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ORIGINAL ARTICLE

Study of the surface quality of carbon fiber–reinforced thermoplastic matrix composite (CFRTP) machined by abrasive water jet (AWJM)

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Abstract

Carbon fiber-reinforced thermoplastics (CFRTP) have great interest nowadays due to their excellent mechanical properties and lightness. However, in opposition to thermoset matrix composites, there is a lake in the research about machining processes of these materials. Their low glass transition temperature is a handicap when conventional machining is used. An alternative is abrasive water jet machining (AWJM) because it does not cause thermal damage. However, the surface quality produced by this process must be studied and related to the cutting parameters. This article studies the surface quality generated by water jet machining in a low melting point thermoplastic matrix composite material. The kind of thermoplastic used is a TPU (polyurethane). The combination of a high-strength material (carbon fiber) with a low-strength material (thermoplastic matrix) makes machining difficult and can generate a poor surface finish. The influence of cutting parameters has been evaluated through an ANOVA analysis. A mathematical model that relates the surface quality with the cutting parameters has been established by means of a response surface methodology (RSM). The combination of a hydraulic pressure of 250 MPa with a traverse speed of 300 mm/min and an abrasive mass flow of 170 g/min produces the best surface quality. Finally, the main flaws when CFRTP is water jet machined have also been identified.

Keywords AWJM · CFRTP · Surface quality · RSM · ANOVA · C/TPU

1 Introduction

Most literature about machining of composite materials is focused in carbon fiber-reinforced plastics with thermoset matrix (CFRP), mainly due to the fact that they are difficult to machine materials [1–3]. CFRP materials stand out for their excellent weight/mechanical property ratio. This makes them strategic materials for the aeronautical sector in order to reduce the final weight of the aircraft.

However, carbon fiber-reinforced thermoplastics (CFRTP), a composite material with thermoplastic matrix, are being considered as an alternative in recent years [4–6]. Its manufacturing process differs from thermosets. This is based on the fabrication of stacks by thermoforming. Nevertheless, high temperatures are generated during the process. Thermoplastic polymers do not release gases or water vapor if they are correctly dried before processing [7]. As well, once joining, CFRTPs have a high impact resistance, excellent chemical resistance, and a long service life. Also, they have an excellent weight/mechanical properties ratio, and high recycling efficiency. In addition, high-performance

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thermoplastics can achieve higher operating temperatures than thermosets [8, 9]. In terms of manufacturing processes, they can achieve lower process times than CFRPs [9, 10]. Therefore, CFRTPs are being considered as strategic materials for the future development of the transport sector. These materials can minimize the final weight of the structure, which both reduce CO_2 emissions [10].

These materials must be machined to obtain a final geometry, which usually have to satisfy high quality requirements. There are few scientific literatures about the machining of CFRTPs, and it is mainly focused in conventional operations such as drilling, milling, or disk cutting [11–13].

Conventional machining operations can produce several defects, caused by high process temperatures. In addition, process rates can be unproductive resulting in low material removal rates. This may require specific geometries to avoid defects such as internal delaminations or matrix degradation. The low melting temperatures of thermoplastic polymers usually result in matrix losses, producing a defect denoted as burr according to [4]. This fact, together with the abrasive wear generated by carbon fibers, makes the conventional machining of CFRTPs a difficult task.

An interesting alternative process is abrasive water jet machining (AWJM), a very useful non-conventional machining for the cutting of dissimilar materials at once [14–16]. It is a flexible process that generates low thermal damage to the machined surface as there is no continuous tool-material contact along the machining process [17–19]. Compared to conventional processes such as milling, abrasive particles are used in water jet machining. These particles have cutting edges that allow the machining of the material by overlapping of small impacts that deform the material. At each instant, a quantity of abrasive particles travels in the water jet in order to perform the cut. In addition, although there is wear in the elements that make up the AWJM equipment (nozzle and mixing tube), this is much less than that produced in cutting tools in conventional processes.

Also, it is a process that can generate more reduced forces during the machining process than those resulting from processes such as milling [20].

As there is little literature focused on abrasive water jet machining in thermoplastic matrix composite materials, research on thermoset composite materials is considered. Due to their nature, the results obtained can be taken as reference.

Mayuet et al. [21] developed a study about the type of defects caused in the water jet machining of CFRP. It is composed by a 0/90° thermoset composite material with a thickness of 4 mm. This research shows that the main defect caused was delaminations, which can be reduced by a combination of high hydraulic pressure and high abrasive mass flow.

Another relevant defect is the opening of the water jet channel, called taper angle. This defect is related to the transverse traverse speed and the loss of kinetic energy in the cutting channel [16, 22, 23]. In this line, one of the main requirements when a machining process is industrialized is the surface quality. High surface quality requirements can be reached in AWJM by applying high hydraulic pressures, increasing the water jet kinetic energy and reducing its divergence. Ming et al. [24] have studied the influence of cutting parameters in the surface quality through response surface methodology, obtaining a mathematical model that allows to predict optimal ranges for cutting parameters. At the same time, it is appointed that abrasive flow mass is the main factor that affects surface quality, followed by the stand-off distance and the hydraulic pressure.

Similar results have been obtained by Kumaran et al. [25], who concludes that high hydraulic pressures with low transverse traverse speeds improve the surface quality. This research used an ANFIS model in the range of 220 and 260 MPa for hydraulic pressures, 20 and 40 mm/min for transverse traverse speed and 1–3 mm for stand-off distance. Also Ahmed's [26] and Jagadish's results [27] are in agreement with Kumaran, but in these cases making use of a RSM statistical model to study the influence of cutting parameters.

El-Hofy et al. [17] studied the influence of cutting parameters in two different CFRP configurations in the range of 100–350 MPa, 50–150 mm/min, and 2–4 mm for stand-off distance, concluding that hydraulic pressure is the most important factor in surface quality. Both plates are composed of an epoxy resin cured by autoclave with fibers of T800 module and a final thickness of 10.4 mm. This does not match with the results obtained by Ming [24]. El-Hofy indicated that increasing hydraulic pressure, rises the water jet kinetic energy, reducing the lag generated by the high transverse feed and so, improving the final surface quality. Nevertheless, in terms of cutting thickness, Jagadeesh et al. [28] demonstrated that the increase of thickness in CFRP machining has heavy wear effects on surface quality, while the increase in traverse speed significantly deteriorates surface quality.

On the other hand, the study of abrasive water jet machining on thermoplastic matrix composite materials—CFRTP—has not been sufficiently studied, highlighting the works developed by Pahuja et al. [14, 29] and Kakinuma et al. [30].

Pahuja et al. carried a study on the AWJM machining of a *fiber metal laminate* (FML) composed by titanium and graphite sheets bonded by a thermoplastic (PEEK) matrix. In this research, main defects were taper angle and surface quality. RSM was used to obtain a predictive mathematical model in order to predict the formation of these defects, together with a new one, so-called "hydro-distortion", that comes given by the different machinability of the stacked materials [14, 29].

Kakinuma addresses a wider technological study, by comparing different non-conventional technologies like *ultrasonic vibration-assisted drilling* (UVD), *ultrafast feed drilling*

(UFFD), and *abrasive water jet drilling* in CFRTPs. It is composed of a PA66 nylon thermoplastic with a fiber content of 45% and a final thickness of 3 mm. In this case, it is reported that the application of high pressures may cause general damage to the surface of the CFRTP. It is also remarked that surface quality in AWJM is worse than UFFD, due to the fact that the surface is covered by the matrix, which has been melted and adhered. However, for both processes, average roughness (R_a) values are similar and close to the values required in the industry [30].

