# Experimental and Analysis in Abrasive Water jet cutting of carbon fiber reinforced plastics

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## Résumé

*Différents types de processus sont utilisés pour percer des composites; Cependant, chaque type a ses propres caractéristiques. Parmi ces procédés, l'usinage par jet d'eau abrasif (AWJM) est largement utilisé dans différents domaines de l'industrie aérospatiale pour l'usinage de composites grâce à l'absence de température et au contact de la pièce avec l'outil. AWJM a rencontré des difficultés lors de la coupe de matériaux composites en époxy renforcé de fibre de carbone tels que la précision de coupe et la bonne qualité de surface. Dans le présent travail, différentes conditions de coupe, y compris le débit d'abrasif, la vitesse de déplacement du jet et la distance entre la buse et la pièce, sont testées lors de la découpe d'un composite à base d'une résine époxy renforcée par un tissu de carbone. Pour la conception expérimentale, la méthodologie de surface de réponse (RSM) a été utilisée pour évaluer la modélisation et l'analyse des réponses telles que la rugosité de surface et la conicité des trous. Les principaux résultats expérimentaux ont montré que la distante de buse-pièce le débit d'abrasif étaient les principaux paramètres affectant la rugosité de la surface (Ra) et la conicité du trou.*

## Abstract

*Various kinds of processes are used for drilling composites; however every type has their own characteristics. Among these processes, Abrasive water jet machining (AWJM) is largely used in different fields as aerospace industries for machining composites thanks to absence of temperature and contact tool with the work piece. AWJM proved some challenges when cutting carbon fiber reinforced plastic (CFRP) composites materials such as cut accuracy and good surface quality. In the present work, different cutting conditions including abrasive flow rate, jet traverse speed and standoff distance are tested in the cutting of woven fabric carbon reinforced plastics. For the experimental design, response surface methodology (RSM) was used for evaluating the modeling and analysis of responses such as surface roughness and hole taper. The main experimental results demonstrated that the stand-off distance and the abrasive flow rate were the major parameters affecting the surface roughness (Ra) and the hole taper.*

**Key words : Composite\ AWJ \ milling \ CFRP \ RSM**

# 1 Introduction

Conventional machining processes require direct contact between the cutting tool and the part to be machined, which make tool wear and a bad quality of the machined component. So to improve these problems, Abrasive water jet machining (AWJM) is one of the advanced machining processes for machining CFRP. Siddiqui [1] , investigated the abrasive water jet cut kerf quality characteristics of CFRP who found that water jet pressure and quality level are the most significant factors affecting surface roughness and kerf taper, otherwise abrasive flow rate has the least effect on Ra and taper among the three process parameters. He observed that as the quality level increases (at low traverse speed) Ra decreases whereas kerf taper decreases with increase in water jet pressure.

Over all the studies are interested with linear profiles for investigating the Abrasive water jet (AWJ) cutting quality of CFRP composites, however there is no much database for studying the effects of this process on holes quality. The Delamination factor has been proved as one of the most critical defects when machining Carbon Fiber Reinforced Plastic (CFRP) composite material with linear Abrasive Water Jet (AWJ) [2]. Therefore, results could be different for machining holes [3]. For obtaining the best surface quality and minimum kerf taper, so a higher level of water jet pressure and lower level of abrasive flow rate are desirable. Then surface roughness at the bottom of the cut is affected by traverse speed [1]. Furthermore, in order to minimize machining costs, the abrasive mass flow rate may be reduced because the surface roughness changes by increasing the abrasive mass flow rate [4]. For Rahmah et al. [5], experimentally studied the AWJM of Kevlar/phenolic composites. They found that abrasive flow rate has least significant effect on surface roughness and kerf taper while surface roughness is affected by jet penetration depth, water pressure level, standoff distance and traverse speed. During investigation of the AWJ drilling models, Ramulu et al. [6], found that dimensions accuracy of the drilled holes are affected by abrasive flow rate and drilling time. Other authors [7,8], studied the machinability of polymer composites using AWJ. They proved that top and bottom kerf width and kerf taper increased with standoff distance and water pressure and decreases with feed rate. In other study for machining a CFRP composite with AWJ [9], the dominant parameter affecting the surface roughness was jet pressure, followed by the standoff distance and traverse speed.

