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# Surface integrity while trimming of composite structures: X-ray tomography analysis

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## A B S T R A C T

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### Keywords:

Trimming CFRP  
Crater volume  
X-ray tomography  
Machining temperature

The aim of this paper is to study the influence of the process parameters (cutting speed and feed) of the conventional trimming on cutting forces, machining temperatures, tool wear and machining quality of Carbon Fibers Reinforced Plastics (CFRP) using PCD tool. The machining quality was characterized using three different techniques such as Scanning Electron Microscopy (SEM), 3D optical topography and X-ray tomography. The originality of this work is based mainly on the multi-scale characterization of the machined surfaces. In fact, a new parameter based on the measurement of the volume of craters is proposed and compared to the surface roughness criterion (Sa) and the X-ray tomography images. The obtained results show that, with the crater volume criterion as well as the X-ray tomography images, the effect of the machining parameters and the wear of the tool on the textured surfaces are well correlated to surface roughness criterion (Sa). In addition, it was observed that the feed speed and tool wear were the major factors affecting the cutting forces and the machining temperatures.

## 1. Introduction

Composite materials have been used widely in recent decades, especially fiber reinforced plastics composites (FRPs). This kind of material has been attracted by various industrial fields like aerospace, transportation, sports equipment, because of possessing valuable features such as high strength to weight ratio, high stiffness to weight ratio, high corrosion and wear resistance [1]. To conform to each certain application, composite parts are frequently fabricated to near net shapes. In many cases, the machining operations are commonly needed after demolding to get the final dimensions of the composite structures. The applications of each cutting process mainly depend on specific requirements of assembled composite parts. For instance, drilling is applied to make holes for riveting of the panels [2–4], edge trimming is used to remove excess materials in the sides (free edges) [5,6]. Although composite materials offer many advantages, their machinability is a huge challenge and remains an open problem. Given that composite materials consist of minimum two constituents, e.g. carbon fiber reinforced and matrix owning different mechanical, thermal and physical properties which make composite materials inhomogeneous and anisotropic. Thereby, machining of carbon/epoxy materials is

accompanied by a series of brittle fractures because of shearing and cracking of matrix materials under applying of cutting forces due to the interaction between cutting tool and workpiece [7–10]. As a result, several kinds of damage such as delamination, uncut fibers, thermal and/or mechanical degradation of the matrix, inter laminar cracks are created, and making the machining surface becomes more irregular than that of metallic materials [11–13]. In addition, cutting parameters, tool wear and the relative angle between the direction of cutting speed and fiber direction are crucial factors affecting the damage induced [5,11,12]. In fact, in the experimental work of Morandea et al. [14], the influence of lead angle of the cutting tool on the cutting forces and the machining quality during milling of multi directional composite made of CFRP have been investigated. Authors have shown that, milling with cutting tool which is characterized by a lead angle of 19° leads to reduce the cutting force, rate of wear and the size of the delamination compared to the case when milling is conducted with a cutting tool of 60° of lead angle. Recently, an acoustic emission (AE) technique has been used by Prakash et al. [15] for on line monitoring of the tools wear during trimming of unidirectional specimens made of CFRP. Thanks to this technique of instrumentation, the relationship between AE signal and length of machining for different kinds of geometry of tools has