The literature about the machining of CFRPs and CFRTPs by AWJM does not show convergence in the published results. For both materials, it seems that hydraulic pressure is the main parameter, but the influence of abrasive flow mass is also considered as very relevant.

In the same way, the defects generated in the water jet machining of CFRTPs are not detailed and studied in depth in the bibliography. Pahuja and Kakinuma set new advances in water jet cutting of thermoplastic composites. Both study the surface quality obtained after machining in terms of roughness average means (R_a). Pahuja et al. [29] focus on machining hybrid structures joined by thermoplastic matrix (TiGr) and Kakinuma et al. [30] established a comparison of technologies for drilling operations in CFRTP. In this way, Kakinuma makes an approximation to the final state of the surface quality in CFRTPs after machining operations. This article concludes that the use of abrasive water jet machining in CFRTPs achieves R_a values obtained by other technologies in the industry for a thickness of 3 mm.

From the literature studied on the machining of CFRTPs, no relationship has been identified between AWJM cutting parameters and the surface quality obtained. Based on the literature on the machining of thermoset composites, hydraulic pressure and abrasive flow appear to be the most influential parameters on surface quality. However, this may differ in machining of thermoplastic composites. In addition, literature indicates that according to the combination of cutting parameters, there may be three regions of different surface quality after abrasive water jet machining. A first region affected by the erosion of abrasive particles, a second with a smooth surface and a last one with a high roughness due to the loss of cutting capacity of water jet.

This article studies the influence of cutting parameters in water jet machining of CFRTP composite materials, focusing towards a relevant aspect that is not enough studied in the bibliography, the final surface quality.

This requirement has been evaluated in terms of R_a in three different regions of the machined surface. Mathematical models have been proposed from a response surface methodology, while the influence of parameters has been studied by an ANOVA analysis. In addition, main defects have been identified, and optimal ranges for cutting parameters are proposed.

2 Materials and methods

A TPU thermoplastic matrix CFRTP was selected for trials, with the characteristics shown in Table 1. The carbon fiber weave used is type Twill 200 g/m^2 with a thickness of 0.25 mm. The applied matrix is polyurethane thermoplastic with a melting temperature of 145 °C. Delamination is a critical defect in thin materials. For this reason, in this study, it has been decided to machine a 1.53-mm-thick composite in order to observe the influence of cutting parameters on thin materials.

A surface response methodology (RSM) was previously established. Several studies [24, 29, 31, 32] have used this methodology to relate the parameters studied with the input variables. A total of 20 trials have been obtained by combining the three levels per variable according to the established methodology (Table 2).

These parameters have been designated based on the limitations of the equipment used as well as the levels most employed in the literature reviewed [16, 17, 21, 24, 27, 28].

The objective of using an RSM is to establish an empirical model that establishes multiple linear regression. An ANOVA analysis has been performed using this methodology to subsequently obtain a series of contour diagrams or response surfaces. A second-order polynomial is used to obtain these response surfaces (Eq. 1). This kind of mathematical model is widely used in research on non-conventional machining processes in order to relate the defects studied with the selected cutting parameters [31–34].

$$Y = C_0 + \sum_{i=1}^{k} C_i x_i + \sum_{i=1}^{k} C_{ii} x_i^2 + \sum_{i<j}^{k} C_{ij} x_i x_j + \varepsilon \qquad (1)$$

Table 1 CFRTP characteristics

Ply orientation	Number of plies	Thickness	Thermoplastic	Fiber/matrix (%)
[0°/90°]s	7	1.53 mm	TPU (polyurethane)	74.20 / 25.80
	Tensile strength (MPa)	**Young modulus (GPa)**	**ILSS (MPa)**	
	567.36	45.98	199.10	

Table 2 Cutting parameters set

Parameter	Level 1	Level 0	Level 1
Hydraulic pressure-P (MPa)	120	250	340
Traverse speed-v (mm/min)	100	300	500
Abrasive mass flow-$\dot{m}$ a (g/min)	170	225	340

Y corresponds to the expected response, in this case the mean surface roughness (Ra), x_i are the parameters used in the study, C_0, C_i, C_{ii}, C_{ij}, the regression coefficients, and ε the random error of the model.

A water jet machine (TCI Cutting, BP-C 3020, Valencia, Spain) has been used with a nozzle diameter of 0.8 mm, an orifice diameter of 0.3 mm, and a nozzle length of 94.7 mm. The AWJM machine is equipped with an ultra-high capacity pump (KMT, 158 Streamline PRO-2 60, Bad Nauheim, Germany).

Slots with lengths of 15 mm were machined for each combination of cutting parameters (Fig. 1). Machining starts 10 mm before the material to achieve a constant flow of water and abrasive.

A 120 mesh Indian garnet abrasive size has been used during machining to improve the cutting capacity of the water jet. Figure 2 shows the main chemical composition of the abrasive particles used during machining.

After machining, the surface quality was evaluated through the arithmetic mean roughness parameter (R_a). Although there are more parameters to evaluate the surface quality obtained, the R_a parameter has been widely used in diverse bibliography [16, 24, 35–37] allowing, thus, a comparison of results for the machining of different materials and cutting conditions. A roughness meter was used (Mahr Perthometer PGK 120, Göttingen, Germany), following *ISO 4288:1999* standard. Literature indicates the existence up to three zones of different surface quality in abrasive water jet machining [16, 38]. These zones present a high initial roughness due to the erosive effect, a soft zone where the water jet stabilizes and a zone of poorer surface quality due to the loss of kinetic energy. In addition, due to the low thickness of the material, areas with groove or lag defects are not appreciated. Due to this, parameters such as W_t (maximum height of waviness) used to evaluate the waviness in this type of defect have not been applied [39].

In accordance with the literature [16, 24, 40], three regions of different surface quality are appreciated after machining. Due to the low thickness of the composite, an auxiliary tool has been manufactured to ensure the placement of material on the roughness meter.

R_a was evaluated at three points equidistant at 0.4 mm (Fig. 3) by using a goniometer placed on the evaluation table of the roughness meter, referred to as *Entry*, *Central*, and *Outflow*. Measurements were made at 0.35 mm from the edges. A cut-off of 2.5 mm was established for a total evaluation length of 12.25 mm. Stylus with 2 μm tip radius and 90° tip angle was used for the measurements. Finally, scanning electron microscopy (Hitachi, VP-SEM SU1510, Schaumburg, EEUU) techniques were used in order to characterize the defects produced during the process.

3 Results

3.1 SEM defect identification

As indicated in the literature, the formation of an EAZ at the jet entry is an inherent defect of this process. This is appreciated in Fig. 4, where the change in surface quality is appreciated visually.

Remains of abrasive particles after the impact of the water jet at the entry of the material appear to be adhered to the surface generated after the cutting [21]. They may have adhered to the surface because of the loss of kinetic energy during the process. These particles can generate a rougher zone by increasing the values of R_a at the input.

Two defects in the machining of CFRTPs by AWJM are seen in Fig. 5. On the one hand, there is an area where carbon fibers are visible without matrix in form of delamination. This is due to the erosive effect of the water jet that has eliminated the matrix. This is consistent with the results obtained in [21].

On the other hand, the thermoplastic matrix does not seem to detach in the outflow area of the water jet, remaining adhered to the generated surface. This defect is known as burr in the studies performed in [4, 13], due to the fact that the thermoplastic matrix is removed by the temperatures achieved in conventional processes, leaving the carbon fibers without reinforcement. However, in machining by water jet cutting, the defect generated is the opposite, being the carbon fibers removed in the correct way while the thermoplastic matrix does not detach from the surface giving rise to a fraying defect.

These defects at the outflow may alter the values of R_a, which could result in higher values at the outflow than in the intermediate or entry zones, as in test 9 corresponding to a *pressure* of 250 MPa, a *mass flow* of 225 g/min and a *traverse speed* of 300 mm/min.

