HIGH SPEED TRIMMING OF CARBON FIBER REINFORCED POLYMERS

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Abstract

In this work a multidirectional CFRP is trimmed at high speed using a burr tool made of tungsten carbide. In order to analyze the influence of the machining parameters on the total cutting forces and quality of the machined surface, sharp and used tool are considered. Total cutting forces, surface roughness and damaged zones (observed via SEM images) are higher when considering a used tool. Total cutting forces and surface roughness are also mainly influenced by the cutting parameters. To estimate the effect of tool wear and cutting parameters on the total cutting force and surface roughness depth, a statistical method (ANOVA) has been used. The results show that machining parameters (feed speed and cutting speed) and cutting distance are the major factors, responsible for the variation of total cutting forces and machining surface quality.

1 Introduction

Trimming the edges of a composite part is the first and mandatory machining operation carried out after the composite parts are demoulded. The anisotropy of long fiber composite make poor machinability. This lead to the appearance of different damages [1-7]. These damages are located in the free edges of the laminate (fibres pullout or/and delamination) [1] or through the thickness (fibres pull-out and resin degradation) [6,7]. The defects in the free edges are mainly influenced by the tool geometry, the machining parameters and the type of machining (up/down milling) [6]. The damage on the machined surface is influenced by the relative angle measured between the cutting speed direction and the fibre orientation, the machining parameters (feed, cutting speed) and the tool wear [6,7]. Some authors [6,8] show that the defects increase with increasing cutting forces. In the reference [8,9], it is shown that the cutting forces increase with the feed rate. The experimental results of Ucar & Wang [9] show that the cutting force decreases with the increase in cutting speed (<36m/min). Konig et al. [8] report that the cutting force increases when the cutting speed is increased (>400m/min). [6,8] explains that this difference may be related to thermal effects induced by the increase of the cutting temperature. It is presumed that the increase of cutting temperature during machining make the material softer otherwise easier to cut. Consequently Ucar et al. should register a decrease in cutting forces. Indeed [7] observed a decrease on the cutting forces (normal and feed forces), even when machining at temperatures higher than the Tg. Consequently the augmentation of the cutting force is not related only to machining temperatures but also and mainly to the clogging of the removed material on the tool cutting edges, which generates larger cutting edges and than more contact surface so higher cutting forces are recorded. It is true that this phenomenon is related to machining temperature but also to the tool material and geometry and finally to the machined composite part (glass transition temperature, volume content, matrix specification…) [7].

To investigate the effect of cutting speed and feed rate during trimming multidirectional CFRP, an experimental study has been carried out using a full factorial experimental design. Total cutting forces and machined surface quality have been measured by using dynamometer and surface roughness tester. Tools and machined surfaces were analyzed via Scanning-Electron-Microscope (SEM). To estimate the contribution percentage of each cutting parameter on total cutting forces and surface roughness depth, analysis of variance (ANOVA) is carried out

2 Experimental design

Experiments were conducted using full factorial design (3 x 3 = 9 tests). Table 1 resumes the trimming parameters and the experimental details. To get consistent values and in order to remove the influence of tool wear, each experimental condition was performed with a new tool. The radial depth of cut is fixed to 2 mm to accelerate the tool wear. For each machining condition and for each tool, a machining distance of 260 cm is achieved.

Composite Material (T700/M21)	Ply thickness : 0.26 mm, Fibre content : V_f = 59 % Staking sequence with respect to the feed direction : $[90/90/-45/0/45/90/-45/ 90/45/90]_S$ Young modulus : E_l = 142 Gpa, E_t = 8.4 Gpa Shear modulus : G_{12} = 3.8 Gpa, Glass transition temperature : Tg = 187 °C Energy release rate G_{IC} = 0.35 N.mm, G_{IIC} = 1.21 N.mm
Tool	Tungsten carbide burr tool Diameter : 6mm
Cutting conditions	Feed speed (mm/min) : 125, 250 and 500 Spindle speed (rpm) : 18570, 37140 and 74280 Radial depth of cut (mm) : 2

Table 1 Summary of material parameters and experimental details

Machining is performed by using a “DUBUS" 4-axis milling machine with a maximum spindle speed of 75000 rpm (Fig. 1-a.). A piezo-electric dynamometer (Kistler 9272) was used for the measurement of the total cutting forces (Fig. 1-b).