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been identified. It was concluded that the geometry of the router tool (burr tool) with a flat cutting edge has better performance by generating lower cutting force and better surface finish compared to the helical fluted tool. In addition, in the work of Slamani et al. [16], which focuses on the statistical analysis technique when trimming of multi-directional specimens made CFRP, it was mentioned that the effect of cutting speed on the cutting forces is found negligible. Sheikh Ahmad et al. [12] have revealed that trimming of CFRP at high cutting speed and low feed speed produces low values of theoretical chip thickness and generates better surface quality. Inversely, the combination between low cutting speed and high feed speed gives poor quality of machined surfaces due to the high values of chip thickness which make difficulties in trimming. On the contrary, Haddad et al. [5,17] have shown that when trimming is conducted with high cutting speed (1400 m/min) and low feed speed (125 mm/min), surface defects are more than other cutting conditions used (less cutting speed and high feed speed). The authors (Haddad et al. [17]) have explained that the difference of results compared to the work of Sheikh Ahmad et al. [12] is attributed mainly to the rapid wear rate of cutting tool used (which is made of tungsten carbide). It means that when the feed speed decreases, the contacting time between the CFRP specimen and cutting tool increases. Other hand, an increase in the cutting speed generates a wider contacting surface between the machined specimen and the cutting tool. Similar result has been obtained by Cadorin et al. [4] when drilling of 3D composite made of carbon fiber. In this case, Cadorin et al. [4] have proposed to use a cutting tool made of diamond grits to increase the wear resistance and have made the texture of the machined surface little independent of the contacting time of the tool with the machined surface. Actually, when machining is conducted with cutting tool made of tungsten carbide, the increasing of the contacting time and the frictional phenomenon, make cutting tool rapidly wear and very high machining temperatures induced. In fact, machining temperatures recorded by Haddad et al. [17] at small feed speed and higher cutting speed were higher than the glass transition temperature of the machined composite materials. As known, the wear of cutting tool generates poor surface integrity, higher cutting temperatures, and forces as well [5,11]. The natural abrasive of the carbon fiber is an avoidable reason causing tool wear. Consequently, the using of cutting tool materials having the high wear resistance is necessary. These tool materials like cemented tungsten carbides coated with diamond layer, ceramics, and polycrystalline diamond (PCD) have been used in composite machining. Among mentioned tool materials, PCD tool provides good thermal conductivity, low coefficient of friction, superior tool life, and higher productivity. Hence, cutting PCD tool is widely recommended for machining of composite materials. However, the cost of the PCD tool is much higher compared to the tungsten carbide cutting tools or other materials, few authors have investigated the machinability of CFRP with cutting tools made of PCD inserts [18–25]. In the work of [24], authors have focused on the influence of the machining parameters on the cutting forces and the machining quality during trimming of unidirectional specimens made of carbon/epoxy laminates. In this work the machining surface is characterized by the average roughness criterion (Ra). In fact, the presence of machining defects in structures in service creates many stress concentration sites which can affect the mechanical properties of composite structures [26–28]. Hence, machining quality should be correlated to mechanical properties to identify the impact of the machining quality on the structural integrity. The surface roughness criterion (such as Ra or Sa), initially used for the qualification of the surface quality of metal, is widely adopted to characterize the quality of composites too. However, extending the utilization of this parameter for composites to correlate the machining damage to the mechanical behavior has given rise to ambiguity in research communities. For example, if we refer to the work of Squires et al. [29] it is observed that an increase in surface roughness (Ra) leads to reduction in the compressive strength. Based on this result, it seems that the surface roughness (Ra) is a good indicator to

characterize the machined surface of composite materials. Nevertheless, the results of the tension tests conducted by Ghidossi et al. [30] on unidirectional (UD) specimens made of glass/epoxy have showed a totally converse results, i.e. tensile strength increases with the increasing of the surface roughness (Ra). In addition, for the multi-directional (MD) laminates, recently Haddad et al. [28] have revealed that the compressive strength of the machined specimens is strongly influenced by the machining quality and mainly the temperature of machining. Their results reveal that the compressive strength of specimens characterized by a temperature of machining superior or equal to 290 °C is 30% lower to the compressive strength of specimens with a temperature of machining around 130 °C. Although this reduction of the compressive strength is accompanied with increasing surface roughness, it cannot make any conclusions about the relationships between the surface roughness and the compressive strengths. Moreover, the incapability of surface roughness in characterization of machining damage of composite has been also documented by other studies such as [31–34]. Thus, it can be said that surface roughness does not hold good for composites, its correlation with mechanical properties is totally absurd, hence a new parameter is proposed which will better quantify the machining damage and correlates to mechanical properties. Recently, in the work conducted by Hejjaji et al. [35] it is observed that generated the machining quality obtained after milling of CFRP with the abrasive water jet process, can be quantified as crater volume, which was well correlated to the tensile strength rather than the surface roughness (Ra).

The main objective of this work is to analyze the impact of cutting parameters and tool wear on the cutting forces, temperatures of cutting as well as the machining damage during trimming of CFRP structures. The trimming process is conducted using PCD tool with different techniques of instrumentations which include dynamometer and infrared camera. Machining quality and the surface texturing are characterized using SEM observations, X ray tomography technique and 3D optical topography measurements. The quantification of machining damage is conducted using the surface roughness criterion and the crater volume thanks to 3D contour processing technique.