The main defect in the machining of composites by water jet machining is delamination [21]. Delaminations are

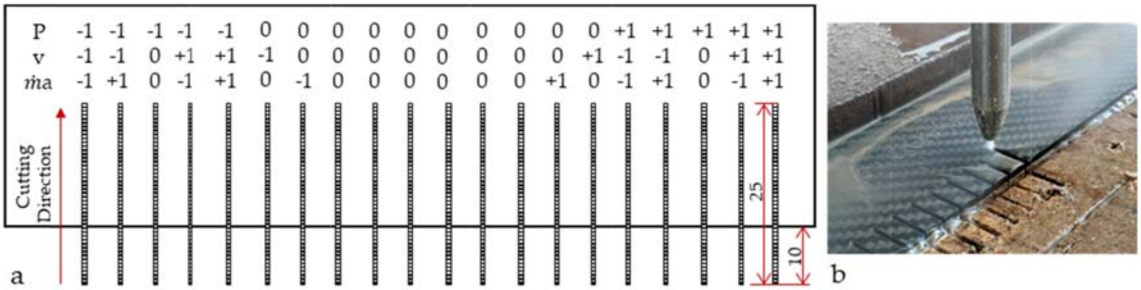


Fig. 1 **a** Graphic representation of the experimental design. **b** Trials carried out

considered as the collapse or rupture in the area of union of the layers that compose the composite material due to the formation of a crack perpendicular to the cut [23].

When the water jet hits the material, the thickness of the unmachined material is constantly reduced. This produces a decrease in its resistance to deformation that may result in the adhesion between layers not supporting the stresses generated producing the delamination defect [21].

At the same time, when the initial separation of the layers is generated and the material is not completely mechanized, the flow of water penetrates through the small cavities generated.

This produces, on the one hand, an increase in the maximum length of the delaminations produced and, on the other, the possibility of penetration and incrustation of abrasive particles in the generated cavities [41], increasing the size of the delamination produced (Fig. 6).

This defect has been only generated for the combination of a *pressure* of 120 MPa with a *mass flow* of 340 g/min and a *traverse speed* of 100 mm/min. This is usually also in the machining of thermoset matrix composites and has been reported previously in [21, 28, 42].

Abrasive particles are introduced in the cavities increasing the separation between the layers that compose the CFRTP. The combination of a very low *traverse speed* with a very high *mass flow* eases the elimination of the thermoplastic matrix. This allows the abrasive particles to remove the carbon fibers and produce delamination.

3.2 Influence of cutting parameters on surface quality

The values of R_a obtained in the three regions (Entry, Central, and Outflow), as well as their arithmetic mean roughness and standard deviation (average R_a), are indicated in Table 3.

In most tests, the highest values of R_a are observed in the area corresponding to the inlet of the water jet. The first contact of the abrasive particles with the material produces an area very affected by erosion until the jet is able to penetrate the thickness of the material. Nevertheless, in two tests, the values

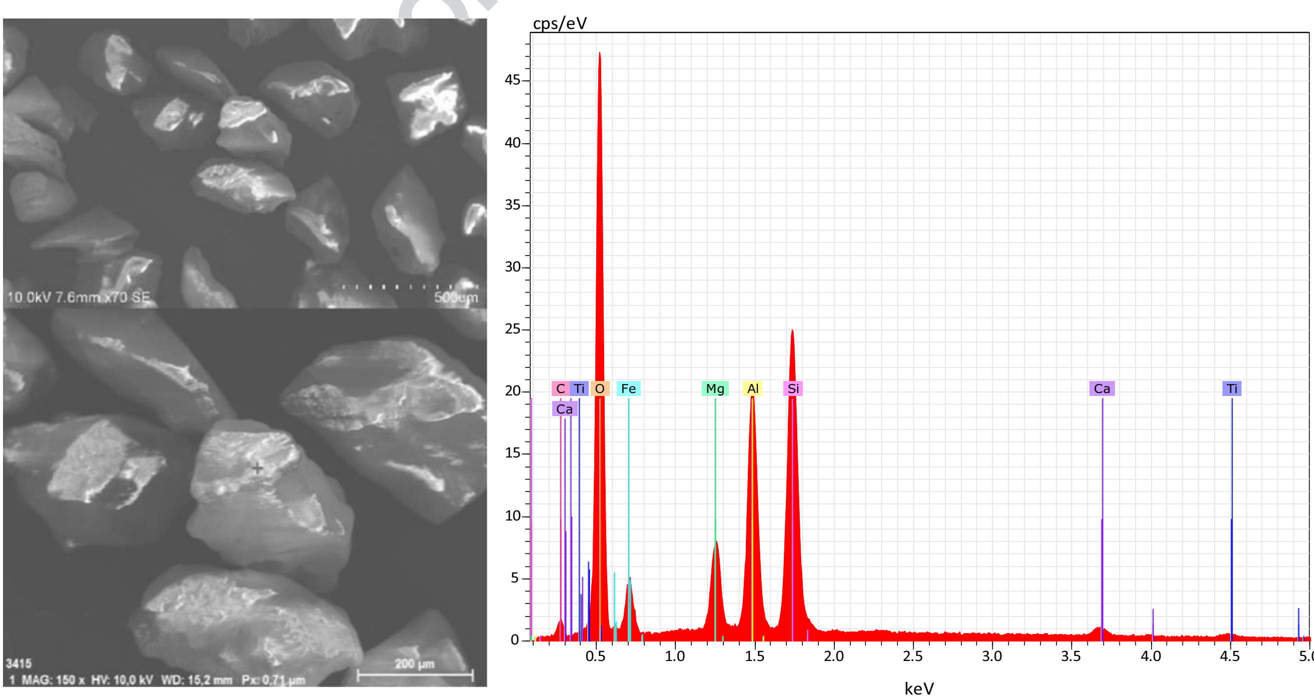


Fig. 2 SEM images at 70× and 150× of the abrasive particles used and chemical composition by EDS analysis

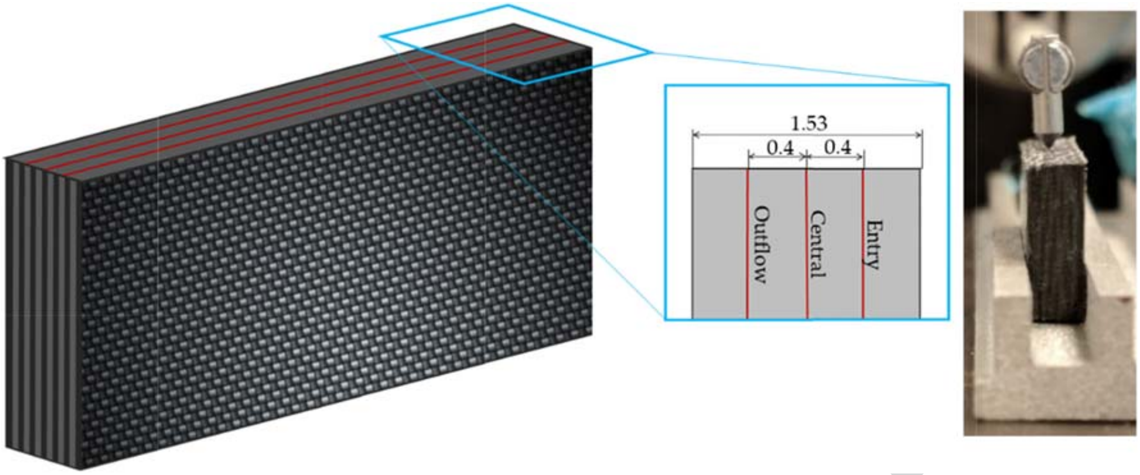


Fig. 3 Surface quality methodology

of R_a at the output are higher than the values at the entry side. Due to the low viscosity of the thermoplastic polymer [43], the integration between matrix and reinforcement (carbon fibers) can be overcome by the shear stresses generated by the water jet when machining the material. This produces that the thermoplastic matrix is not completely eliminated, and may remain adhered to the surface [30] or not detach completely at the end of the cut, causing a fraying defect.