To quantify the state of the machined surface, the Scanning Electron Microscopy (SEM) images and surface roughness depth measurements have been taken. The surface roughness depth (Rz) was measured by surface roughness tester (Mitutoyo SJ 500). The sampling length is set to 5 mm (2 x 2.5 mm) perpendicularly to feed speed direction; this measurement is done without cutt off (to prevent overflow on test pieces which have an average of 5.2 mm thickness).

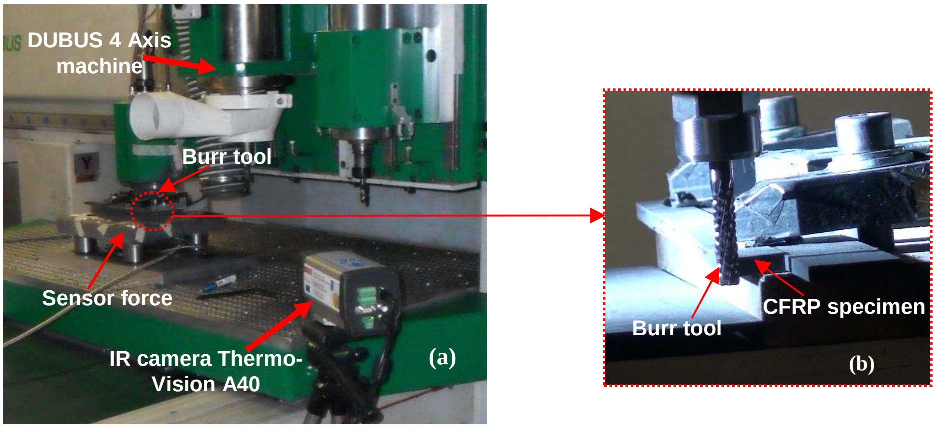

Figure 1. Experimental device for trimming tests. (a) Overview of the experimental test (b) Zoom of the surrounded area on the figure (a).

3. Results and discussion

The effect of cutting parameters on the total cutting forces and surface roughness is studied at two fixed cutting distances. This is done to eliminate the effect of tool wear. The cutting distance of 0.5 m is supposed to be sufficient for lapping the tool before the generation of tool wear. In this case the tool is considered to be fresh or sharp. Considering the severe cutting condition it was supposed that after a cutting distance of 2 m, the tool is subjected to wear, in this case the tool is considered as a used tool. Each point of roughness and total cutting forces measurement represent an average value of five measurements carried out on the second and the third faces for a sharp tool and the eighth and ninth faces for a used tool. The sharp tool values correspond to the measurement at the cutting distances of: 40 cm, 45 cm, 50 cm, 55 cm and 60 cm and used tool values correspond to the measurement at the cutting distances of: 190 cm, 195 cm, 200 cm, 205 cm and 210 cm.

3.1 sharp tool

3.1.1 Cutting forces

Figure 2 presents the evolution of the total cutting forces (Ft) versus the cutting parameters for a sharp tool. It is observed that, the increasing of the feed speed, increase the total cutting forces (figure 2-a) .This increase can be directly related to the increase of chip thickness (flow of the material removed). For example, varying the feed speed from 125 mm/min to 500 mm/min induces a rise of 190 % in the total cutting forces when the trimming is carried out with a cutting speed of 1400 m/min.

In figure 2-b it was observed that the increasing in the cutting speed induces a decrease in the total cutting forces. For example, when trimming is conducted with a feed speed of 500 mm/min, the increasing of the cutting speed from 350 m/min to 1400 m/min causes a small reduction in total cutting forces. This reduction is around 47 %. This drop in the total cutting forces can be explained by the fact that, the increasing in the cutting speed results in the reduction of the chip thickness. This diminishing on total cutting forces is linked on the one hand to the decreasing of the chip thickness and on the other hand to the increasing of the machining temperature [7].