In the present study, carbon fiber reinforced plastics CFRP were selected and cutted with AWJM process. The influence of process parameters such as traverse speed, standoff distance and Abrasive mass flow rate on the surface roughness and kerf taper of holes was investigated. Furthermore, RSM analysis was exploited to develop an empirical model correlating the input parameters with responses.

# 2 Experimental procedure

## 2.1. Composite material

The material used for the tests is plain-weave carbon reinforced epoxy. Eight layers of the material are used. Each ply was 0.6mm thick given a laminate thickness of 5mm. The layers are orientated in two directions alternatively [0/90, ±45, 090, ±45], as shown in figure1.

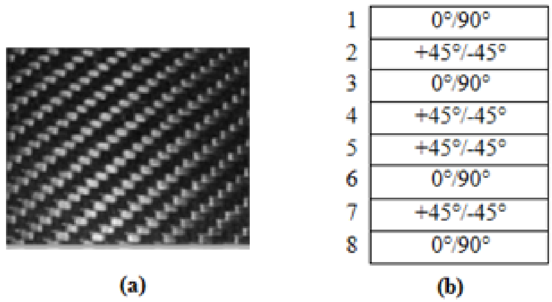


Figure 1. (a) Twill weave CFRP (600g/m²) , (b) CFRP laminate layup

The laminate was prepared through hand layup and vacuum bag process. The initial curing of the laminate was carried out at 1 bar ambient pressure.

## 2.2. Experimental set up

The experiments were conducted on a 3 axis CNC machine (MECANUMERIC model) abrasive water jet cutting system with ultra-high pressure pump capable of providing maximum water pressure of 350 MPa and maximum abrasive flow 1Kg/min an maximum traverse speed 30.000mm/min Cutting was performed on CFRP plates of different thicknesses 4.5mm. The constant process parameters are shown in table 1.

Figure 2. Water jet machine until machining CFRP plate

Three variable process parameters (traverse speed, stand-off distance and abrasive mass flow rate) have been selected for the present study, table 1.

Table 1: parameters and their levels.

| **Parameters** | **code** | **Levels** | | |
|---|---|---|---|---|
| Traverse speed | F (mm/min) | 1000 | 2000 | 3000 |
| Stand-off distance | S (mm) | 2 | 4 | 6 |
| Abrasive mass flow rate | Q (g/min) | 200 | 300 | 400 |

The kerf taper hole results have been inspected by a Stereo Optical Microscopy M80 (SOM) with HD digital Microscope Camera Leica MC170 HD with interface that provides a full high definition live image with a standard capture resolution of 5Mpixels. The camera connected via USB cable with PC.
The controlled parameter has been the surface roughness. Surface roughness (with a cutoff of 0.8 mm) on the cut surface was measured in terms of the average roughness Ra, using a Mitutoyo SJ 201P

instrument. The surface roughness (Ra) of the holes was measured at four angular position on hole surface as shown in Figure 3.

Figure 3. Instruments used in the experimental study:
a) Microscope Leica M80, b) rugosimètre 2D mitutoyo SJ201P

## 2.3. Design experiments

The Design of Experiments (DOE) including RSM used for realizing the machining experiments plan. The Response surface methodology (RSM) is a mathematical model used to describe the relationship between input parameters and their responses. A second order polynomial response can be developed to study the influence of AWJ parameters as given by Equation (1).

$$y = a_o + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^{2} + \sum_{i<j}^{n} a_{ij} x_i x_j + \varepsilon \qquad (1)$$

Where Y is the predicted response, xi and xj are the input variables, xi2 and xi xj are the quadratic and interaction terms of input variables respectively. The regression coefficients are indicated by ai, aii and aij. Design Expert-11 was employed for selecting and developing the appropriate response surface models. From the wide ranges of factors available, it is limited to use three factors and three levels of process parameters as shown in Table1. A central composite design with three control factors at half fraction, with 15 runs of experiments were used to optimize the AWJM conditions (Table 2).