When the roughness meter evaluates the outflow region, the detachment of the thermoplastic matrix in the form of fraying can alter the measurement collected, obtaining these higher R_a values. Therefore, there are no statistically significant differences between the values obtained.

Average values of R_a between 4.77 and 6.95 μm have been obtained. In comparison with the literature studied on abrasive water jet machining of thermoset composite materials, close values have been obtained despite the use of a low melting point thermoplastic matrix [24, 37, 44, 45].

On the contrary, in comparison with the results obtained by Kakinuma in CFRTP (2.5 μm), higher values have been obtained possibly due to the use of a different thermoplastic. Kakinuma uses a modified polyamide 66 thermoplastic resin (Nylon66) that can reach a melting temperature of 260 °C. In comparison, the polyurethane applied in this article has a melting temperature of 145 °C. This can lead to the loss of thermoplastic matrix and result in poorer surface quality.

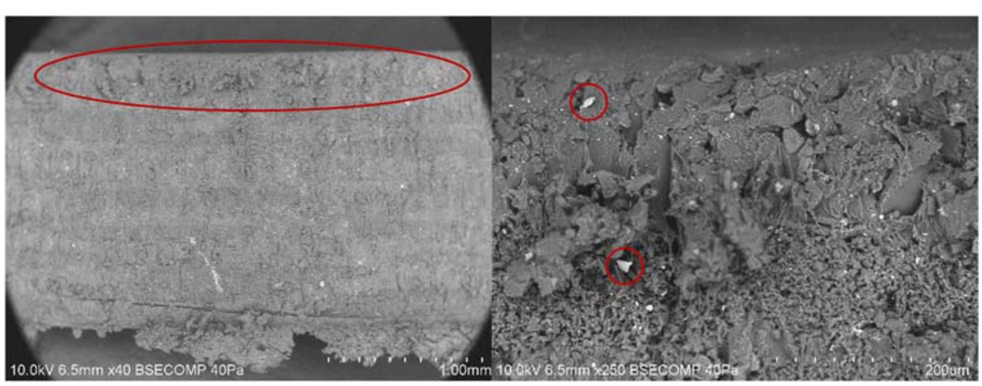
A complementary experimental design has been carried out, in order to validate the results obtained through the response surface methodology. Combinations of cutting parameters not included in the original DOE have been made. The values of R_a obtained have been compared with those predicted by the original model for these same combinations of parameters (Table 4).

The literature researched indicates the formation of three regions of different surface quality after abrasive water jet machining in any kind of material. The creation of these regions is related to the selection of cutting parameters [16, 32].

In the results obtained in this study, there is not a great difference between the three regions evaluated, being the highest values of R_a in the entry zone due to the erosion of abrasive particles at the entry of the water jet. In the same way, in comparison with the results obtained in [16, 24], the formation of a third rougher zone is not observed. This could be due to the properties of the thermoplastic matrix and the low thickness of the material.

The third region is usually associated with a very high loss of kinetic energy from the water jet when the thickness is very high. This loss of kinetic energy reduces the cutting capacity

Fig. 4 Erosion zone due to the action of abrasive particles at the entrance of the water jet at 40× and 250×



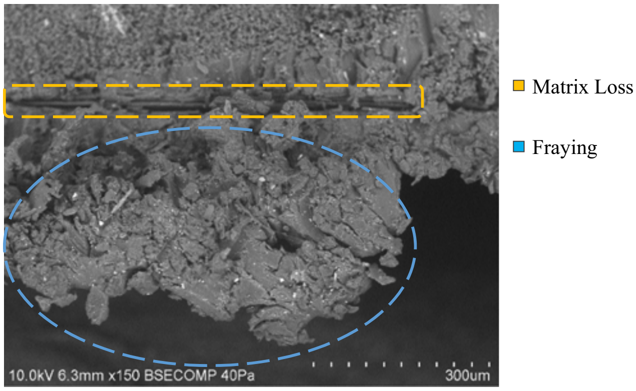


Fig. 5 Burr generated in the output of the water jet and loss of matrix at 150×

of the process, generating defects such as grooves and a worse final surface quality. However, when machining such a small thickness, the loss of kinetic energy suffered by the water jet is not significant. Very homogeneous surfaces are obtained by machining CFRTPs for small thicknesses.

3.2.1 Effect of hydraulic pressure on surface quality

The effect of the variation in *hydraulic pressure* on the surface quality is shown in Fig. 7. An increase in kinetic energy is obtained by increasing the *pressure*, obtaining R_a values that are lower and close to each other, mainly in the intermediate and exit zones. R_a values decrease and a more homogeneous surface is obtained. An increase in *pressure* gives greater kinetic energy to the particles by increasing their cutting capacity [16, 21]. However, an increase in *pressure* produces a greater erosive effect at the inlet leading to higher values at the entry of the jet (Fig. 4).

3.2.2 Effect of traverse speed on surface quality

In agreement with [14, 17, 21], higher R_a values are obtained at the water-jet entry (Fig. 8). Discarding this zone, influence of the *traverse speed* on the *Ra* values is not appreciated. An increase of this parameter generates values of R_a closer in the three evaluated zones, generating a more homogeneous surface.

Of the results obtained, the most homogeneous surface after machining is obtained at a *traverse speed* of 300 mm/min. However, an increase in this value combined with the erosive effect of the jet would result in a greater dispersion, producing a worse surface quality. If the *traverse speed* is not adequate, the abrasive effect at the entry of the jet seems to increase. The use of *traverse speeds* of 100 mm/min offers the lowest R_a values in almost all thickness. Nonetheless, the area affected by erosion is more pronounced. This may be due to an excess of abrasive particles affecting the entrance of the material for a very long time producing an increase in the roughness generated in this area (Fig. 3). On the contrary, an excess of *traverse speed* could indicate that the whole thickness is not machined in a homogeneous way, generating variations between the entry and exit of the jet [24].

However, within the range of selected cutting parameters, there is no influence on the arithmetic mean roughness obtained in the thickness. Very close values of mean R_a are obtained for the three case studies. It could be said that the variation in *traverse speed* seems to affect only the surface quality corresponding to the entry of the water jet into the material.

3.2.3 Effect of abrasive flow rate on surface quality

The influence of the $\dot{m}a$ on the surface quality is plotted in Fig. 9. An increase of the average R_a is obtained by increasing the *abrasive flow* from 170 to 340 g/min, due to a greater number of abrasive particles impacting on the material, reaching a greater cutting capacity.

This is consistent with the results obtained by the ANOVA analysis. It indicates that *abrasive mass flow* is the parameter with the highest statistical significance in surface quality.

