case of peripheral milling, the quality was measured in the

central area of the specimen in order to prevent defects from affecting the measurement, and three measurements were taken on each wall of the slot. In the case of AWJM, three measurements of Ra have been carried out in the different damage zones of the cut section: initial damage region (IDR), smooth cut region (SCR), and rough cut region (RCR).

Table 2. Variable and constant parameters used by AWJM.

Parameter	Value
Traverse Feed Rate, TFR (mm/min)	100/200/300
Hydraulic Pressure, WP (bar)	1200/2500/3800
Abrasive Mass Flow Rate, AMFR (g/min)	225
Standoff Distance, SOD (mm)	2.5

Once the results obtained had been analyzed, the trends between the cut-off parameters and the variables studied were identified by means of statistical analysis. For this purpose, an analysis of variance (ANOVA) with a confidence interval of 95% was performed. The statistical analysis was carried out using Minitab v18 statistical software.

3. Results

Table 3 shows the mean values and deviations of the arithmetic mean roughness obtained for the machining of CFRP slots by milling tool and by abrasive water jet cutting for each combination of parameters used. For the machining by milling tool, the results obtained on each side of the slot (climb milling and conventional milling) have also been added. In the case of abrasive water jet cutting, the roughness values for the three damage zones of the cut section have been added: IDR, SCR, and RCR.

Table 3. Average Ra values obtained in slot milling and AWJM processes.

Slot Milling					Slot AWJM					
Tool	Test	Strategy	Average Ra (μm)	Average Ra of Slot (μm ± μm)	WP (bar)	TFR (mm/min)	Region	Average Ra by Region (μm)	Average Ra of Slot (μm ± μm)	
Tool 1 30 s	1.1	Climb	0.528	1.01 ± 0.48	1200	100	IDR	3.33	3.13 ± 0.28	
		Conventional	1.494				SCR	2.73		
	1.2	Climb	0.676	0.60 ± 0.08		200	RCR	3.32		
		Conventional	0.517				IDR	4.08		
	1.3	Climb	0.635	0.85 ± 0.22		300	SCR	3.74		
		Conventional	1.065				RCR	4.44		
Tool 2 3.5 h	2.1	Climb	1.290	1.00 ± 0.29	2500	100	IDR	5.54	5.43 ± 0.17	
		Conventional	0.717				SCR	5.19		
	2.2	Climb	1.244	1.30 ± 0.06		200	RCR	5.55		
		Conventional	1.357				IDR	4.51		
	2.3	Climb	1.786	1.30 ± 0.49		300	SCR	3.79		4.19 ± 0.30
		Conventional	0.815				RCR	4.27		
Tool 3 7 h	3.1	Climb	0.445	0.84 ± 0.39	3800	100	IDR	4.49	4.41 ± 0.37	
		Conventional	1.225				SCR	3.92		
	3.2	Climb	0.537	0.48 ± 0.06		200	RCR	4.82		
		Conventional	0.420				IDR	5.09		
	3.3	Climb	0.544	0.73 ± 0.19		300	SCR	4.30		4.84 ± 0.38
		Conventional	0.924				RCR	5.12		

The mean values of the arithmetic mean roughness obtained for machining by milling tool range from 0.48 to 1.30 μm , while the mean values obtained for AWJM machining range from 3.13 to 5.43 μm . Generally speaking, the surface finish obtained by the milling process generates lower values than those obtained by abrasive water jetting; this may be due to the abrasive nature characteristic of the AWJM process [38].

However, in order to discuss in greater depth the surface finish generated in both processes, a series of sections will be developed to examine both the different machining zones and the total average finish of the machined surface.

3.1. Preliminary Analysis of the Obtained Results

The following is an analysis of the defects and delaminations that occur during machining by milling; the analysis will be carried out by evaluating the macrographs attached in Figure 2. Overall, for all the slots, it is observed that the area where the most defects are accumulated is where the change of direction of the tool takes place. Regarding the type of delamination, according to Colligan and Ramulu in their research [39], they can be classified into three types according to their appearance for all conditions and cutting modes. The following extract from [39] outlines the three types of delamination that can be had in CFRP machining:

- Type I delaminations are characterized as areas where the surface ply fibers have been broken some distance inward from the trimmed edge and are observed as areas where surface ply fibers are missing along the trimmed edge.
- Type II delaminations consist of uncut fibers that protrude from the trimmed edge and may be delaminated from the next ply some distance from the edge of the part.
- Type III delaminations are observed as loose fibers partially attached to the machined edge tool, causing a “fuzzy” appearance along the top or bottom edge of the machined surface.

As can be seen, all the delaminations occurring in the tool change of direction zone have the same orientation, approximately -30° , and are all Type II. This is because the layer where the delaminations occur was in the first layer of the stack, which was positioned at -30° .

Likewise, it is observed that, as mentioned above, Type II delaminations are the most extensive and occur in the tool direction change zone, while Type I delaminations are more predominant because they occur along the slot. Finally, an example of Type III delamination is found at the entrance of the “Test 1.2” slot, characterized as a fraying of the fiber.

Comparing the results obtained in each slot machine by the same tool, it is observed that the first execution of each tool is the one that generates fewer defects, highlighting that as the machined area increases, more Type I and II delaminations are generated. This is true in general for all three tools used in the experiment.

Analyzing the results obtained with each tool, we found that the results containing the greatest number of delaminations are those obtained with the semi-new tool (3.5 h). Measurements of these delaminations were made with ImageJ v1.8.0 software, obtaining a maximum length of 1.2 mm and 2.0 mm in slots D and F, respectively. These values are between the results obtained by Slamani et al. in their paper [17], whose type II surface delaminations generated on a 3.68 mm thick CFRP part reached dimensions of 1.40 mm and 2.34 mm.

On the other hand, the slots obtained with the new and worn tool share very positive results, with hardly any delaminations. For the new tool, the longest type II delaminations are found in slot B, with a value of 0.9 mm. In slot I, the longest type II delamination generated with the worn tool is obtained, with a value of 0.8 mm. In addition to obtaining a lower value for the maximum type II delamination, the worn tool obtains a lower number of delaminations than the new tool.

The following is an analysis of the results obtained in the tests carried out with the abrasive water jet cutting process. In Figure 3, all the macrographs taken on the working face have been grouped since, although the defectology occurs on both faces of the element,

it is on the working face where a greater number of delaminations are generated, and for this reason, the analysis of this part of the sheet is more interesting.