Table 2. Experimental results of Kt and Ra

| Std | Run | F (mm/mn) | Q (gr/mn) | S(mm) | kt (°) | Ra (µm) |
|---|---|---|---|---|---|---|
| 1 | 13 | 1000 | 200 | 2 | 0,093 | 4,412 |
| 2 | 5 | 3000 | 200 | 2 | 0,078 | 3,787 |
| 3 | 3 | 1000 | 400 | 2 | 0,084 | 6,21 |
| 4 | 10 | 3000 | 400 | 2 | 0,102 | 5,34 |
| 5 | 8 | 1000 | 200 | 6 | 0,095 | 5,967 |
| 6 | 12 | 3000 | 200 | 6 | 0,116 | 6,713 |
| 7 | 6 | 1000 | 400 | 6 | 0,058 | 6,077 |
| 8 | 7 | 3000 | 400 | 6 | 0,11 | 6,717 |
| 9 | 15 | 1000 | 300 | 4 | 0,085 | 3,97 |
| 10 | 9 | 3000 | 300 | 4 | 0,109 | 4,14 |
| 11 | 1 | 2000 | 200 | 4 | 0,097 | 3,837 |
| 12 | 11 | 2000 | 400 | 4 | 0,093 | 5,287 |
| 13 | 4 | 2000 | 300 | 2 | 0,094 | 3,21 |
| 14 | 14 | 2000 | 300 | 6 | 0,096 | 4,307 |
| 15 | 2 | 2000 | 300 | 4 | 0,098 | 3,417 |

# 3 Results and discussions

## 3.1. Influence of parameters on surface roughness

According to Design expert 11, the quadratic model is the best model to fit the response of surface roughness. The model accuracy is estimated with a coefficient $R^2$ equal to 0.99 an adjusted $R^2$ (0.97) and the Predicted $R^2$ (0.91).

Table 3: ANOVA for Quadratic model

| Source | Sum of | df | Mean | F-value | p-value | |
|---|---|---|---|---|---|---|
| **Model** | 20,42619 | 9 | 2,269577 | 56,40713 | 0,000171 | significant |
| **A-F** | 0,000372 | 1 | 0,000372 | 0,009248 | 0,927124 | |
| **B-Q** | 2,415723 | 1 | 2,415723 | 60,03936 | 0,000572 | |
| **C-S** | 4,653968 | 1 | 4,653968 | 115,6678 | 0,00012 | |
| **AB** | 0,0154 | 1 | 0,0154 | 0,382748 | 0,563229 | |
| **AC** | 1,03752 | 1 | 1,03752 | 25,78609 | 0,003841 | |
| **BC** | 1,309771 | 1 | 1,309771 | 32,55251 | 0,00231 | |
| **$A^2$** | 1,215402 | 1 | 1,215402 | 30,20709 | 0,002724 | |
| **$B^2$** | 3,668992 | 1 | 3,668992 | 91,1876 | 0,000213 | |
| **$C^2$** | 0,393123 | 1 | 0,393123 | 9,770505 | 0,026081 | |
| **Residual** | 0,201178 | 5 | 0,040236 | | | |
| **Cor Total** | 20,62737 | 14 | | | | |

The P-values less than 0.05 indicate that model terms are significant. In this case B, C, AC, BC, $A^2$, $B^2$, $C^2$ are significant model terms. Values greater than 0.1 indicate the model terms are not significant.
To make predictions about Ra for given levels which are specified in the original units for each factor, the equation in terms of actual factors generated by the model of RSM as follow:

$$Ra = 14.34 - 0.0033F - 0.058Q - 0.194S - 4.38750e\text{-}07FQ + 0.00018F*S - 0.002QS + 6.875e\text{-}07*F^2 + 0.000119Q^2 + 0.097S^2 \quad (2)$$