It is noticeable that while *Ra* increases, dispersion decreases. A loss of kinetic energy in abrasive particles can occur if the $\dot{m}a$ is increased excessively, where interparticulate collisions would produce also a worse surface finish [46]. An $\dot{m}a$ of 170 g/min seems to generate the lowest mean value of *Ra*. Also, the dispersion generated over the full

Fig. 6 Abrasive particles between the layers of the CFRTP, producing delamination at 40×and 100×

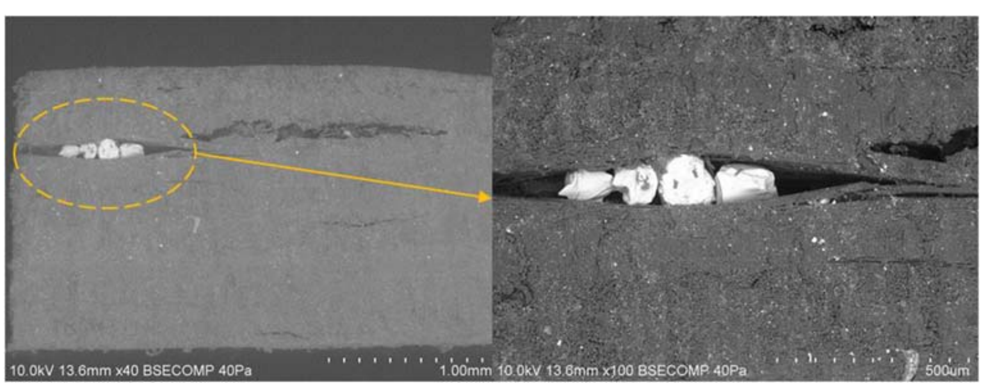


Table 3 Ra values obtained in all tests

Test	Pressure [MPa]	Traverse speed [mm/min]	Abrasive [g/min]	Entry R_a [μm]	Central R_a [μm]	Outflow R_a [μm]	Average R_a [μm ± (*μm*)]
1	120	100	170	6.45	5.87	5.28	5.87 ± *0.48*
2	120	100	340	7.45	6.83	6.58	6.95 ± *0.37*
3	120	300	225	6.99	6.61	5.81	6.47 ± *0.49*
4	120	500	170	6.13	5.00	4.75	5.29 ± *0.60*
5	120	500	340	6.74	6.88	6.57	6.73 ± *0.13*
6	250	100	225	6.76	4.88	5.56	5.73 ± *0.78*
7	250	300	170	6.14	5.39	4.46	5.33 ± *0.69*
8	250	300	225	5.87	5.85	5.35	5.69 ± *0.24*
9	250	300	225	5.09	5.59	5.73	5.66 ± *0.27*
10	250	300	225	5.39	5.01	5.56	5.29 ± *0.23*
11	250	300	225	5.34	5.31	5.10	5.21 ± *0.11*
12	250	300	225	5.80	6.46	5.34	5.90 ± *0.46*
13	250	300	225	5.31	5.59	5.28	5.44 ± *0.14*
14	250	300	340	6.00	5.94	5.76	5.90 ± *0.10*
15	250	500	225	6.63	5.18	5.19	5.67 ± *0.68*
16	340	100	170	4.88	4.74	4.69	4.77 ± *0.08*
17	340	100	340	6.73	5.53	5.45	5.90 ± *0.59*
18	340	300	225	6.87	5.51	5.29	5.89 ± *0.70*
19	340	500	170	6.44	5.69	4.75	5.63 ± *0.69*
20	340	500	340	6.73	5.12	5.13	5.66 ± *0.76*

thickness increases, due to the fact that the amount of particles used for cutting is insufficient to generate a smooth cut at the entry of the material.

3.2.4 Effect of the interaction of cutting parameters on surface quality

The interaction of the cutting parameters and their influence on the surface quality in terms of mean values of R_a is shown in Fig. 10. In this graph, it can be seen again that the *traverse speed* does not produce a considerable variation in surface quality in combination with *hydraulic pressure* and *abrasive flow*. Thus, for example, it can be seen that, although the *traverse speed* increases from 100 to 500 mm/min for an *abrasive flow* of 170 g/min, the values of R_a are very close to 5 μm. On the contrary, as mentioned in the previous sections, an increase in the *abrasive flow* if it generates a considerable increase in surface quality. Thus, there is an increase in

Table 4 Complementary DOE for validation of the mathematical model

Test	Pressure [MPa]	Traverse speed [mm/min]	Abrasive [g/min]	Average R_a [μm ± (*μm*)]	Average predicted R_a [μm]
1	120	300	170	6.13 ± *0.63*	5.68
2	120	100	225	6.51 ± *0.13*	6.56
3	120	500	225	5.58 ± *0.32*	6.15
4	120	300	340	7.72 ± *0.78*	6.87
5	250	100	170	5.28 ± *0.34*	4.95
6	250	500	170	5.08 ± *0.64*	5.09
7	250	100	340	6.71 ± *0.36*	5.99
8	250	500	340	5.33 ± *0.53*	5.75
9	340	300	170	4.71 ± *0.55*	5.32
10	340	100	225	5.38 ± *0.51*	5.51
11	340	500	225	5.71 ± *0.45*	5.81
12	340	300	340	5.20 ± *0.24*	5.83

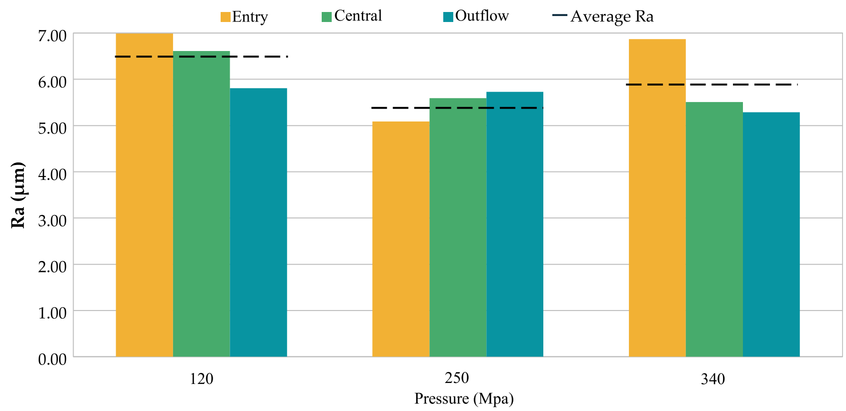


Fig. 7 Variation of R_a in the three zones as a function of pressure ($\dot{m}a$ = 225 g/min; v = 300 mm/min)

the value of R_a from 5 µm to more than 7 µm, due to the loss of cutting capacity of the particles due to their intercollision.

On the contrary, the interaction between the *hydraulic pressure* and the *traverse speed* does show interesting results. Although, according to the ANOVA analysis obtained, they do not have a significant influence on the results obtained, Fig. 10 shows how, for a given value of *hydraulic pressure*, the increase in abrasive particles in the flow worsens the surface quality.

While for *abrasive flows* of 225 g/min and 340 g/min, the R_a values are reduced by increasing *hydraulic pressure* due to the increased kinetic energy of the water jet, for values of 170 g/min, a high *pressure* produces a turning point. This may be due to the fact that, although the kinetic energy of the water particles increases as does their cutting capacity, the amount of abrasive particles required to machine the layers of the composite material is insufficient, thus producing a rougher surface. In addition, if the number of particles is insufficient, the remains of the thermoplastic matrix generated during cutting may not be eliminated, remaining adhered to the surface and producing an increase in the values of R_a [30].

3.3 Statistical analysis

An *ANOVA* analysis of the obtained R_a values is shown in Table 5. In parallel, second-order quadratic models are usually used because they have a high reliability when relating the variables used with the results obtained [28, 32, 47]. The second-order quadratic model applied has a p value less than 0.05, indicating that it is statistically significant.

The *hydraulic pressure* and the $\dot{m}a$ are the variables that directly influence the R_a values. On the contrary, the *traverse speed* has p values greater than 0.05, which would indicate that it is an excluding variable. The significance of each parameter is determined by the value F. Higher values of F indicate a high influence on the response. Observing the analysis carried out, it can be indicated that the main parameter affecting surface quality is the $\dot{m}a$, followed by *hydraulic pressure*. This is consistent with the results of the literature consulted.