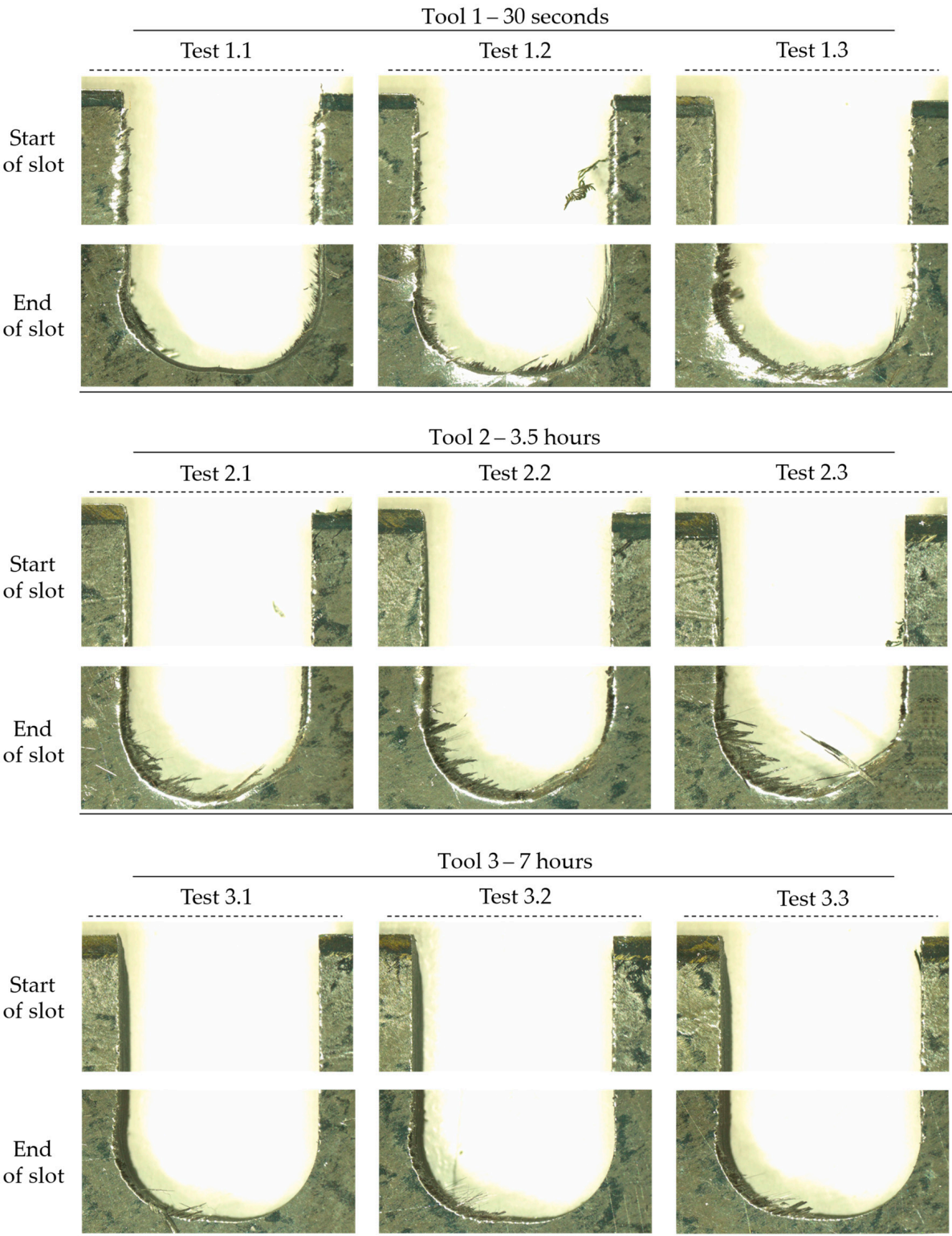


Figure 2. Macrographs of the post-processed areas using slot milling taken on the bottom face of the composite (10× magnification).