From the ANOVA for Quadratic model analysis in table 2, it can be concluded that surface roughness is mostly influenced by stand-off distance (S) (P-val= 0,00012) followed by abrasive flow rate (0,000572). However the transverse speed (0,927) is not significant and has no influence on Ra which is significantly influenced by interaction between transverse speed and abrasive flow rate then this last and the stand-off distance.
The surface roughness of the composites increases at low and high level of transverse speed and abrasive flow rate, while it has a minimum level at medium levels for these factors. In other way, it increased as the increase of stand-off distance.

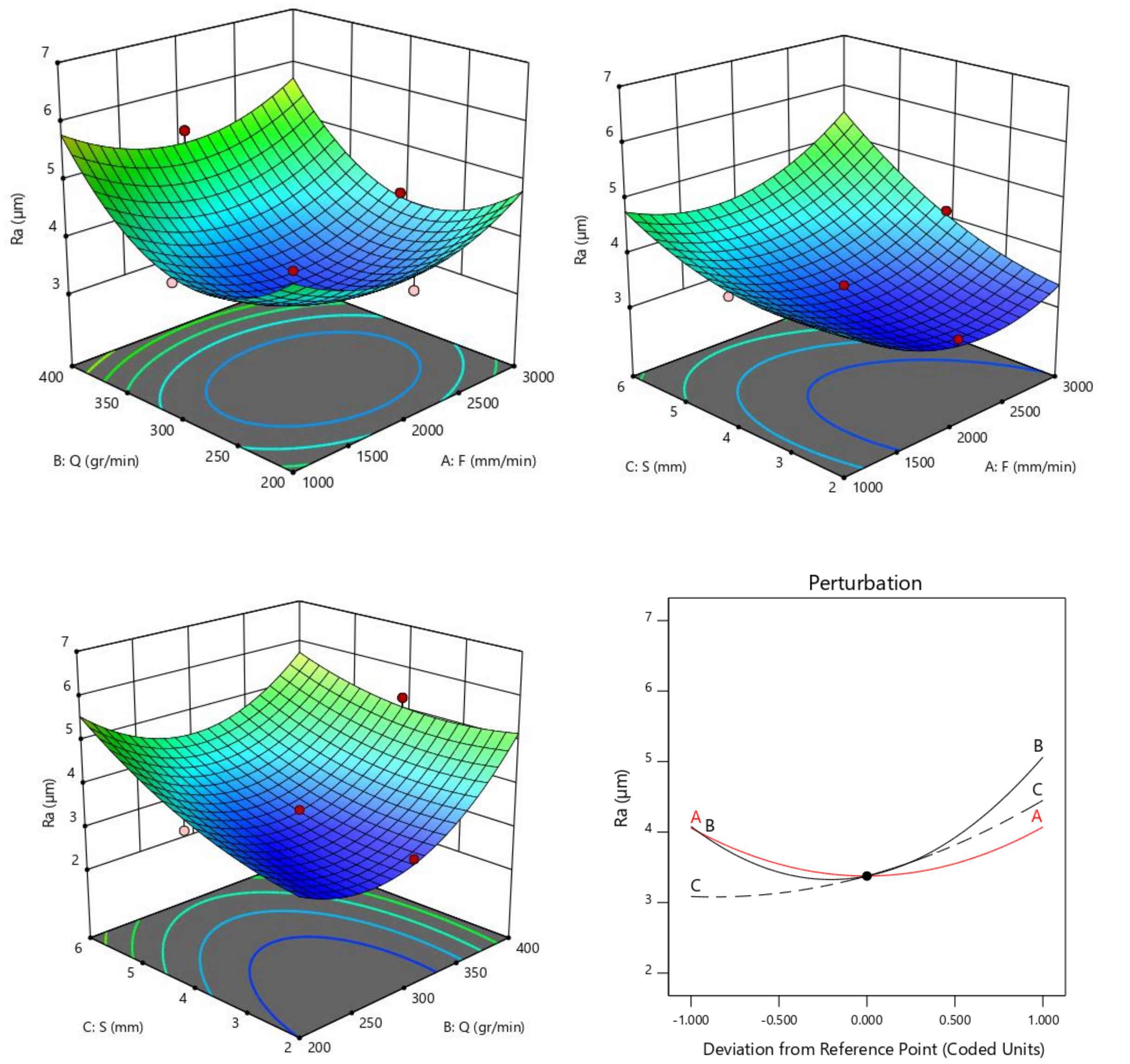


Figure 4. Three-dimensional response surface plots of surface roughness Ra (µm)

## 3.2. Influence of parameters on kerf taper

According to Design expert 11, the quadratic model is the best model suggested to fit the response of kerf taper (Kt). The model accuracy is estimated with a coefficient $R^2$ equal to **0,99 ,** an adjusted $R^2$ (0.98) and the Predicted $R^2$ (0.93). In this case the model terms with the P-values less than 5%, A, B, C, AB, AC, BC are significant.

The interaction terms of the developed model for predicting the Kt response are defined in the next equation:

$$Kt = 0.086 - 2.9e\text{-}5 * F + 1.06e\text{-}4 * Q + 0.00844 * S + 4.375e\text{-}06 * QS - 5.56e\text{-}10 * F^2 - 2.55e\text{-}07 * Q^2 - 0.000639 * S^2 \quad (3)$$

This model is represented it 3D surfaces relating all the input factors with the responses of Kt.

Plots show that the kerf taper increased as the increase both of traverse speed and abrasive flow rate. While it is slightly affected by the standoff distance.

