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Composite Cutting with Abrasive Water Jet

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Abstract

Abrasive Water Jet (AWJ) technology has demonstrated to be an interesting manufacturing process for space, aircraft, boat and automotive sectors due to its specific advantages when machining composite materials. However, AWJ cutting of composite laminates possesses several challenges. It is necessary to develop a methodology to adapt the process parameters for each type of FRP & CFRP material which will allow AWJ trimming operations to be easily carried out on composite materials, since machine manufacturers still do not provide good databases for composite cutting. The presented work aims at studying the behaviour of a machinability model in composite materials. The machinability index for various composite materials with different thicknesses was found experimentally, which showed very different results for different materials. A study of the effect of the abrasive waterjet process parameters on the quality of cut (taper and surface roughness) was carried out.

Selection and peer-review under responsibility of Universidad de Zaragoza, Dpto Ing Diseño y Fabricacion

Keywords: Composite; AWJ; Waterjet; Cutting; Trimming;

Nomenclature

AWJ	Abrasive Water Jet
C	Constant equal to 788
d_f	Focusing tube diameter (mm)
d_o	Orifice nozzle diameter (mm)

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f_a	Abrasive factor (-)
A_a	Abrasive mass flow rate (g/min)
A_w	Water mass flow rate (g/min)
N_m	Machinability number (-)
p	Pressure (MPa)
q	Cutting quality (from 1 to 5)
R	Abrasive loading ratio (%)
R_a	Average roughness (μm)
R_d	Ratio between focusing tube and orifice nozzle diameters (-)
s	Stand-off distance (mm)
t	Thickness (mm)
T	Taper angle (º)
v	Traverse feed rate (mm/min)
v_s	Separation speed (mm/min)
W_{top}	Top width of cut (mm)
W_{bottom}	Bottom width of cut (mm)

1. Introduction

Composite materials have, despite their high market price, gained popularity in today's manufacturing of sophisticated products which have to be light and strong, in order to withstand loads in difficult environments. Examples of such products are components in the space, aircraft, boat and automotive sectors. Due to the heterogenous nature of composite materials, which consist of very strong fibres interwoven into a softer matrix, conventional machining techniques do not work equally well on composites as they do in the processing of metals (Sheikh-Ahmad, 2009).

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Abrasive Water Jet (AWJ) technology has received considerable attention from these industries because of its specific advantages when machine composite materials (e.g. lack of thermal damage, low tool wear, small cutting forces and high productivity). This technology has shown to be a suitable process for machining of composite materials (Snider and Hashish, 2011).

However, AWJ cutting of composite laminates possesses several challenges. There are a few studies that analyse the effect of input parameters on the quality of the cutting edge, e.g. Kalla et al. (2012), Shanmugan and Massod (2008) and Wang (1999), or investigations that optimise process parameters for trimming CFRP materials with good quality, e.g. Etxeberria et al. (2010). Nevertheless, industrial end users still need to develop process knowledge, since machine manufacturers do not provide good databases for composite cutting. It is necessary to develop a methodology to adapt the process parameters for each type of FRP & CFRP material which will allow AWJ trimming operations to be easily carried out on composite materials.

Zeng (2007) defines the machinability of materials as a quantified kinetic response of a workpiece material subjected to a certain machining operation and condition, which refers to the ease or difficulty with which this material can be machined. Machinability is not a material property, like hardness or ductility, which complicates obtaining a quantitative and consistent measure of it under the wide range of combinations and conditions available. In conventional machining, there exists standardised tests which allow quantitative rankings to be obtained (Jamal, 2009). In AWJ technology, Zeng et al. (1999) developed a machinability model which allows the cutting traverse feed rate to be adjusted as a function of other process parameters, such as the required cutting quality, the machinability index and the thickness of the material; equation 1 describes this model.

$$v = \left(\frac{f_a \cdot N_m \cdot p^{1.594} \cdot d_o^{\,1.374} \cdot A_a^{\,0.343}}{C \cdot q \cdot t \cdot d_f^{\,0.618}} \right)^{1.15} \tag{1}$$

According to this model, the machinability index is a constant for any cutting condition within the scope defined by Zeng et al. (1999).