## 2. Experimental procedure

### 2.1. Material preparation

The CFRP laminates used in this study were made of unidirectional Prepregs supplied by Hexcel Composite Company and referenced under HEXPLY US T700 268 M21 34% (T700 M21). Twenty layers of prepregs corresponding to the dimension of 300 mm × 300 mm and a thickness of 0.25 mm were stacked together to create plates with a theoretical thickness of 5.2 mm with the following layup with respect to feed direction:  $[90^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ}/90^{\circ}/45^{\circ}/90^{\circ}]_s$ . These plates were compacted using a vacuum pump in a controlled atmosphere. A mold for the laminate was prepared and placed in a vacuum bagging and evacuated to 0.7 bar (Fig. 1). Curing was then carried out at 180 °C for 120 min during which the pressure was maintained at 7 bars in an autoclave. The mechanical properties of the ply T700 M21 are detailed in [36]. This stacking sequence is used in the structural part of the A350 aircraft of Airbus [27,28]. To reduce the variability of the mechanical properties due to the process of manufacturing, all the specimens used in this study are cured in the same mold. For more detail about the mechanical properties of composite materials, it is referred to the Table 1.

### 2.2. Cutting parameters

A full factorial design of cutting condition including three levels of feed speeds and two levels of cutting speeds was studied. In order to correlate our results to those of the literature work, a radial depth of cut of 2 mm is used for all the specimens tested [5,17,27,28]. In addition,

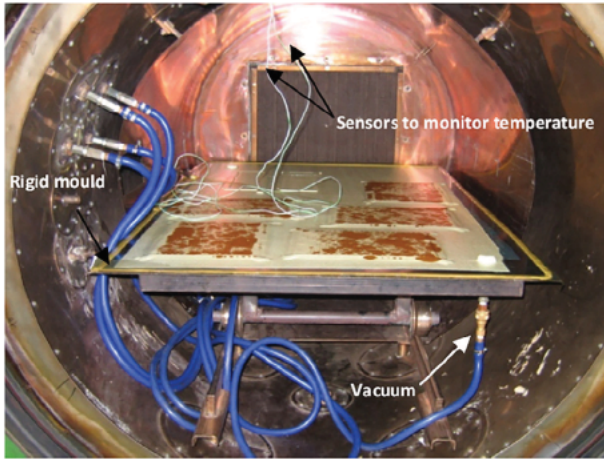


Fig. 1. Composite laminate after the curing process in the autoclave.

**Table 1**  
Mechanical properties of HexPly T700-M21.

Composite materials (T700-M21)	Ply thickness: 0.26 mm Fiber content: $V_{fiber} = 59\%$ Stacking sequence with respect to the feed direction: $[90^{\circ}/90^{\circ}/45^{\circ}/0^{\circ}/45^{\circ}/90^{\circ}/45^{\circ}/90^{\circ}/45^{\circ}/90^{\circ}]_s$ Young modulus: $E_l = 142$ GPa, $E_t = 8.4$ GPa Shear modulus: $G_{lt} = 3.8$ GPa Glass transition temperature: $T_g = 187$ °C Energy release rate: $G_{Ic} = 0.35$ N/mm, $G_{IIc} = 1.21$ N/mm
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with this radial depth of cut, the tool wear can be accelerated in order to generate different level of the machining quality. In fact, for these reasons the cutting conditions and the machining configuration (down milling) were chosen in order to generate different level of mechanical degradations. The impact of these degradations on the mechanical behavior will be investigated subsequently (it is not the aim of this paper). It is important to highlight that, with this experimental design, 18 specimens were prepared according to the standard recommendation AFNOR NF T 51 120 3 (1995). For this, a pre cutting was carried by abrasive water jet process (AWJ) to get the recommended dimensions of each specimen, i.e. 280 mm × 14 mm × 5.2 mm. For each machining condition and for each tool, a machining distance of 168 cm (280 cm × 2 faces × 3 specimens = 168 cm) is achieved.