The mathematical model obtained through the response surface methodology is shown in Eq. 2. It presents an R^2 of 83%, which indicates a good fit with the experimental results.

$$Ra = 5.6144 - 0.3463P - 0.0250v + 0.4260\dot{m}a + 0.438P^2 - 0.042v^2 - 0.127 + 0.176P*v - 0.170P*\dot{m}a - 0.094v*\dot{m}a \quad (2)$$

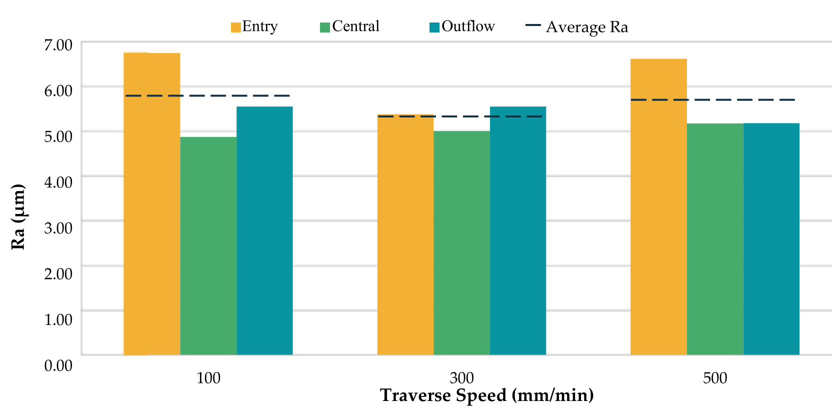


Fig. 8 Variation of R_a in the three zones evaluated as a function of traverse speed (P = 2500 bar; $\dot{m}a$ = 225 g/min)

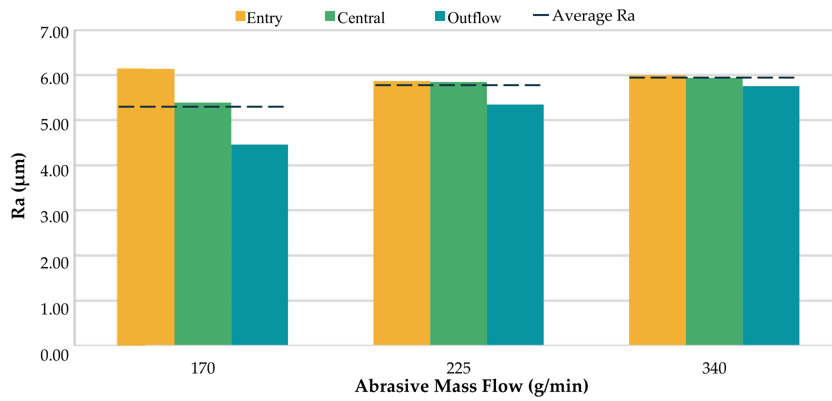


Fig. 9 Variation of R_a in the three zones evaluated according to the established $\dot{m}$ a ($P = 2500$ bar; $v = 300$ mm/min)

3.4 Response surface

Contour surfaces have been obtained using a RSM, plotting the interaction of two input parameters in the output variable, by keeping as constant the rest of parameters.

The selected parameters have been the hydraulic pressure and the $\dot{m}a$, as they are the most significant parameters according to the ANOVA analysis.

As is seen in Fig. 11, the most influential parameter on surface quality is the *abrasive mass flow*. A value close to 170 g/min combined with *hydraulic pressures* between 120 and 340 MPa offers the lowest R_a values.

On the other hand, a combination of a *pressure* of 120 MPa and a *mass flow* of 340 g/min considerably increases the R_a values resulting in poorer surface quality. This is due to the low kinetic energy given to abrasive particles reducing their cutting capacity.

Different surface qualities are appreciated in Fig. 10a, which corresponds to the worst surface quality (P = 120 MPa; $\dot{m}$ $a = 340$ g/min), and Fig. 10b, related to the best surface quality ($P = 250$ MPa; $\dot{m}$ $a = 170$ g/min).

A more homogeneous surface is obtained for the optimal combination of cutting parameters, according to the mathematical model obtained (Fig. 12a). The EAZ appears to be smaller and no burrs are produced at the outflow of the water jet. This can be seen in the surface quality appreciated in the first section of the thickness corresponding to the initial zone of entry of the water jet. In this zone, the erosion generated at

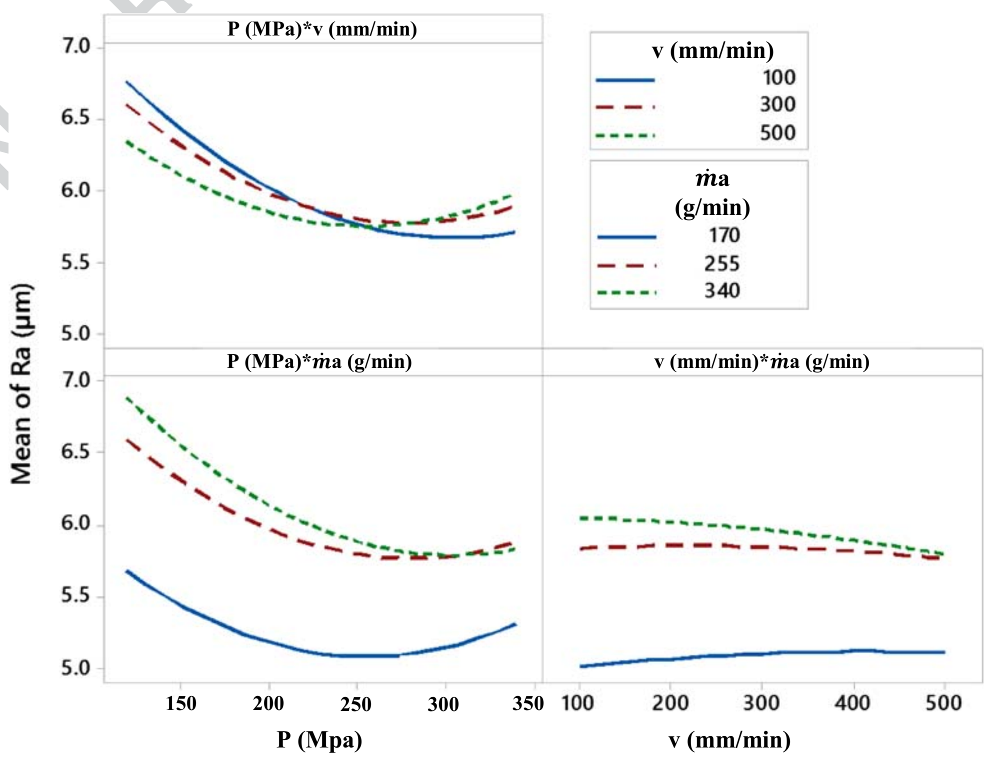


Fig. 10 Effect of the interaction of input variables on the surface quality obtained in terms of R_a

Table 5 ANOVA analysis of the R_a values obtained

Source	DF	Adj SS	Adj MS	*F* value	*P* value
Model	9	4.21331	0.46815	5.74	0.006
P (MPa)	1	1.27804	1.27804	15.68	0.003
v (mm/min)	1	0.014	0.014	0.17	0.687
$\dot{m}a$ (g/min)	1	1.86589	1.86589	22.89	0.001
P (MPa)**P* (MPa)	1	0.39246	0.39246	4.81	0.053
v (mm/min)**v* (mm/min)	1	0.00592	0.00592	0.07	0.793
$\dot{m}$ a (g/min)*$\dot{m}a$ (g/min)	1	0.19789	0.19789	2.43	0.15
P (MPa)**v* (mm/min)	1	0.24261	0.24261	2.98	0.115
P (MPa)*$\dot{m}a$ (g/min)	1	0.24819	0.24819	3.04	0.112
v (mm/min)*$\dot{m}a$ (g/min)	1	0.06432	0.06432	0.79	0.395
Error	10	0.81522	0.08152		
Lack-of-fit	5	0.46115	0.09223	1.3	0.389
Pure error	5	0.35407	0.07081		
Total	19	5.02854			

the beginning by the abrasive particles seems to be less visible, offering a more homogeneous surface in the whole thickness.