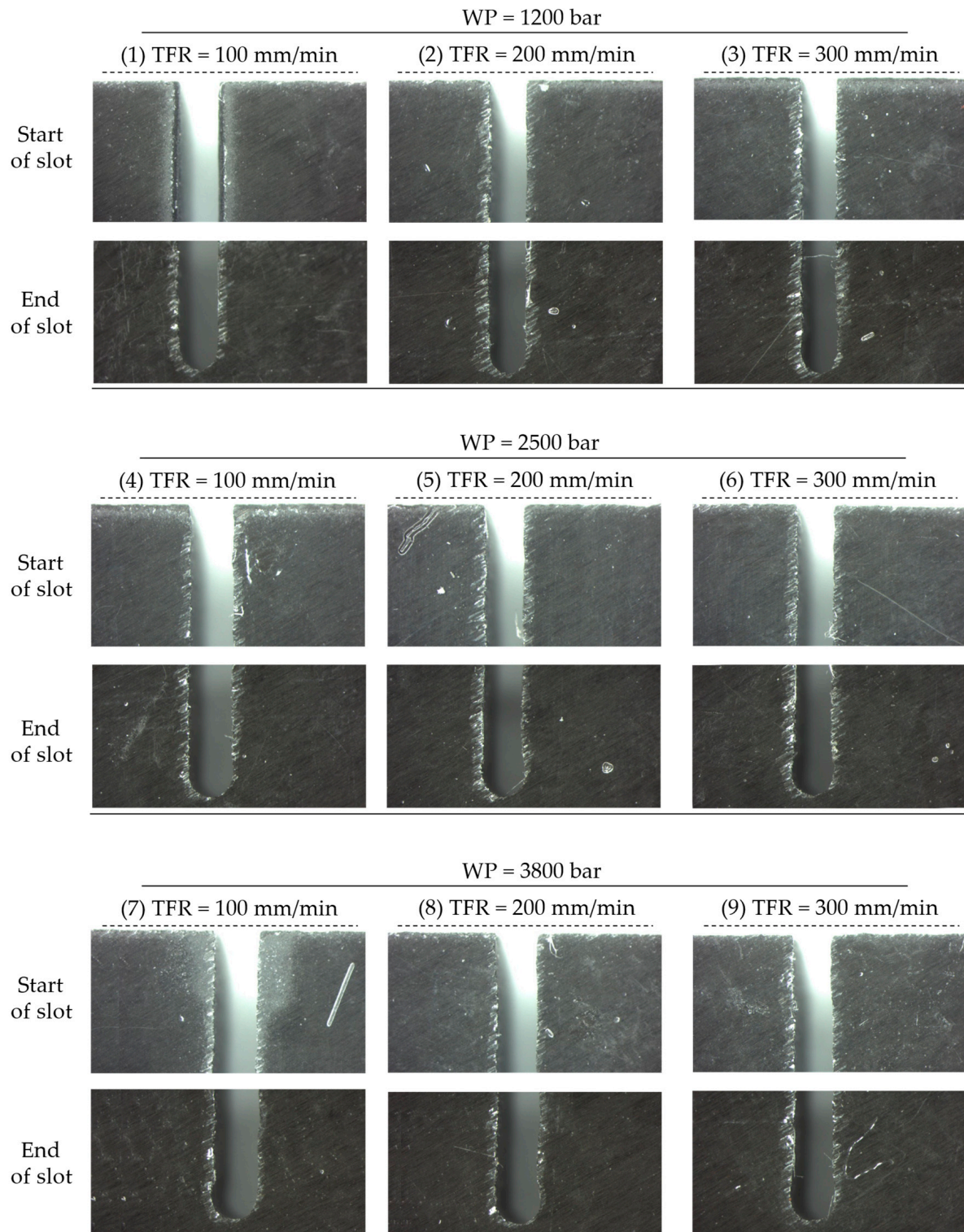


Figure 3. Macrographs of the post-processed areas using abrasive water jet machining taken on the bottom face of composite (20× magnification).

In general terms, Type I delaminations are the most predominant along all the slots made, with Type III delaminations appearing punctually along the slots, while Type II delaminations are random and of very small size.

The Type I delaminations, as occurred previously in the milling process, are found to be oriented at -30° ; this is due to the fact that the exposed layer was stacked in that

direction. Therefore, it can be concluded that the most prominent abrasive water jet delaminations are Type I and are generated on the exit face of the abrasive water jet, which, in this case, coincided with the bottom face lamination. Furthermore, the orientation of these delaminations will coincide with the orientation of the layer in which they are found. This agrees with what Kumaran et al. concluded in their paper [31] after machining a 6 mm thick unidirectional laminate. In this case, they observe the same type of delamination in the contour reaching the conclusion that this type of delamination depends on the fiber orientation.

Regarding the influence of the cutting parameters on the delaminations, comparing the slots carried out with the same pressure, it is observed that those performed with lower feed speed (100 mm/min), slots 1, 4, and 7, are the ones that generate a lower number of Type I delaminations. Meanwhile, the slots machined with feed rates of 200 mm/min and 300 mm/min show similar results, but in any case, they do not equal the finish obtained with 100 mm/min, being the ones with the highest speed those that show a slightly higher number of delaminations for the executions with 1200 bar and 3800 bar.

Fixing the speeds and comparing the slots with different pressures, it is generally observed that the slots machined at higher pressures offer better results. That is to say, slots 7, 8, and 9 have a lower number of Type I delaminations than those tested at the same speed but with lower pressures. Therefore, as a partial conclusion, the lower the feed speed and the higher the abrasive water jet pressure, the better the results obtained at the macroscopic level (delaminations).

Finally, it should be noted that in slot 1, a particularity is observed: in the first millimeters of this slot, the best results are obtained, providing a surface with almost no delaminations, as observed in the macrograph of the entrance of slot 1. However, in the macrograph of the exit of the jet from slot 1, the number of delaminations expected for these cutting parameters begins to be generated, that is, a higher number of delaminations than slots 4 and 7. This may have happened due to a higher abrasive mass flow rate that may have occurred at the beginning of the slotting operation. In such a way that, after stabilization of the abrasive mass flow rate, the result at the end of the slot corresponds to what was expected.

In general terms, the results obtained show that abrasive water jet cutting generates repetitive results that can be directly related to the preset cutting parameters. On the contrary, in machining by milling, in addition to the variability associated with the cutting parameters, the wear suffered by the tool must be taken into account, resulting in a less predictable cutting process. Regarding the type of delamination, each process has a specific type of macrogeometric deviation, with Type II delamination in milling and Type I in AWJM; the latter can also be taken into account depending on the type of defect that can be assumed in CFRP cutting.

3.2. Analysis of the Surface Finish Obtained in Slot Milling

Regarding the analysis of the surface finish, Figure 4 shows a graphical representation of the mean values and deviations of the Ra variable obtained for the machining of slots by milling. It should be remembered that the mean values were obtained by taking 3 Ra measurements on each wall of the slot (climb milling and conventional milling). In general terms, it seems that there is no trend defining a clear difference between the values obtained on both slot walls. However, a predictable state is shown in the down direction zone results on the left wall of the slot, and it is somewhat less predictable in the up wall results on the right wall of the slot.

The difference between these behaviors may be due to the different material removal mechanisms occurring in each zone of the slot. It is well known that the direction of feed in milling affects the chips generated during the process. The finish obtained on the entry walls is obtained after the removal of the crescent-shaped material, while the material removal technique on the exit wall is carried out with the typical opposing milling scheme

(Figure 1b). This may justify the somewhat more predictable behavior of the average Ra values obtained for a pro and climb milling strategy.