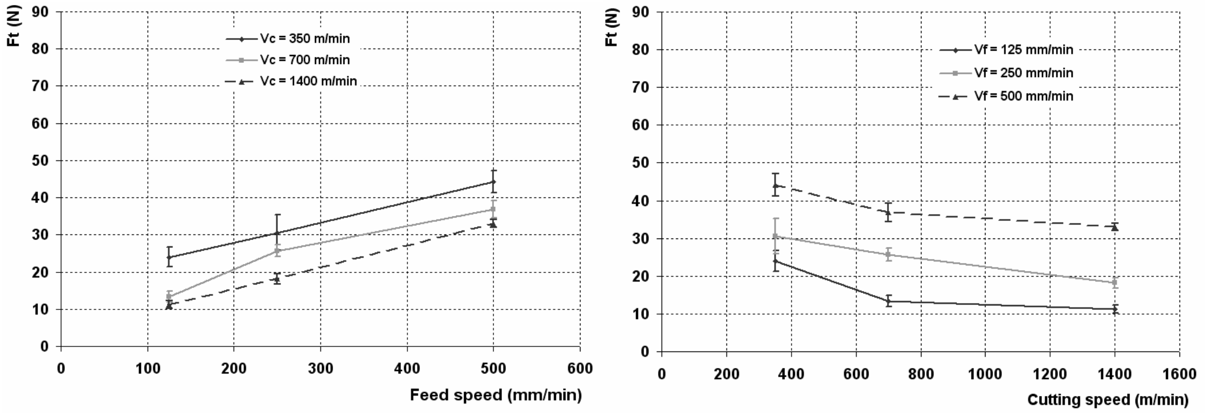

Figure 2. Evolution of total cutting forces with an sharp tool versus cutting parameters. (a) feed speed. (b) cutting speed

3.1.2 Quality of the machined surface

Figure 3 illustrates the evolution of surface roughness depth (Rz) as a function of cutting parameters. It is observed that, the roughness depth (Rz) is slightly influenced by the feed speed. When the trimming is conducted with the cutting speeds of 350 m/min and 700 m/min and for all feed speeds, the variation of the roughness values is insignificant (Fig. 3-a). In these conditions of machining, averages roughness values are measured between 50 µm and 65 µm. However, the increasing of the cutting speed until 1400 m/min causes a rise in the roughness depth values. In this case, Rz is ranging from 86 µm to 111 µm when the feed speed varies from 125 mm/min to 500 mm/min (Fig. 3-b). This difference between measured values of the roughness depth when trimming is carried out with 1400 m/min compared to the cases of machining with 350 m/min and 700 m/min can be associated to the difference of the cutting edge radius of the tool. It is supposed that, the high speed trimming (1400 m/min) coupled to the heterogeneity of the composite material, and the abrasive nature of the carbon fibres favor the increasing of the cutting edge radius. The increasing of the rounded edge radius leads to the increase of the specific cutting pressure.

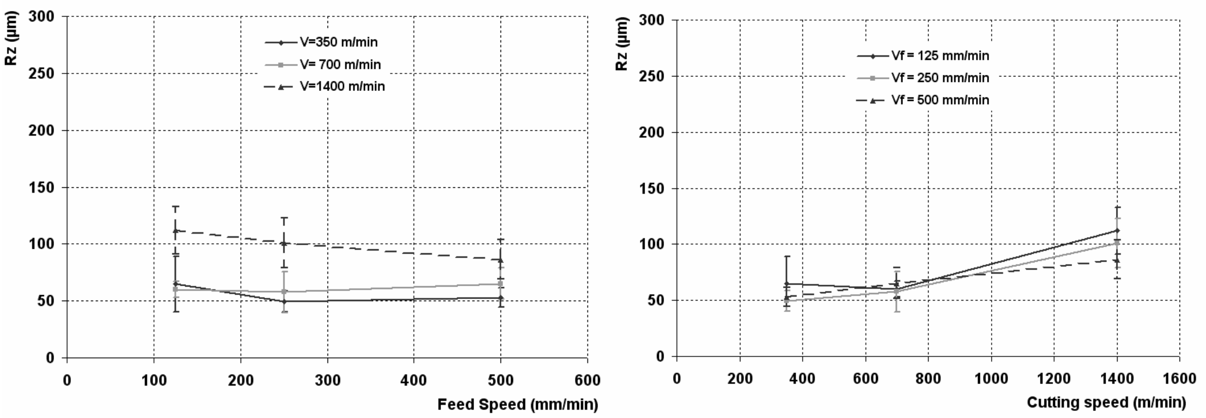

Figure 3. Influence of cutting parameters on the average surface roughness depth (Rz) obtained for an sharp tool, (a) influence of feed speed, (b) influence of cutting speed

The SEM observation of the machined surface obtained at a feed speed of 500 mm/min and a cutting speed of 700 m/min show a small regions of the fibre pull outs (Fig. 4-a). From this image, a neat machined surface can be observed. Similar results have been observed when the cutting speed is inferior or equal to 700 m/min, and for all feed speeds (125 mm/min, 250 mm/min and 500 mm/min). However, with the increase of the cutting speed (1400 m/min), fibres pull out areas increase (Fig 4-b). In addition, areas of matrix degradation appear. These damages are more important when the feed speed decreases (Fig 4-c). These results confirm and explain the high average roughness values observed above (Fig. 3-b). This poor quality of surface can by explained by the fact that, the radius edge value is more important compared to the ship thickness (≈ 0.17 µm). Therefore, fibres are pushed and pulled.