The machinability index of an unknown material is commonly found experimentally by finding the separation speed for certain cutting conditions (Zeng, 2007). The separation speed is defined as the maximum speed at which a material of a particular thickness can be cut at these cutting conditions. This model is well accepted by manufacturers and end users, and it defines a good starting point to increase the cutting data base. However, there is not much work related to study how this model works in composite materials.

The presented work aims at studying the behaviour of the machinability model in composite materials. The machinability index for various composite materials was found experimentally and a study of the effect of the abrasive waterjet process parameters and the quality of cut (taper and surface roughness) was carried out.

2. Methodology

Experiments were carried out on a Byjet L2030® machine, using two different CFRP composite materials with two different thicknesses. The characteristics of these materials are specified in table 1.

Table 1. Materials used for experimental tests

Material	Thickness (mm)	Ply Orientation	Type of Ply	Ply density (g/m^2)	Fibre volume content (%)	Tensile Modulus (GPa)
M1	6 and 12	0º/90º	F593 Hexcel	193	45-53	51.7
M2	6 and 12	0º/90º	8552 Hexcel	168	60	135

2.1. Determination of machinability index

To find the machinability index defined by Zeng et al. (1999) in composite materials, the separation speed of the materials defined in Table 1 was found using two different cutting tools. In AWJ technology, the tool is defined by the orifice and the focusing tube diameter, the abrasive mass flow rate, the pressure and the stand-off distance (Fig.1).

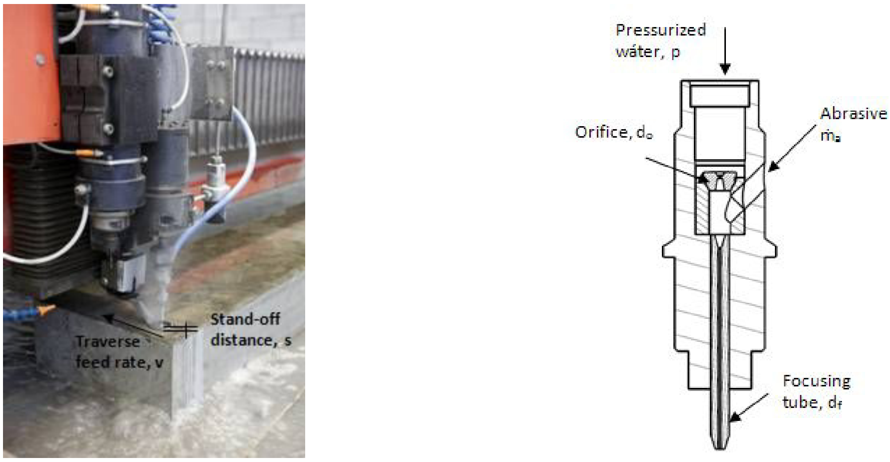


Fig.1. Process parameters in AWJ

For the experimental tests, the pressure was fixed to 360 MPa and the stand-off distance was fixed to 2 mm. Although there are some works from Hashish (1999) and Henning et al. (2011) related to the optimisation of the cutting tool in AWJ to ensure efficient operation, still there does not exist a general trend to select the orifice, the focusing tube diameter and the abrasive mass flow rate; so different approaches can be found for different manufacturers and end-users. Therefore, 2 different combinations (shown in table 2) were selected for experimental tests. The ratio between focusing tube diameter and orifice diameter, R_d, of the selected tools is close to 3, which is suggested as an optimum value by many manufacturers. The abrasive loading ratio, R, calculated as the ratio between the abrasive and water mass flow rate (A_a and A_w respectively) was selected within the most common operating range (7-15% according to Hashish (2011)).