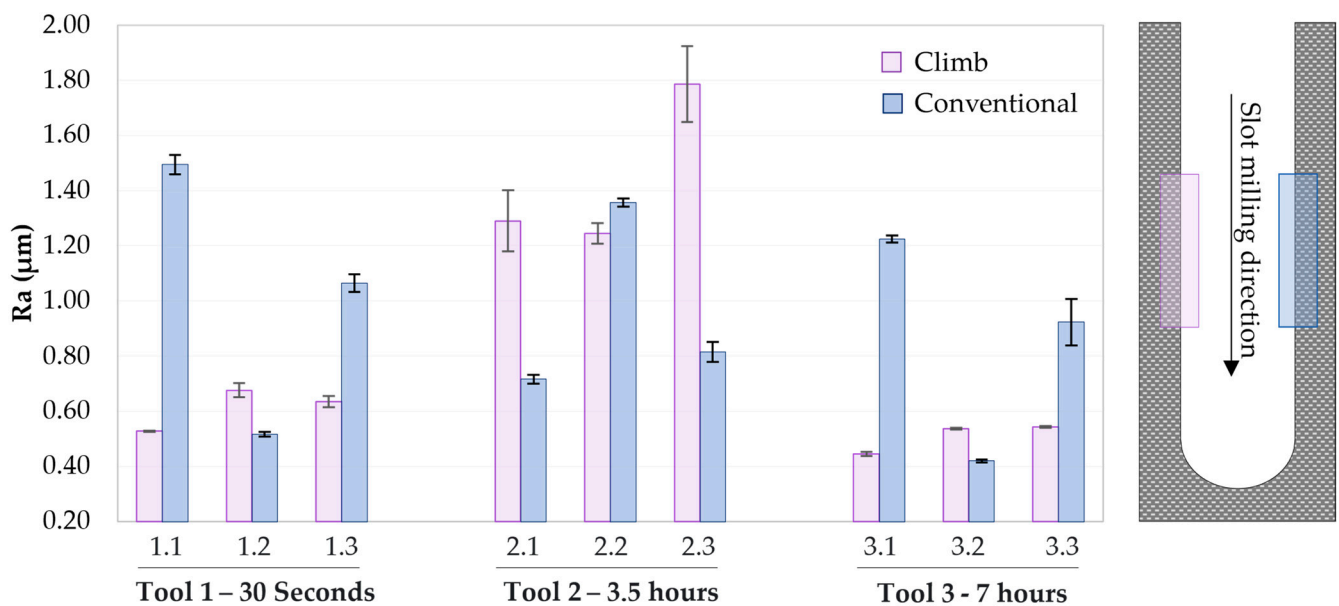


Figure 4. Graphical representation of average values of the arithmetic mean roughness (Ra) obtained in each slot zone post-processed by slot milling.

For the 30 s tool and the 7 h tool, the left wall (climb milling) has a better surface finish than the right wall (conventional milling). These better results may be due to the fact that in the entry of the slot, a greater number of teeth work to generate the removal of the crescent-shaped material to give a more regular geometry. On the other hand, to eliminate the typical geometry of opposed milling, fewer teeth are used, and the material removal can be more abrupt, even generating a greater number of vibrations, starting with a chip width much greater than the final one.

On the other hand, it can be seen that the tool that has machined an intermediate time (tool 2; 3.5 h) is the one that has generated the highest average Ra values in the downward slotting with 100% diameter. In fact, this tool, in its three evaluated slots, has generated the largest deviations of the experiment. This randomness of the results obtained may be due to accumulated tool wear. When machining this type of composite, abrasive wear may appear due to the carbon fibers or adhesion on the cutting tool due to the resin used in the material. It may be that tool 2 had punctual wear at the time of the tests carried out, such as adhesion wear due to the matrix composite or flank wear of a tool's cutting edge.

Once the behavior of the surface finish obtained for each section of the cutting slot has been analyzed, it is necessary to talk about the total surface finish obtained for each slot machined by milling. Therefore, in Figure 5, the mean values of each slot can be seen, together with the standard deviation of each combination of parameters. Averaging the values obtained in each slot without differentiating the climb milling from the conventional milling, the error bars shown in Figure 5 have increased in length with respect to Figure 4.

These average Ra values are between 0.5 and 1.3 μm, results that are in agreement with those obtained by other authors under similar cutting parameters when machining CFRP parts. For example, Schornik et al., in their research [28], obtained Ra values of 0.6 μm by opposing milling at 200 mm/min feed rate. On the other hand, Gara and Tsoumarev, in their article [30], use a tool similar to the one used in our article with a diameter of 8 mm and a number of teeth of 14. The researchers obtain a value of 1.53 μm in their opposed milling with a cutting speed of 100 m/min.

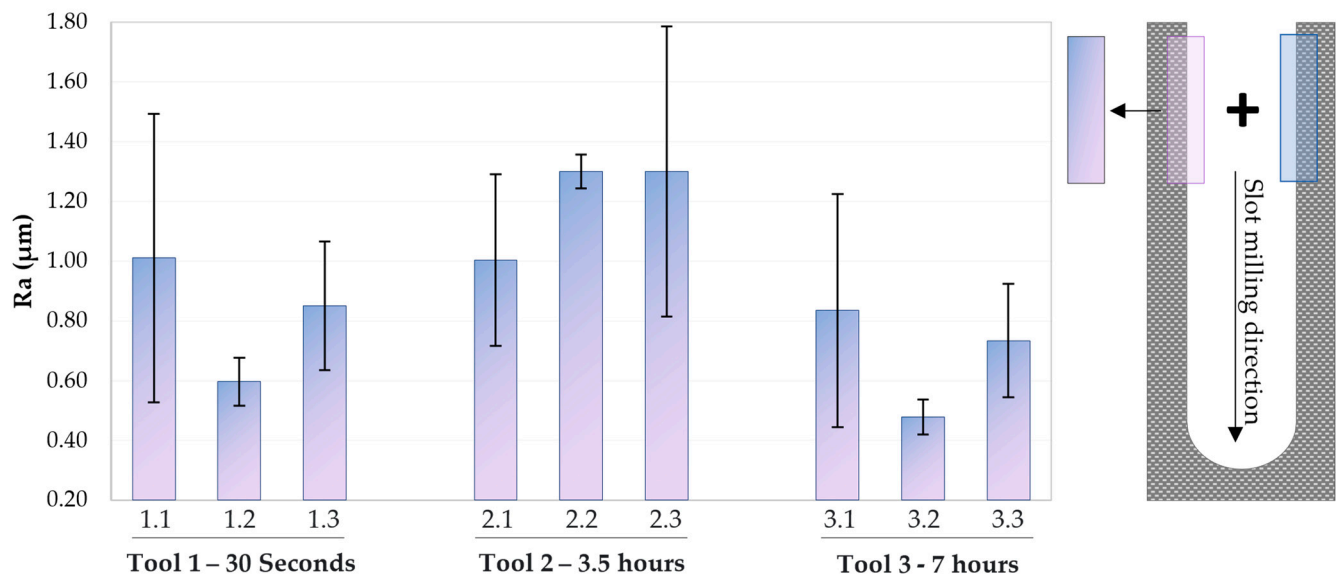


Figure 5. Graphical representation of average values of the arithmetic mean roughness (Ra) obtained post-processed by slot milling.

The data obtained show that the worst microgeometric results obtained were in slots 2.1, 2.2, and 2.3, that is, with the tool in a semi-new state after 3.5 h of use. Again, it may be that the punctual wear of the tool produced by the adhesion of the resin or the abrasion of the fibers has made the condition of the tool unsuitable for machining, as shown in Figure 6.