On the other hand, in Fig. 12b, the difference in surface quality is visually appreciated in this area in comparison with the rest of the thickness. This would indicate that the EAZ is larger for this combination of cutting parameters. In addition, the increase in *hydraulic pressure* gives a greater cutting capacity to the water jet, being able to completely eliminate the thermoplastic matrix at the exit of the material eliminating the defect of fraying at the exit.

However, in both of cases, the loss of the matrix by the erosive effect of the jet is appreciated, producing cracks with visible carbon fibers.

Figure 13 shows a graphical representation of the optimization of surface quality (R_a) according to the mathematical model obtained. A combination of *v* of 100 mm/min, an $\dot{m}a$ of 170 g/min and a *P* of 280 MPa should give the lower R_a, of about 4.92 μm. The figure also indicates the degree of desirability of the result obtained. Individual and composite desirability assess how well a combination of variables satisfies the goals you have defined for the responses.

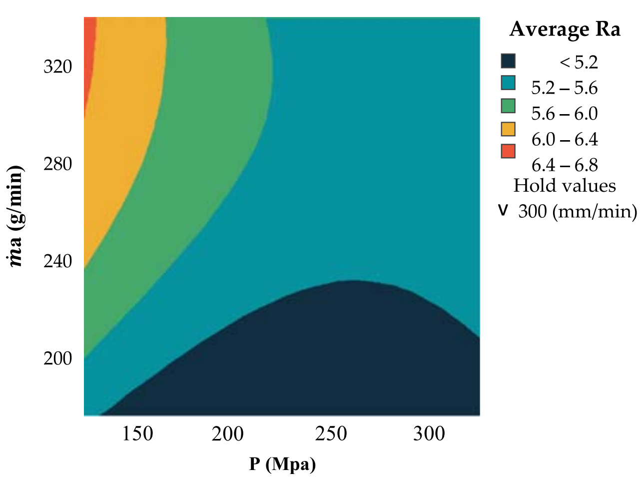


Fig. 11 Contour plot of R_a as a function of *P* and $\dot{m}$ a

Individual desirability (d) evaluates how the settings optimize a single response; composite desirability (D) evaluates how the settings optimize a set of responses overall. Desirability has a range of zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits. In the result obtained, the desirability obtained is 0.93 which would indicate that the combination of cutting parameters indicated offers a result according to the desired.

3.5 Mathematical model validation

Figure 14 represents a comparison between the experimental and the predicted values, showing very close results, with a maximum error of 7.87%. This fact indicates the high reliability of the process.

In order to validate the mathematical model, a comparison between combinations of not used parameters in the original DOE and the predicted values has been carried out in the same way (Fig. 15).

Although there are major differences, the maximum error obtained was 13.07%. A very good fit has been obtained for the mathematical model used. It is worth noting the disparity of results obtained in the literature about CFRTP machining. In addition, this error can be caused by the anisotropy of this type of materials and defects such as fraying that may alter the surface quality values. This model could be used to predict and improve the surface quality in the abrasive water-jet machining of CFRTPs.

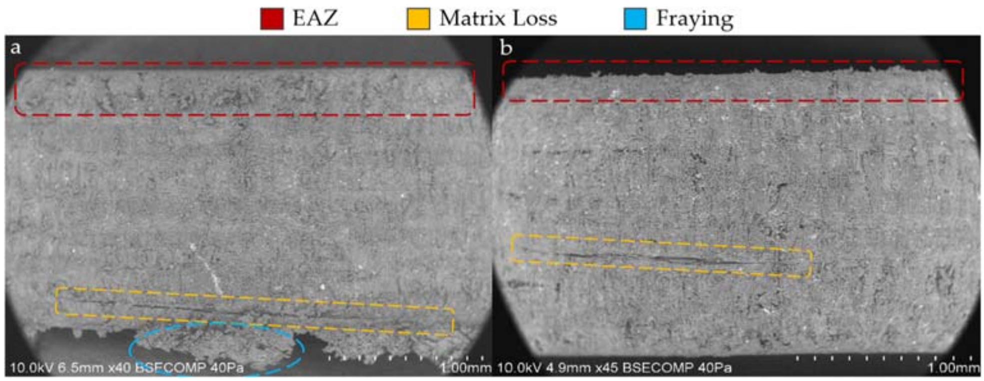


Fig. 12 Surface quality comparison obtained for **a** worst combination at 40×. **b** Optimum combination at 45×

4 Discussion

As indicated in the results obtained in [16, 29, 48], the results show the formation of a first zone with greater roughness. This is due to the erosion generated by the abrasive particles in the first moments of machining, which generates a zone with an affected area, a rounding at the entrance and the adhesion of abrasive particles as shown in Fig. 4 producing a worse surface quality in terms of R_a.

The use of a thermoplastic matrix compared to thermosets results in a number of defects. On the one hand, as in CFRP machining [23, 45], defects such as fiber pull out are produced due to the shear stresses of abrasive particles and water. This, in combination with the low viscosity of thermoplastic matrices, increases the detachment of the matrix from the reinforcement or carbon fibers. This results in visual defects where the reinforcement is free or visible. Nevertheless, unlike CFRP, the matrix is not completely eliminated at the water jet exit, generating a final fraying in the form of a cosmetic defect as shown in Fig. 5, being a characteristic defect of CFRTP machining [30, 49].

The combination of a reduced pressure of 120 Mpa and a high flow rate of 340 g/min does not allow the water jet to machine the material homogeneously. This reduces its cutting capacity due to the low kinetic energy of the water jet and the intercollisions of the abrasive particles as explained in [23, 46]. Due to this, the water jet eliminates part of the matrix, generating internal cavities that allow the abrasive particles to be deposited in these cavities, giving rise to the formation of delaminations in the interlayer (Fig. 6).

Although the literature indicates the formation of three regions of different surface quality due to the dispersion and reduction of the kinetic energy of the water jet [24, 40], the results obtained only show the formation of two regions. The first one has a higher roughness due to the erosive effect of the abrasive particles and a second smooth region, with close R_a values between the central and outflow regions. This may be due to the fact that, compared to most literature [28], the thickness of the machined material is very small, less than 2 mm. This avoids the dispersion of the water jet itself, generating a homogeneous and smooth cut throughout the thickness, without forming defects such as lag and an increase in the R_a values at the water jet outlet.

In the indicated literature, it is explained that pressure is the most significant parameter in the surface quality obtained [17, 25, 27]. The increase in hydraulic pressure is directly related to the increase in the kinetic energy of the jet particles and their cutting capacity. This allows a lower dispersion when the jet cuts the material, allowing the cutting capacity to be constant throughout the thickness and generating a homogeneous surface in terms of R_a as seen in Fig. 7.