Table 2. Tested tools for machinability test

Tool	d_0 (mm)	d_f (mm)	R_d (-)	A_a (g/min)	A_w (g/min)	R (%)
T1	0.35	1.02	2.91	330	2915	11
T2	0.25	0.76	3.04	200	1481	14

The separation speed was found by linearly varying the traverse feed using an acceleration value of 0.042 m/s^2, until the material was not cut through. The separation speed was determined as the speed where the material was not cut through; the machinability index was obtained from equation 1. Thus, 4 values of separation speeds were found for each material. Each test was replicated 3 times.

2.2. Machinability model behavior in composite materials

According to machinability model, to obtain the desired cutting quality for a certain cutting conditions of process parameters, the traverse feed rate should be adjusted using equation 1. That means for any material, any thickness and any cutting condition (within the scope specified by Zeng et al. (1999)), the obtained cutting quality should be the same that if the percentage of traverse feed rate relative to the separation speed (calculated at these specific cutting conditions) is maintained constant.

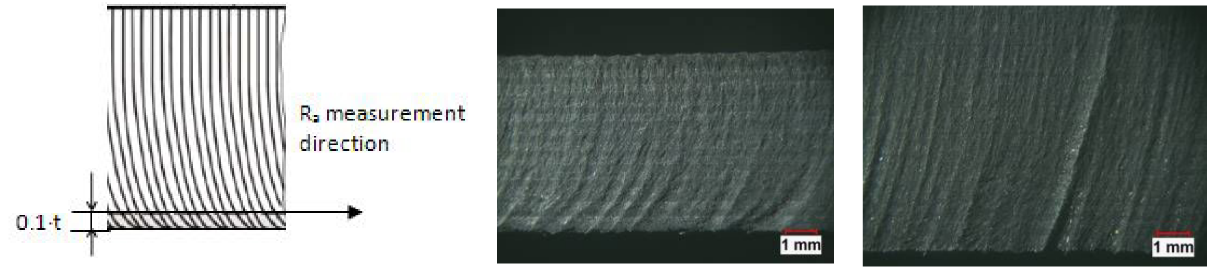
To validate this model in composite materials, a factorial design has been defined, where the effect of four factors was analyzed: the material, its thickness, the percentage of traverse feed rate relative to the separation speed and the cutting condition. The cutting conditions were defined as a combination of the pressure, the abrasive mass flow rate and the stand-off distance. The selected levels for these four factors are showed in table 3.

Table 3. A Factorial Design to machinability model validation

Material	t (mm)	v/v_s (%)	Cutting condition			
			Name	p (MPa)	A_a (g/min)	s (mm)
M1 and M2	6 and 12	10 and 50	C1	260	800	4
			C2	360	800	1
			C3	360	200	4

The separation speed was calculated for each material, thickness and condition using equation 1 and the machinability indexes obtained in previous analysis. The orifice diameter was fixed to 0.25 mm and the focusing tube diameter to 0.76 mm. An additional point was added to the design and repeated twice in order to study non-linearity in the system and estimate the experimental error. The additional test point was performed in all material and thicknesses, for which the traverse feed rate was a 30% of the separation speed, the pressure was 310 MPa, the abrasive mass flow rate was 500 g/min and the stand-off distance was 2.5 mm.

The results of the cutting quality, defined by the cutting surface roughness and the taper angle, have been analysed using the ANOVA technique. The average mean surface roughness (R_a) of the tests was evaluated in a length of 15 mm using a Gaussian filter and a length of cut of 2.5 mm. The roughness measurements were taken at 10% of the thickness (0.1 t) from the bottom edge as indicated in Fig. 2.