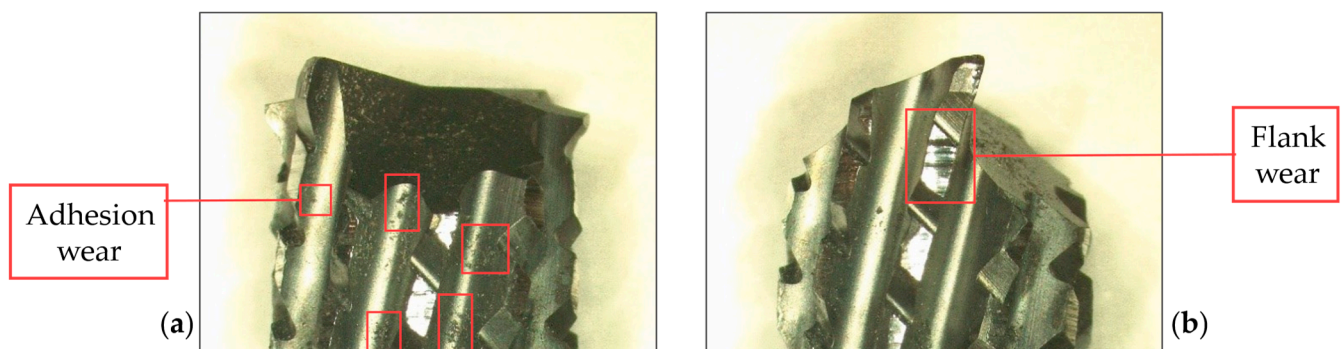


Figure 6. Macrographs of the wear of tool with several minutes of operation time: (a) Adhesion wear due to composite matrix; (b) Flank wear of a tool's cutting edge.

Consider the wear on the tool after making these three slots. In Figure 6a, particles adhere to the surface of the tool. An increase in temperature during machining can cause adhesion of the resin used in the composite; a modification of the geometry of the tool can be seen.

On the other hand, in Figure 6b, the flank wear caused by one of the teeth of the cutting-edge tool can be observed. These wear mechanisms may have caused the very random results generated in tool 2.

As for the other two tools (tools 1 and 3; 30 s and 7 h), very similar roughness values are obtained. It is again observed that the results obtained with the tool with the longer tool time are better than those obtained with the new tool. It is worth noting the result obtained in slot 3.2 with a Ra value of 0.48 μm and a deviation of 0.06 μm, being the lowest of those generated in the experiment of slotting by milling.

3.3. Analysis of the Surface Finish Obtained in Slot AWJM

After having analyzed the surface finish results obtained in machining by milling, this section will analyze the finish of the slots carried out by AWJM. The results will be shown analogously to the milling results in order to facilitate the understanding of the discussion carried out.

In Figure 7, we can see the mean values of each damage zone in each slot obtained: IDR, SCR, and RCR. It is worth remembering that in each of the damage zones, three measurements were performed with the roughness meter so that each cut slot has a total of 9 measurements of the Ra value. First of all, it is worth noting the deviation that each of the Ra values obtained in each section of the slot has. The deviations obtained are minimal, not being appreciable on the scale at which the graph is displayed. This range of deviations leads to the conclusion that the AWJM process results in a wide reproducibility and repeatability of the results obtained.

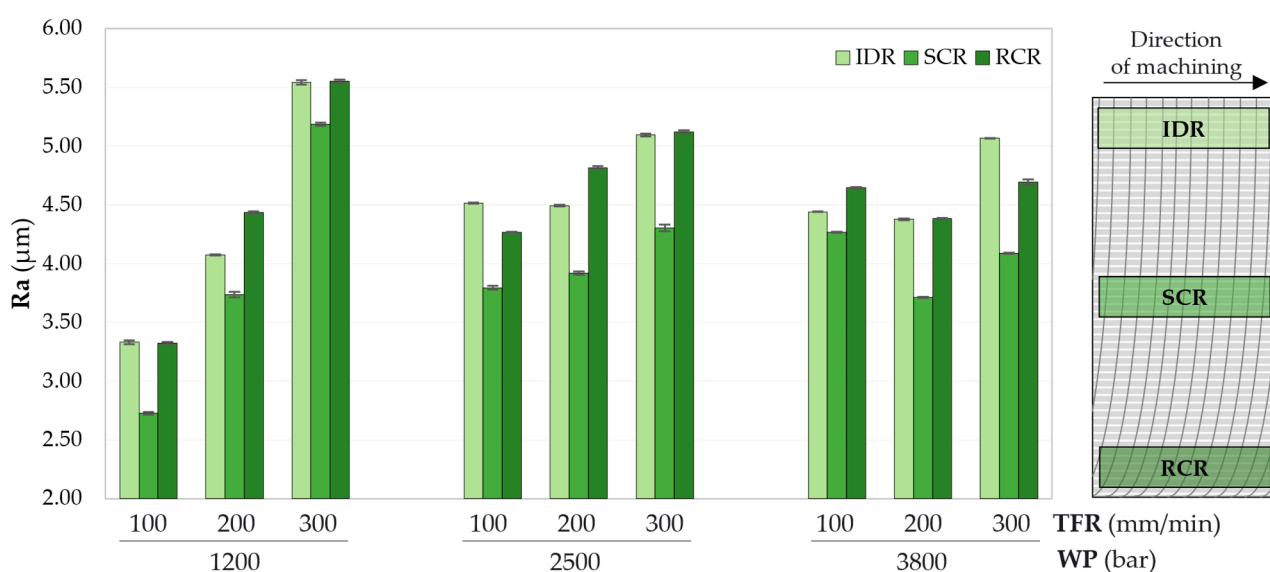


Figure 7. Graphical representation of average values of the arithmetic mean roughness (Ra) obtained in each damage region of section post-processed by AWJM.

Regarding the average values obtained, it can be seen that, in general, the lowest Ra values are obtained for the SCR smooth cutting region in all the combinations of parameters used in the experiment. This makes sense since, in this zone, the kinetic energy of the water jet is stabilized and generates a more homogeneous shear. Authors such as Ruiz et al., in their article [40], make a distinction between three cutting zones in the section of their material, arriving at a similar discussion. Ruiz shows in his article trends of values similar to those obtained in our experiment with better surface qualities in the smooth cutting region.