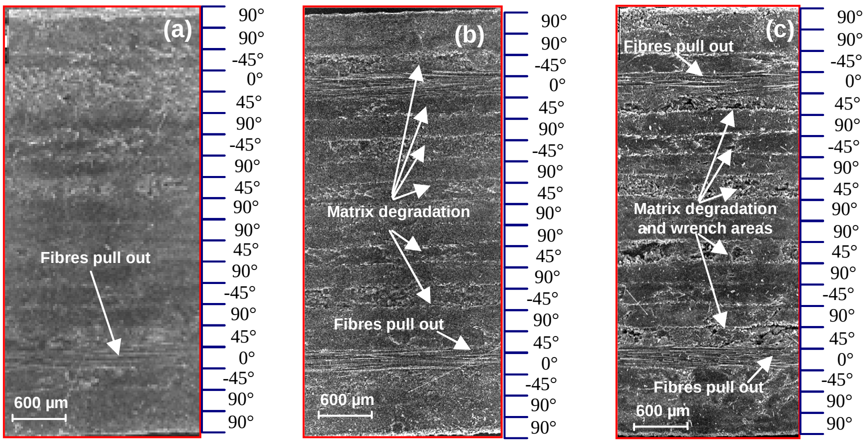

Figure 4. SEM observations of machined surface for an sharp tool and for various machining parameters (a) Vc = 700 m/min, Vf = 500 mm/min, (b) Vc = 1400 m/min, Vf = 500 mm/min and (c) Vc = 1400 m/min, Vf = 125 mm/min.

3.2 Used Tool

3.2.2. Cutting forces

Figure 5 represents the influence of cutting parameters on the total cutting forces obtained for a used tool. It is also found that total cutting forces increase with the increasing of feed speed, and decrease with the increasing of cutting speed. These results are similar to those observed when the tool is supposed to be fresh (Ref Fig. 2). However, the level of the recorded forces is more important compared to the case where the wear of the cutting edges is supposed to be null. It is also observed that the feed speed and the cutting speed have more influence on the total cutting forces. For example when changing the feed speed from 125 mm/min to 500 mm/min, at a cutting speed of 1400 m/min, an increase of 283 % in the total force has been observed. However these values are less important with new tool. This phenomenon is related to the increase of the rounded cutting edge. This is more important for a high cutting speed (1400 m/min,) and low feed speed (125 mm/min), where the tool is subjected to higher amount of wear. [7]

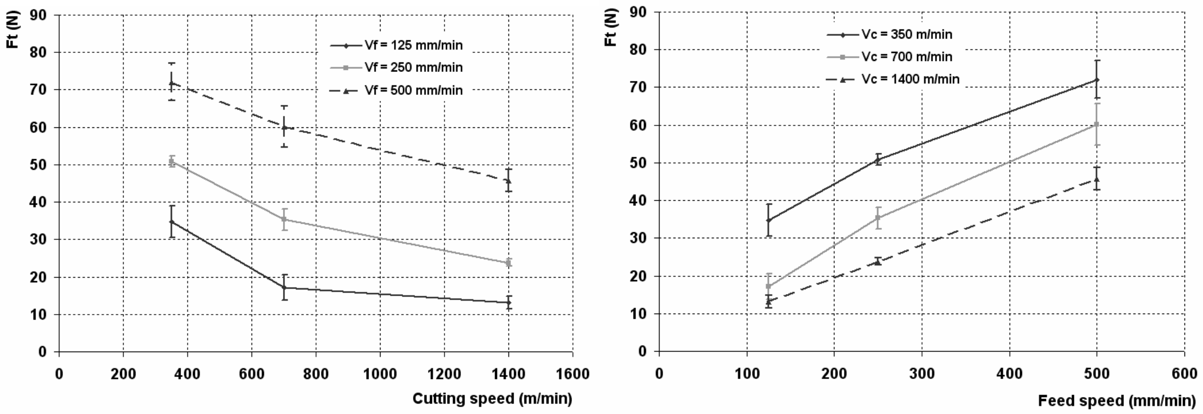

Figure 5. Evolution of total cutting forces as a function of cutting parameters. (a) cutting speed. (b) feed speed.