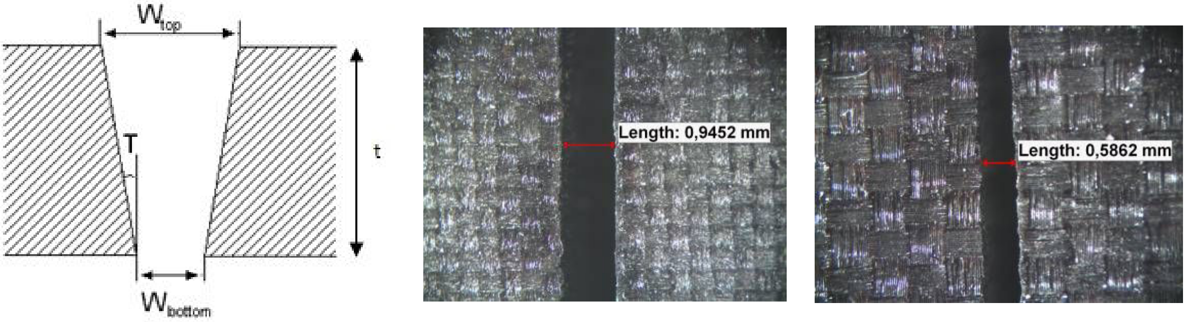


(a) (b) (c)

Fig. 2. Roughness: (a) measurement description; (b) Material M2, 6 mm, C3, v/v_s=50% (c) Material M2, 12 mm C3, v/v_s=50%

The taper angle of the tests was calculated using equation 2. The top and bottom width of cut (W_{top} and W_{bottom} respectively), were measured with a stereoscopic microscope with a magnification of x30 and image processing software with a resolution of 7 μm as showed in Fig. 3.

$$T = \arctan\left(\frac{W_{top} - W_{bottom}}{2 \cdot t}\right) \tag{2}$$



(a) (b) (c)

Fig. 3. (a) Kerf profile; (b) Measurement of W_{top} Material M1, 6 mm, C2, v/v_s=10% (c) Measurement of W_{low} Material M1, 6 mm, C2, v/v_s=10%

3. Results and discussion

3.1. Determination of machinability index

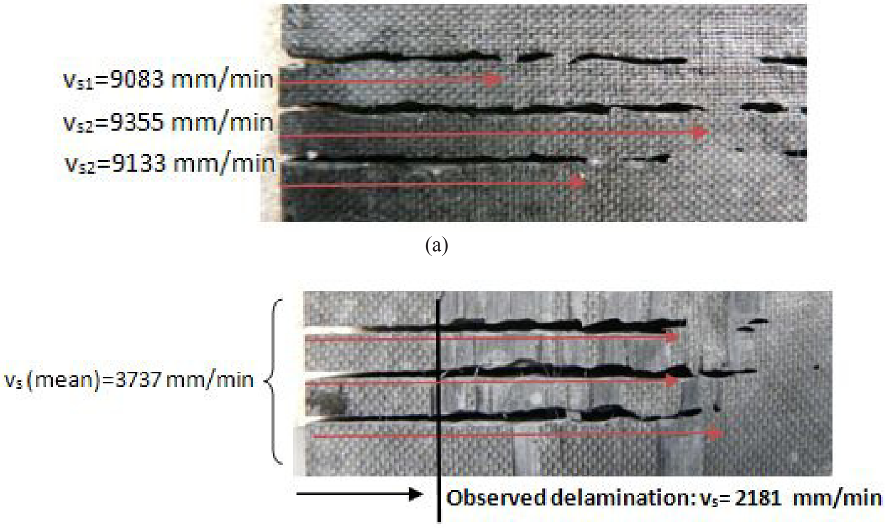
The experimental results of separation speeds and machinability index are shown in table 4. The mean value and the standard deviation of the machinability index were calculated from all tests done in each material (4 conditions per material and 3 replicates per condition). In all materials, the standard deviation is less than or equal to 6% of the mean value. These results indicate that there is a high correlation coefficient between the experimental results and the machinability model.