On the other hand, Figure 7 shows how the initial damage region (IDR) and the rough cut region (RCR) are the ones that obtain the highest Ra values, with results being very similar to each other. These values make physical sense since, in the initial damage region, all the kinetic energy of the abrasive water jet is impacted. A large amount of kinetic energy accumulates on the top surface of the material, and it looks for a path through the slot section to pass through the material. However, much of this abrasive water jet remains on the surface of the material and fails to pass through. This generates a rounding zone on the surface of the material, which can be seen in Figure 8.

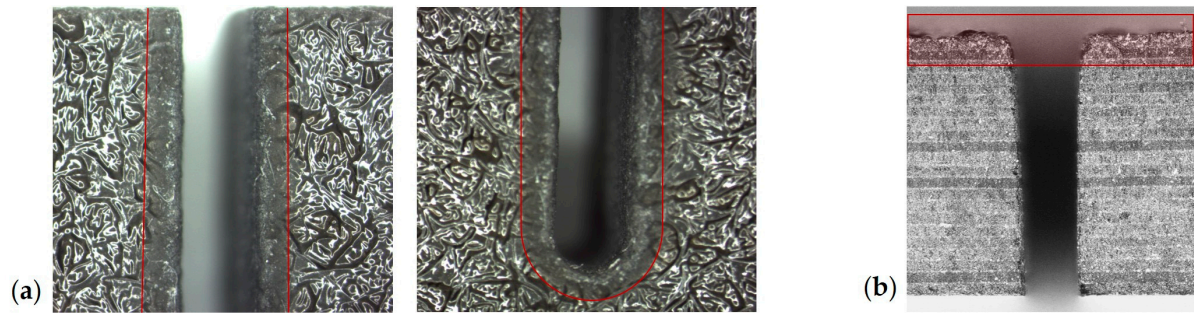


Figure 8. Macrographs of the Initial Damage Region (IDR): (a) Top view; (b) Side view.

The curvature produced in the upper part of the material causes the surface finish in that zone to be superior to that obtained in other zones of the cut section. Authors such as Dhanawade et al., in their research [41], talk about the initial damage region. Dhanawade, in his article, mentions that the water jet can lose kinetic energy upon impact with the upper surface of the material, generating irregularities in the form of a taper angle at the beginning of the cut section, as observed to have occurred in our experiment (Figure 8b).

As regards the RCR zone, it can be noted how, after passing through the intermediate zone (SCR), the Ra values tend to rise, generating a worse surface finish. As the water jet passes through the cut section, it progressively loses kinetic energy. This effect is more noticeable in thick materials. Along the section of the material cut by AWJM, a curved trajectory can be seen that shows how the water jet has not traversed the material perpendicularly but has lost kinetic energy due to the resistance that the material is giving it and the forward speed of the head. In fact, there are many authors who corroborate this effect; among them, authors, such as Ramakrishnan S. in his article [42], show how the lagging effect or jet delay is generated in a similar way to the experiment performed on CFRP in our article, although the material is different in his research on the AWJM machining of a titanium alloy.

Once the effect of the surface finish on the different zones of the cross-section has been analyzed, the average values obtained in each slot are studied. Thus, Figure 9 shows the mean value of Ra for each combination of cutting parameters together with the deviation generated in each slot.

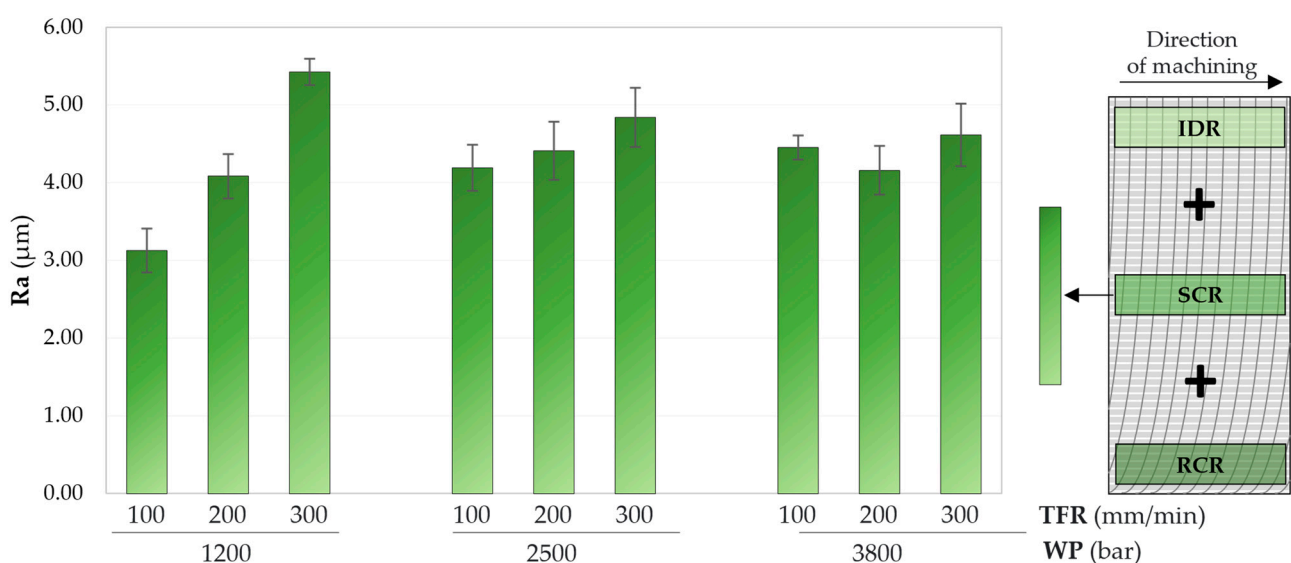


Figure 9. Graphical representation of average values of the arithmetic mean roughness (Ra) obtained in each slot post-processed by AWJM.

First of all, it is worth noting the significant increase in the deviations of the experiment in general. This effect is not surprising since it is obtained by averaging the different values of the three cutting regions in the same slot. As mentioned above, the IDR and RCR regions presented similar Ra values; however, the intermediate SCR region had lower Ra values, generating a larger deviation when averaging these regions.

In terms of the cutting parameters, it can be observed that as the traverse feed rate increases, the surface finish obtained is worse, generating higher values of Ra. Thus, it can be seen that the combination of 300 mm/min and 1200 bar is the one with the highest Ra value since it is the combination of parameters with the lowest kinetic energy. This upward trend related to the traverse feed rate becomes progressively less prominent as the hydraulic pressure increases. In fact, the upward trend for the pressure of 3800 bar is practically nonexistent. It is more complex to show clear differences between the traverse feed rate of 100 and 300 mm/min at this hydraulic pressure.