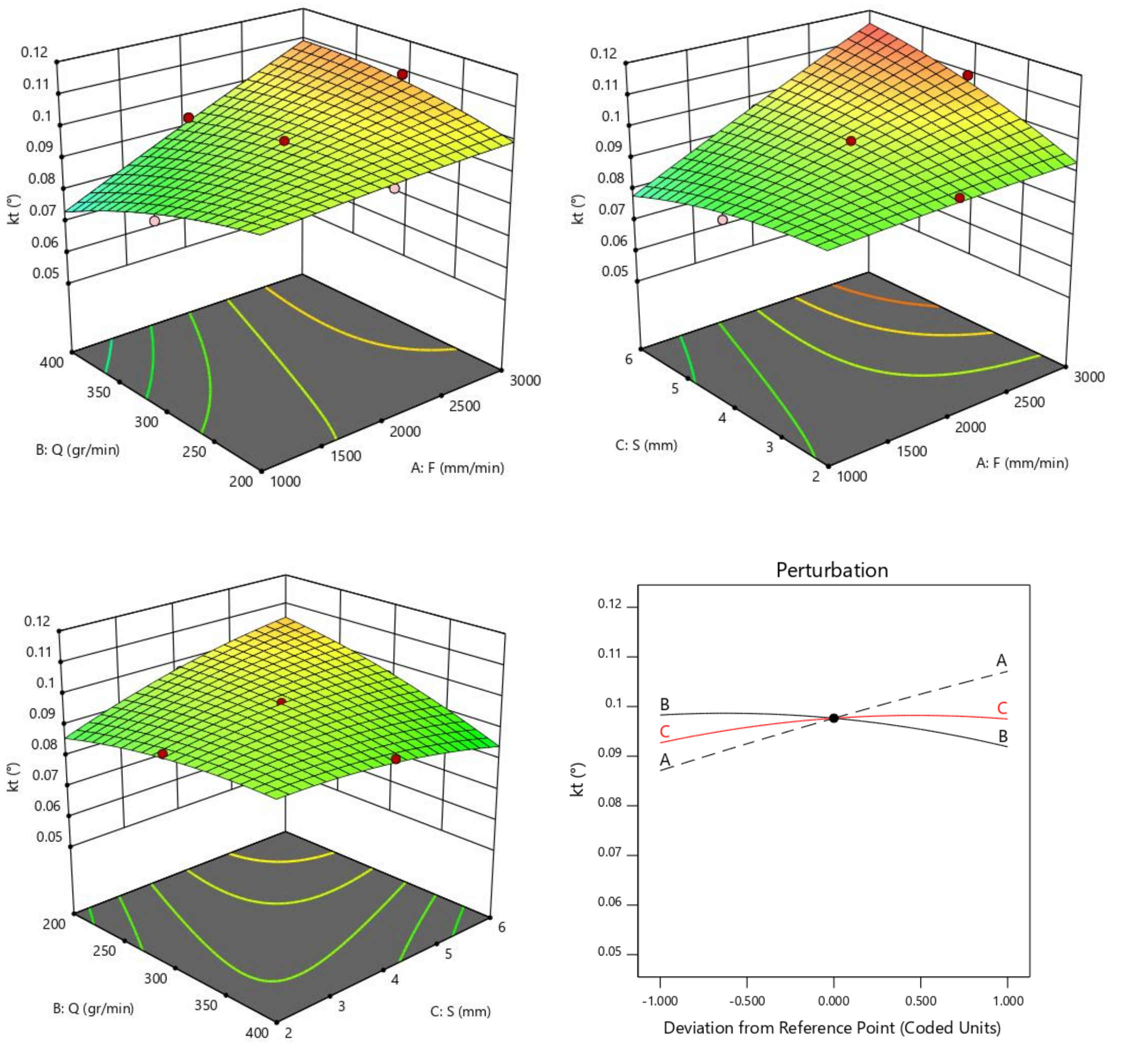


Figure 5. Three-dimensional response surface plots of Kerf taper KT

The plot of predicted versus the actual values of CFRP FOR both responses are much correlated. Most of the values were observed to fall close to a straight line, indicating the accuracy of prediction.

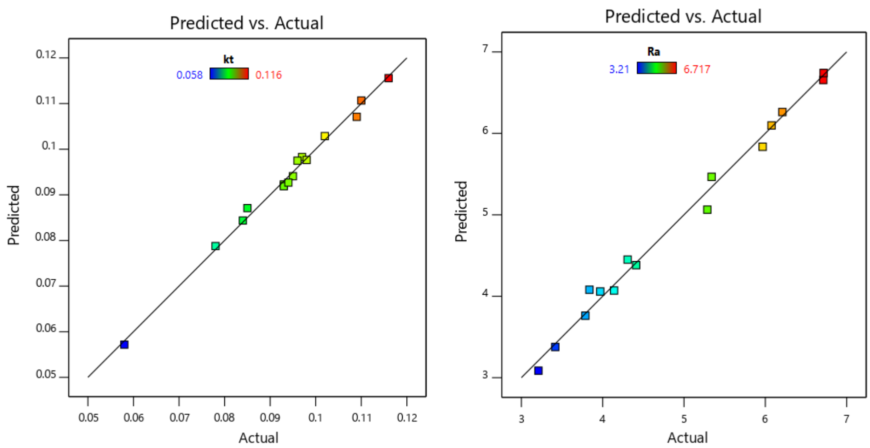


Figure 6. Predicted versus actual values of responses

# 4. Conclusion

The relation between the input process parameters of AWJM and its effect on the surface roughness and kerf taper for a woven fabric CFRP composite was examined using RSM analysis and obtaining the following conclusions:

- Both low and high traverse speed level and abrasive flow rate are not suggested for AWJ process in this case as they lead to high level of surface roughness.
- Minimum level of surface roughness can be attained if medium traverse speed and abrasive flow rate with minimum level of stand- off distance.
- The kerf taper increased as the increase both of traverse speed and abrasive flow rate. While it is slightly affected by the standoff distance
- The RSM models were developed for both responses Ra and Kt , relating the machining parameters. The predicted models were significantly correlated with the experimental results, and the error was minimum within the acceptable level.

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