3.2.2. Quality of the machined surface

Figure 6 shows the influence of cutting parameters on the average roughness of the machined surface. It is observed that, the surface roughness depth values (Rz) are more important compared with those obtained for a sharp tool. The measured values fluctuate between 64 µm and 223 µm for a cutting distance of 2 m and from 50 µm to 111 µm for a cutting distance of 0.5 m. This can be explained by the effect of tool wear (cutting edge radius). It is also observed that, when trimming is carried out with cutting speeds of 350 m/min and 700 m/min, the measured roughness values are between 64 µm and 88 µm. However, when the cutting speed reaches 1400 m/min, an important variation in surface roughness depth is observed. In this case the measured values are observed between 105 µm and 223 µm. The same tendency is noticed during trimming with a sharp tool. However, magnitudes measured are more important. For example varying the cutting speed from 700 m/min to 1400 m/min induces an increase of 153.4 % surface roughness depth for a feed speed of 125 mm/min, this value is more important compared to the sharp tool and for the same cutting parameters (Fig. 3).

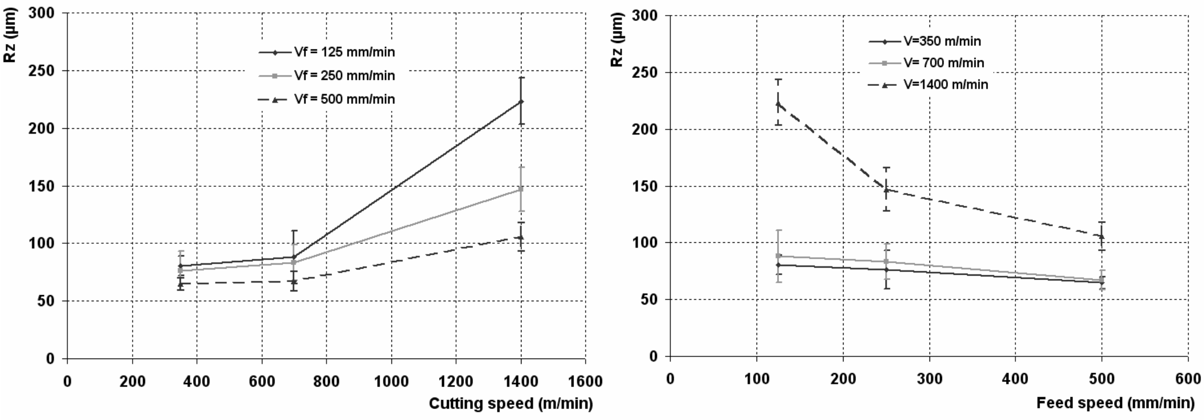

Figure 6. Influence of cutting parameters on the average surface roughness depth (Rz) obtained for a used tool.

SEM observations of the machined surface after trimming with various feed and cutting speeds are presented in Figure 7. From these pictures presence of different damages like: matrix degradation, fibre pull out and uncut fibre in the free edge of the specimens are noted. These damaged zones are present on all the conditions of machining when trimmed using used tool. In addition, the extent of these damages is more important comparing to those observed when trimming is carried out with sharp tool (Fig.4).

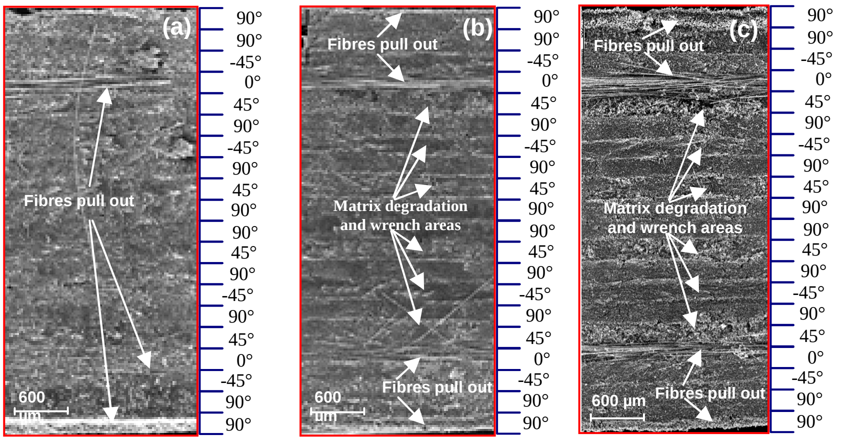

Figure 7. SEM observations of machined surface for a used tool and for various machining parameters (a) V_c = 700 m/min, V_f = 500 mm/min. (b) V_c = 1400 m/min, V_f = 500 mm/min. (c) V_c = 1400 m/min, V_f = 125 mm/min.