On the other hand, it should be noted that the lowest value of Ra, i.e., the best surface finish obtained, is generated by a hydraulic pressure of 1200 bar. In principle, this effect may be surprising since it is generally thought that the higher the pressure, the higher the material removal. However, there are many investigations that show how a higher hydraulic pressure can generate higher Ra values due to the turbulences generated by the water jet and the abrasive particles at higher hydraulic pressure [43].

3.4. Scientific-Technical Discussion between Milling and AWJM

Once the surface finish results obtained for each cutting technology have been discussed, it is necessary to carry out a joint scientific-technical discussion of both processes. In general terms, it can be seen that the average Ra values obtained for slot milling were lower than those generated in AWJM. The material removal generated during the milling process occurs horizontally. Each of the cutting tool's teeth penetrates horizontally into the material to be machined. In the case of the experiment carried out by AWJM, the removal of material occurs vertically, i.e., the water jet impacts the surface of the material until it passes through the cutting section.

This material removal mechanism must be taken into account since the composite material used in our experiment consists of multiple layers of fiber and resin arranged horizontally. In the case of water jet machining, the impact of the jet on the top surface of the material can cause separation of the layers through a shearing effect. However, when performing the milling operation, the layers of the composite material may be less damaged by the effort involved.

Figure 10 presents a graphical representation of the Ra values obtained for the same feed rate of 200 mm/min in both machining processes. Having the same TFR, the milling results vary according to the tool wear (Tool 1, Tool 2, and Tool 3), while the AWJM values vary according to the applied cutting pressure (1200, 2500, and 3800 bar). In this figure, it can be clearly seen what has been explained above: under similar parameter conditions, the values of Ra are higher in AWJM than in milling. In our experiment, Ra values were four times higher in AWJM than in milling.

However, regarding the deviations shown in the experiment, it is noted that both processes show very low values, denoting the reproducibility and repeatability of both experiments. The abrasive water jet cutting process even generates lower deviations than those originated by milling.

On the other hand, it is necessary to examine the relevance of the results obtained at the statistical point of view. Therefore, Figure 11 shows a graphical representation of the results of an analysis of variance (ANOVA) carried out for each of the processes examined in this article. First, it can be seen how the significance of the parameters used in the milling process is lower than the significance of the AWJM parameters. This can be seen both in the p and F values generated by the analysis and in the model fit, which has different R^2 values between the two processes. Thus, the water jet cutting process generates an R^2 of 98.17%, denoting the good fit of the results obtained in our article.

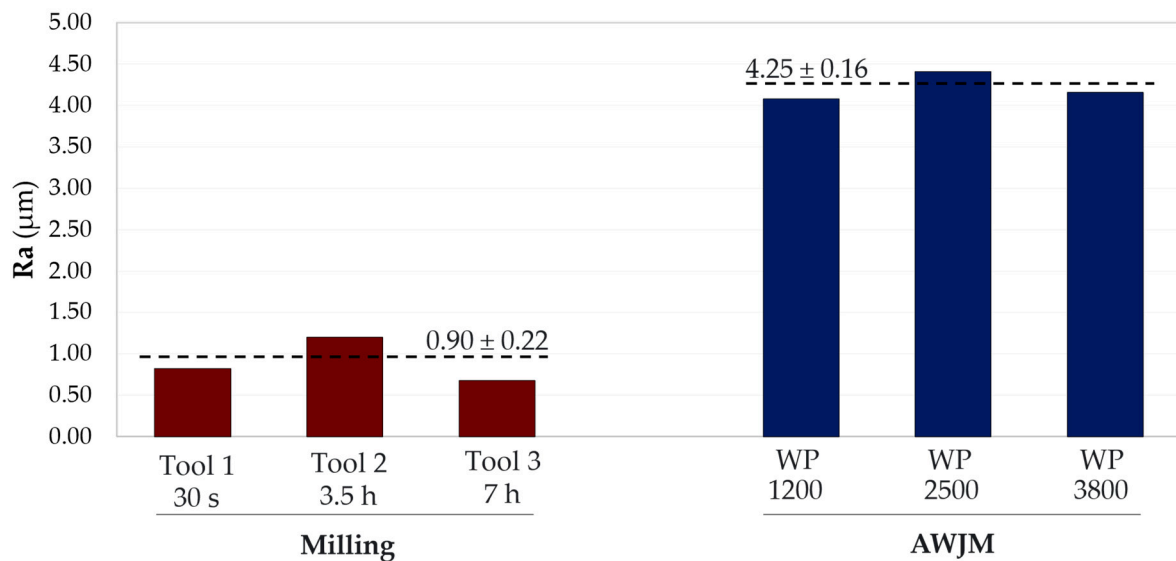


Figure 10. Graphical representation of average values of Ra values for a TFR of 200 mm/min post-processed by milling and AWJM.

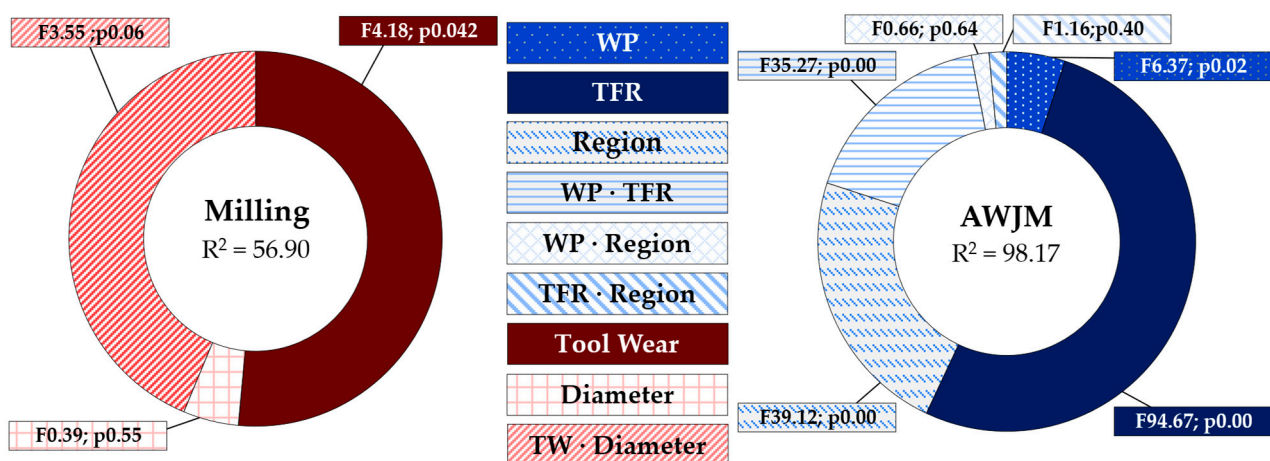


Figure 11. Statistical contribution of cutting parameters using F -value and p -value of AWJM and milling slots.