On the other hand, the *traverse speed* has a fundamental role in combination with the erosion of the abrasive particles at the entry of the water jet [16, 28]. If the *traverse speed*

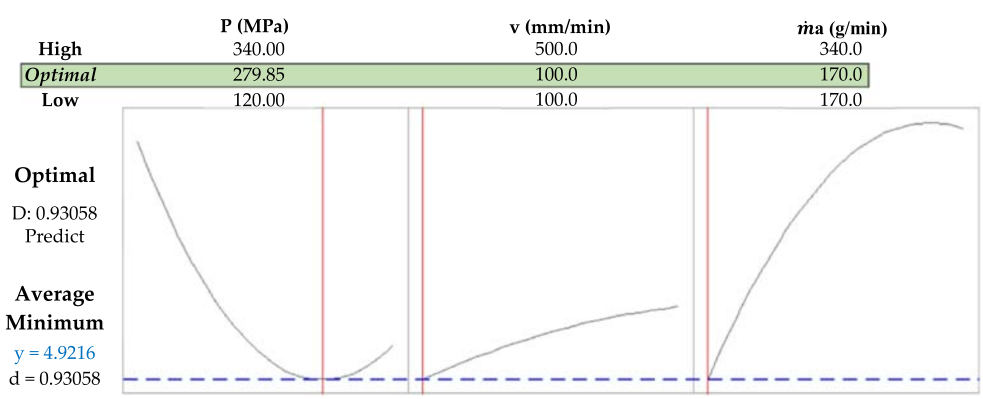


Fig. 13 Cutting parameter combination that minimizes R_a

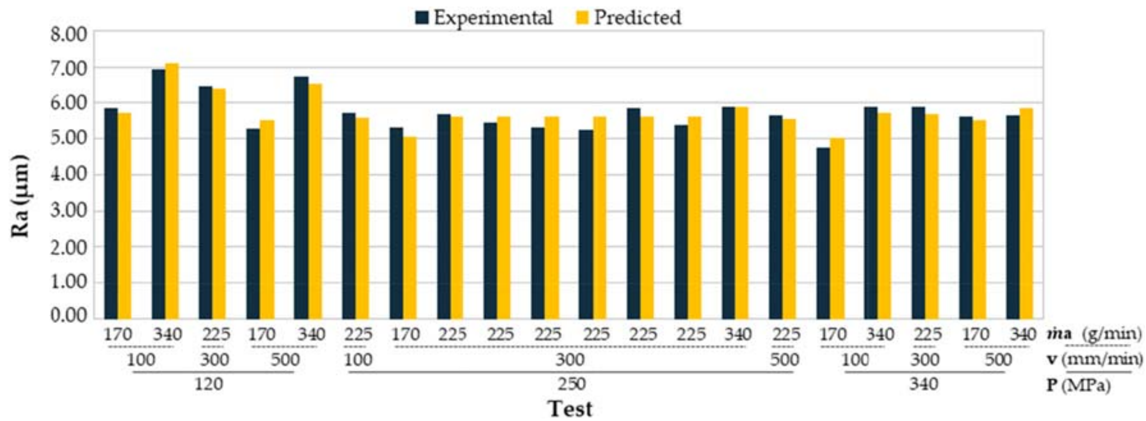


Fig. 14 R_a values (experimental and predicted)

increases to 300 mm/min, there is a dispersion between the amount of particles that are machining the upper part of the material compared to the lower part of the material (Figs. 8 and 9). This produces a difference in cutting capacity along the thickness that produces a rougher area. Nevertheless, due to this increase in speed, the amount of abrasive particles that erode the entry zone of the water jet in a time interval is reduced, producing a less rough initial zone with R_a values in the three closest levels.

5 Conclusions

An experimental study on the influence of cutting parameters in surface quality, focused in the water jet machining of thermoplastic matrix reinforced with carbon fiber composite materials, has been carried out.

An experimental design based on a response surface methodology has been developed, obtaining a quadratic mathematical model that relates the input variables with the surface quality, in terms of average roughness, R_a.

The model obtained by a second external experimental design has been corroborated in order to compare the predicted values with the experimental data. An error of 13% has been obtained, which can be considered small due to the nature of the material and the randomness of the results obtained in the literature.

The cutting parameters used have been close to those used in the literature reviewed. In both thermoset and thermoplastic composite materials, hydraulic pressure and abrasive mass flow have a high influence on surface quality. In addition, it appears from the results obtained that the *traverse speed* used does not affect the surface quality.

On the other hand, the main defects caused by AWJM in thermoplastic composites are mainly delamination at the interface, burr-shaped matrix detachments in the form of fraying at the exit and a constant area of erosion caused by the erosive effect of the abrasive particles of the water jet in the first moments of the cut.

The surface quality of thermoplastic matrix composite materials (TPU) in three different thickness zones has been studied according to the cutting parameters established. It has been observed that the zone with the worst surface quality is the

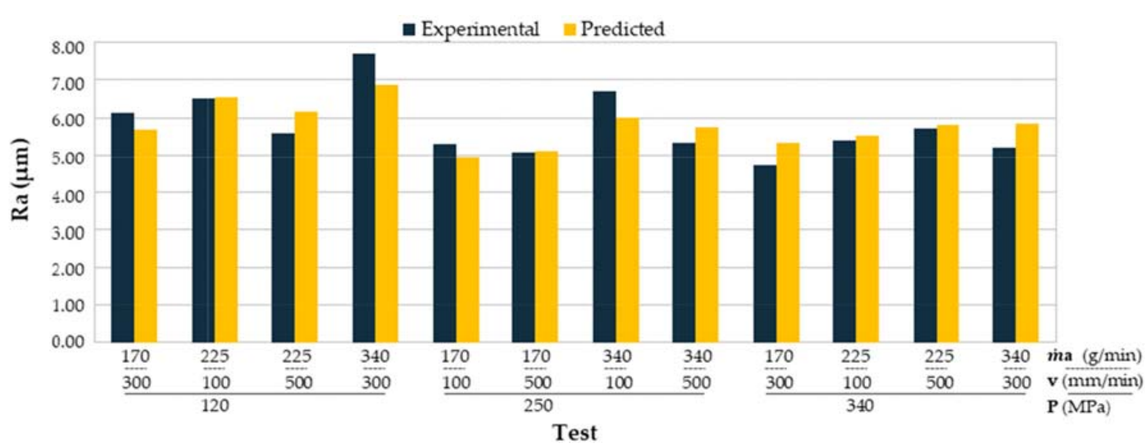


Fig. 15 R_a values in the second tests (experimental and predicted)

initial zone due to the erosive effect of abrasive particles, which even seem to adhere to the thermoplastic matrix. However, the formation of fraying at the outflow of the water jet can lead to a deterioration of the surface quality of the material.

The combination of thermoplastic with carbon fiber reinforcement can make machining difficult. It has been appreciated that the thermoplastic matrix does not separate from the composite and can alter the surface quality. However, the values of R_a obtained are very close to those of studies focused on thermoset matrix compounds. Also, it can be concluded that surface qualities suitable for industry are obtained without requiring secondary operations.

Finally, a combination of cutting parameters that minimizes R_a has been found by using a RSM, resulting on *hydraulic pressure* of 280 MPa, *abrasive mass flow* of 170 g/min, and a *traverse speed* of 100 mm/min, producing very smooth and homogeneous surfaces.

Authors' contributions F.B. and A.S. 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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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Nomenclature section $\dot{m}_a$, abrasive mass flow; ANOVA, analysis of variance; AWJM, abrasive water jet machining; CFRP, carbon fiber-reinforced plastics with thermoset matrix; CFRTP, carbon fiber-reinforced thermoplastics; EAZ, erosion affected zone; EDS, energy-dispersive X-ray spectroscopy; *P*, hydraulic pressure; Ra, arithmetic mean roughness; RSM, response surface methodology; SEM, scanning electron microscope; TPU, thermoplastic polyurethane; UFFD, ultrafast feed drilling; UVD, ultrasonic vibration-assisted drilling; *v*, traverse speed

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