Table 4. Results of separation speed and machinability index

Material	Thickness (mm)	SEPARATION SPEED, v_s (mm/min)		MACHINABILITY INDEX, N_m (-)	
		Tool1	Tool2	Mean, μ	Desv. Std., σ
M1	6	9190	5855	633	38
	12	4119	2275		
M2	6	5167	3041	380	21
	12	2181	1400		

The results show that composite materials have a significantly higher machinability index than metals (e.g., Aluminium 2024 has a machinability index of 215.3, and stainless steel 316 82.5), which means that composite materials can be cut significantly faster than metals. Furthermore, the results also show that different composite materials cannot be grouped as one general group, and composites with different composition should be treated as different when creating data bases for AWJ cutting machines. In this case, the material M1 presented a higher machinability index than the material M2, which indicates that M1 can be cut faster than M2. It may be related to the fibre volume content and/or to the tensile modulus of these materials, since material M1 has lower values than M2 for such properties (see Table 1).

Moreover, when cutting the material M1, the separation speed was reached without observing delamination (Fig. 4a). However, when cutting the material M2, delamination was observed before the separation speed was reached as indicated in Fig. 4b, so the separation speed criterion has found not to be adequate for composite material. Thus, the separation speed has been re-defined as the maximum speed at which a material of a certain thickness can be cut using certain cutting conditions without observing any delamination. The separation speed of material M2 specified in Table 4 is the one which meet the requirement of no-delamination.



(a)

(b)

Fig. 4. Lower view of machinability tests: (a) material M1, t=6 mm, tool T1; (b) material M2, t=12 mm tool T1

These results also show that tool selection is an important aspect to take into account in order to increase productivity. For example, when cutting material M2 with a thickness of 12 mm, the separation speed obtained with the tool T1 is 180% higher than the one obtained with the tool T2. However, other aspects such as process costs and abrasive consumption per machined length should also be taken into account when selecting a tool according to Hashish (2011).

3.2. Machinability model behavior in composite materials

The ANOVA analysis of the first approach is showed in Table 5, which consists of analyzing the effect of the material, its thickness and the cutting condition on the cutting quality. The F value for a term is the test for comparing the variance associated with that term with the residual variance, i.e., it is the mean square for the term divided by the mean square for the residual. Thus, a high F value indicates that that term is significant. The p-value is the probability of getting that F value of this size (related to the degree of freedom of that term) if the term did not have an effect on the response. In general, a term that has a probability value less than 0.05 would be considered a significant effect (Box et al., 2005).

Table 5. ANOVA analysis for Taper and R_a

Factor	Taper angle, T		Roughness, R_a	
	F value	p-value	F value	p-value
Material	0.049	0.8264	0.01	0.9057
Thickness	8.36	0.0078	0.27	0.6089
v/v_s	0.67	0.4211	18.88	0.0003
Cutting condition	2.49	0.0839	2.30	0.1056

The analysis of Table 5 shows that for the taper angle, the machinability model is not valid, since the thickness is a significant factor. Those results indicates that when cutting the same material with different thickness, different percentage of traverse feed rate relative to the separation speed should be used in order to obtain similar taper angle. Fig. 5 shows the results obtained for the taper angle as a function of the material thickness. The results varied from 0.50º to 2.67º in material M1 and from 0.11º to 3.27º in material M2. The taper angle for the thickness of 6 mm is clearly higher than for the thickness of 12 mm. These results indicate that for a specific material, the taper angle may be a function of the absolute traverse feed rate more than a function of its respective percentage to the separation speed.