In general terms, the milling parameters show a p -value close to 0.05, from which the influence begins to be greater. In the AWJM process, a clear influence of the TFR parameter, the cutting region of the section, and the hydraulic pressure are denoted. On this occasion, it is the traverse feed rate parameter that has the greatest significance, showing a p -value of 0 and an F -value of 94.67.

Authors such as Abidi et al. in their research [44] have conducted experimental studies of CFRP machining by milling and AWJM, reaching similar conclusions to those generated in this article. Abidi describes in his research that he obtains results of higher quality and a lower number of uncut fibers on the surface for machining by AWJM. Likewise, Abidi describes how the delaminations generated in the milling process are greater than in AWJM, but the surface finish is better than in AWJM.

Other authors, such as Pahuja et al. in their research [45], analyzed the surface finish of a composite material similar to the one used in this article by milling and AWJM. Pahuja, in his research, noted that better surface finish results were obtained in milling than in AWJM. In addition, Pahuja mentions that a combination of low hydraulic pressure and high traverse feed rate generated the highest roughness value, coinciding with the results of our experiment.

3.5. Socio-Economic Discussion between Milling and AWJM

Once a scientific-technical discussion of the results obtained in this work has been carried out, it is necessary to carry out a discussion from other points of view. Specifically, in this section, the aim is to compare the experiment carried out in socio-economic terms where sustainability, environmental and social aspects are some of the most relevant factors.

In terms of sustainability, this research highlights the importance of finding sustainable methods for machining carbon fiber reinforced polymers (CFRP). The abrasive water jet cutting (AWJM) technique is presented as a more sustainable alternative to conventional milling because of its ability to eliminate the use of cutting fluids. It is well known that cutting fluids are a significant problem in terms of sustainability due to the hazardous waste they generate and their environmental impact. AWJM, by dispensing with these fluids, significantly reduces environmental pollution and the costs associated with the handling and treatment of these wastes. However, it should be noted that the AWJM process uses abrasive particles that, when mixed in water with the CFRP chip, can be difficult to recycle.

On the other hand, operation times are reduced in AWJM, ensuring robustness in the results obtained. This fact, together with the low deviations caused in the AWJM experiment, implies that the part will fulfill its objective with greater robustness, reducing the possibility of failure or repairs and extending its useful life.

Regarding the environment, AWJM machining is more favorable because it minimizes the adverse thermal effects on the material, which not only prolongs tool life but also avoids the generation of hazardous waste from the use of cutting fluids. In contrast, as mentioned above, conventional milling requires the use of these fluids to lubricate and cool the tools, which implies a considerable environmental impact due to the management and disposal of these fluids. Although techniques such as minimum quantity lubrication (MQL) used to mitigate these effects, they are not able to completely eliminate the associated environmental problems.

From an occupational safety perspective, the use of cutting fluids in conventional milling can cause damage to operator health, including skin irritations and respiratory problems due to inhalation of toxic vapors. In addition, the compound chips generated during the machining process by milling are suspended in the air if the CNC equipment does not have a good dust extraction system. This problem does not occur in abrasive water jetting since the inertia of the water jet allows the carbon fiber particles to be introduced into the water tank, where they can be recycled later.

Economically, although conventional milling with this type of high-carbon steel tool offers longer life and better finish quality, the costs associated with these tools and cutting fluids are high. In contrast, AWJM may represent a higher initial investment in equipment but has lower long-term operating costs due to the elimination of cutting fluids and less tool wear.

4. Conclusions

The main conclusions of this article will be developed below. In this research, a comparative of machining by slot milling and abrasive water jet cutting of carbon fiber reinforced polymers, in terms of surface finish and defects and delaminations generated, has been developed. The following points can be identified as conclusions:

- As for defects and delaminations obtained in milling, they tend to accumulate in the area where the tool changes direction, highlighting Type II delaminations in that area due to the orientation of the material layer. On the other hand, milling has been found to be less predictable due to tool wear, while abrasive water jet cutting produces more consistent results related to preset cutting parameters. Each machining process generates a specific type of macrogeometric delamination in general: Type II in milling and Type I in AWJM.
- Regarding the surface finish obtained in machining by milling, no clear trend has been observed in the differences in Ra values (average roughness) between the left (climb milling) and right (conventional milling) walls of the slots. However, the results on

the left wall are more predictable. In addition, the difference in roughness behavior may be due to the different material removal mechanisms in each slot zone.

- The tool with the longest machining length, i.e., with the longest working life (7 h), achieved the lowest Ra value (0.48 μm with a deviation of 0.06 μm) in slot 3.2, highlighting the importance of controlled and uniform tool wear.
- As for AWJM machining, it has been noticed that the lowest Ra values are obtained in the smooth cutting region (SCR) for all parameter combinations. This is because the kinetic energy of the water jet is stabilized in this zone, generating a more homogeneous cut. In addition, the combination of 300 mm/min and 1200 bar presents the highest Ra value. However, this effect decreases with increasing hydraulic pressure and is practically nonexistent at 3800 bar.
- The lowest value of Ra, i.e., the best surface finish, is obtained at a hydraulic pressure of 1200 bar. This may be unexpected as higher pressure is expected to remove more material, but previous research indicates that higher hydraulic pressure can generate higher Ra values due to turbulence in the water jet and abrasive particles.
- After analyzing the data statistically, it could be seen that the parameters of the abrasive water jet cutting (AWJM) process are more significant than those of the milling process. The abrasive water jet cutting process (AWJM) shows an excellent model fit, with an R^2 of 98.17%, indicating that the results obtained fit the parameters analyzed in the study very well.

In summary, the comparison between conventional milling and AWJM in CFRP machining highlights the importance of balancing environmental sustainability, occupational safety, and economic efficiency. AWJM emerges as a more sustainable and safer alternative, although both methods have their own advantages and challenges that must be carefully managed to optimize results.

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