Based on these SEM observations, it can be concluded that the maximum damage was observed when the machining is performed with high cutting speed (1400 m/min) and lower feed speed (125 mm/min).

The damaged zones are observed for fiber directions + 45 ° measured with respect to the feed rate direction, which considering the type of machining (down milling) becomes - 45 °. These results are in accordance with literature when orthogonal cutting is considered [11].

3.3. ANOVA analysis

To calculate the contribution of each parameter, analysis of variance (ANOVA) with 95% confidence interval is estimated using commercial software "Minitab 16". Three levels for each cutting parameters (V_c and V_f) as presented in paragraph 1 and 10 levels for the cutting distance (L_c). The selected cutting distances (L_c) correspond to the middle of each machined face (13 cm, 39 cm, 65 cm, 91cm, 117 cm, 143 cm, 169 cm, 195 cm, 221 cm and 247 cm).

Table 2 shows the results of the ANOVA analysis obtained for the total cutting force (Ft). It is observed that the feed force is mainly affected by the feed speed (49 %) followed by tool wear (27.7 %) and cutting speed (11 %). We obtain R² = 99.5 %. This is directly related to the choice of the sources of variances (cutting speed, feed speed and cutting distance). It can be concluded that even if the trimming is carried out with temperatures higher than the Tg, the main parameters affecting the total cutting forces are cutting parameters (V_c, V_f) and cutting distance.

sources of variances	V_c	V_f	L_c	$V_c . V_f$	$V_c . L_c$	$V_f . L_c$	Error
Contribution percentage	23,07	45,48	22,61	1,49	4,04	2,7	0,57

Table 2. Summary of percentage contribution of cutting parameters and cutting distance on the total cutting forces "Ft" (R² = 99.42 %)

The ANOVA analysis curried on the average surface roughness depth give R² = 95.4 % (Tab.3). It is observed through SEM images (Fig. 4 and Fig. 7) that fibre pull outs and matrix degradation are obtained in localized regions. This induces large perturbations on the surface roughness depth measurement. Including these perturbation, coefficient R² = 95.42 %, can be considered as accurate. Concerning the influence of each parameter it is observed that cutting speed affects mainly the surface roughness depth with a percentage contribution (Cp) of 55.5 %. However the feed speed with Cp = 12.30 % and cutting distance with Cp = 14.7 % still have significant influence.

sources of variances	V_c	V_f	L_c	$V_c . V_f$	$V_c . L_c$	$V_f . L_c$	Error
Contribution percentage	55,46	12,3	14,65	8	2,1	2,8	4,58

Table 3. Summary of percentage contribution of cutting parameters and cutting distance on the average roughness depth Rz (R² = 95.42 %)

4. Conclusion

This paper presents experimental results of high speed trimming of composite with quasi-isotropic stacking sequence made from UD prepreg. Based on the experimental analysis and the ANOVA analysis, the following conclusions were drawn.

1. Total cutting forces are influenced by the feed speed, the cutting distance followed by cutting speed. It is observed that, the increase of the feed speed or the cutting distance induces higher total cutting forces. However, increasing the cutting speed reduces the total cutting forces. This result is in accordance with work of Ucar & Wang [9].

2. At low cutting speed (350 m/min and 700 m/min), SEM images show few mechanical damages. These damages are mostly fibre pull out, for a fresh tool and fibre pull out and some areas of matrix degradation for a used tool. With higher cutting speed of 1400 m/min, various damages were observed; the damages are fibre pull outs and matrix degradation for fresh tool. These damaged areas are more important for a used tool.
3. The most damaged zones correspond to fibers direction -45 °. This result is on accordance with the works [10, 11] when considering orthogonal cutting.
4. From ANOVA analysis it is noticed that, the quality of the machined surface is mainly affected by the cutting speed (with a Contribution Percentage Cp= 55.46 %) followed by cutting distance (with Cp = 14.65 %) and finally by the feed speed (Cp = 12.3 %). While, the total cutting forces are mostly influenced by the feed speed (45.48%) followed by the cutting speed (Cp = 23.07 %) and cutting distance (Cp = 22.61 %).

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