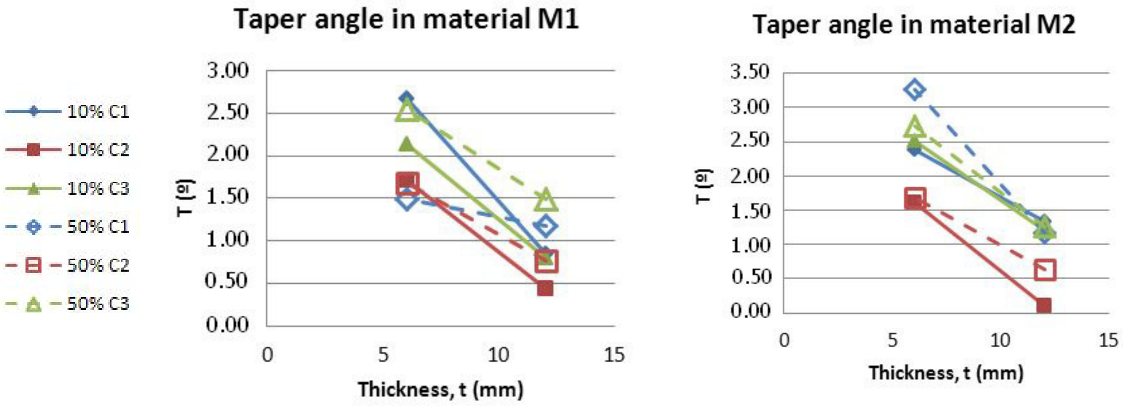


Fig. 5. Results of taper angle vs. material thickness for different materials traverse feed rates and cutting conditions.

On the other hand, for the roughness analysis, only the traverse rate is a significant factor, as Table 5 indicates. Thus, the machinability model is valid in composite material if the cutting quality is defined only with the roughness. That means that when cutting a certain material, similar values of roughness will be obtained if same percentage of traverse feed rate relative to the separation speed is used. Fig. 6 shows the results obtained for the roughness as a function of the traverse feed rate relative to the separation speed. In the material M1, the lowest value of the parameter R_a obtained is of 7.96 μm, which is obtained in the specimen of 12 mm in thick, with the condition C2 of Table 3 and for 10% of traverse feed rate. Regarding the material M2, the lowest value of the parameter R_a obtained is of 7.29 mm, which is obtained in the specimen of 6 mm in thick, with the condition C2 of Table 3 and for 10% of traverse feed rate.

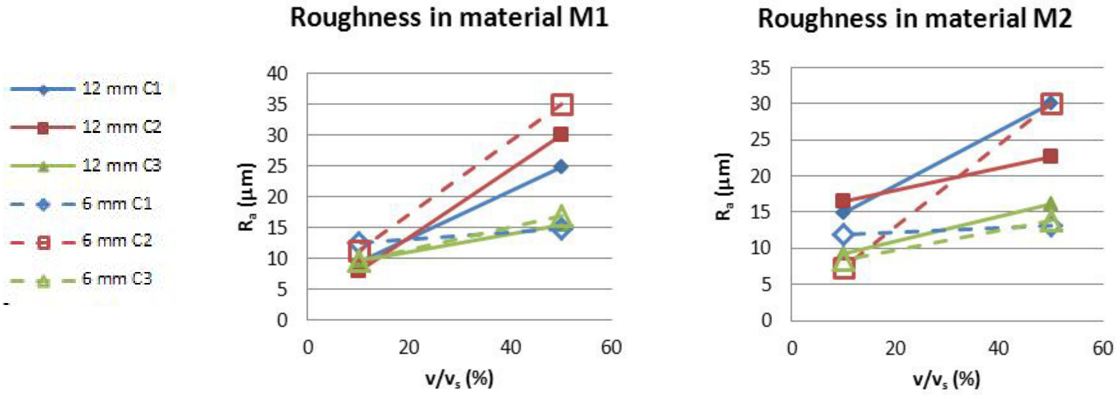


Fig. 6. Results of roughness vs. traverse feed rate relative to separation speed for different materials, thicknesses and cutting conditions.

4. Conclusions

The main conclusions obtained from this experimental work are:

- The machinability index of different composite materials is very different, so they have to be studied separately. This index may be related to the tensile modulus and/or to the fibre content of the composite materials, but further research is required in order to relate the machinability index with the material properties.
- The separation speed has to be re-defined for this kind of material as the traverse rate at which the material can be cut without delamination.
- Tool selection is an important aspect to take into account in order to increase productivity.
- The taper angle may be a function of the absolute traverse feed rate more than a function of its respective percentage to the separation speed
- The machinability model can be used to adapt the traverse feed rate for the required roughness.

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