In order to better analyze the damage generation in function of the machining parameters, a new polycrystalline diamond cutter with two straight flutes (PCD) was used for each cutting condition (Fig. 2). The machining is conducted without lubricant (dry machining). The detail information of experimental parameters is presented in Table 2.

**2.3. Trimming setup and data acquisition**

Trimming process was carried out on a “DMU 85 mono BLOCK” 5 axis milling machine with maximum spindle speed of 18,000 rpm. The specimens were fixed firmly by cap screws on a specific device designed and manufactured for this study. The acquisition of cutting forces was recorded using a dynamometer (Kistler 9272). The dynamometer was connected to a Kistler charge amplifier (Model 5019). The force signals were obtained after being converted from the charge signals by the amplifier. Machining temperatures were registered by an infrared camera referenced under ‘Thermo Vision’ A40. The details of experimental devices used trimming test are shown in the Fig. 3.



Fig. 2. PCD tool used with two straight flutes.

**Table 2**  
Summary of experimental conditions for trimming of CFRP laminates.

Cutting tools	PCD tool: helix angle = 0°, rake angle = 5°, clearance angle = 7° Diameter = 6 mm Number of cutting edge = 2
Cutting conditions	Radial depth of cut ( $a_e$ ) = 2 mm Full factorial design Feed speed (mm/min): $V_f = 500, 1000$ and $1500$ Cutting speed (m/min): $V_c = 150$ and $250$

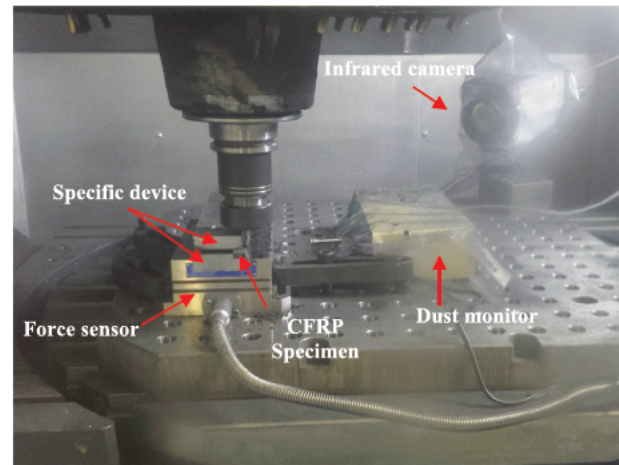


Fig. 3. Experimental devices for trimming tests.

**2.4. Characterization of the machined surface**

The machining quality has been investigated by three different techniques. The first technique concerns the 3D topographer “Altisurf 520” which works based on the principle non contact stylus (Fig. 4). The evaluation area of 8 mm × 4.5 mm (corresponding to direction of length and thickness respectively) was scanned with a spatial resolution of 4 μm. 3D average surface roughness is extracted from the topography using “Digitalsurf” software using Gaussian filter (cut off = 0.8 mm). Moreover, craters occurring on the machined surface were estimated by their volume by analyzing the topography surface using the software Mountain maps. The volume calculation is performed based on the polynomial (with degree 3) approximation technique [37]. The second technique of the surface characterization is based on the use of the Scanning Electron Microscope (SEM). For this, the SEM used is referenced under “JEOL JSM 5310”. Finally, to quantify the damage



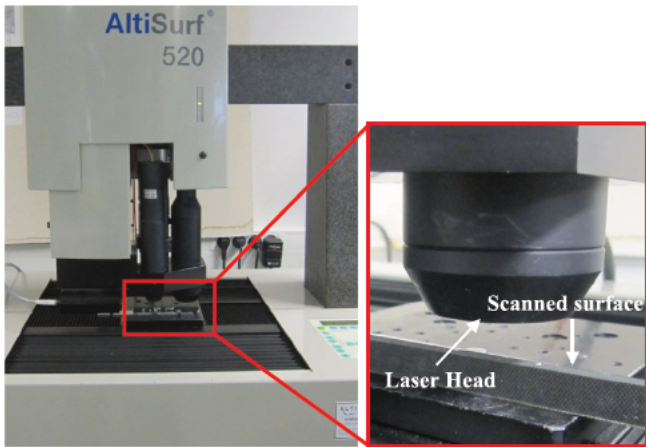


Fig. 4. Confocal Microscope – For 3D topography measurement.

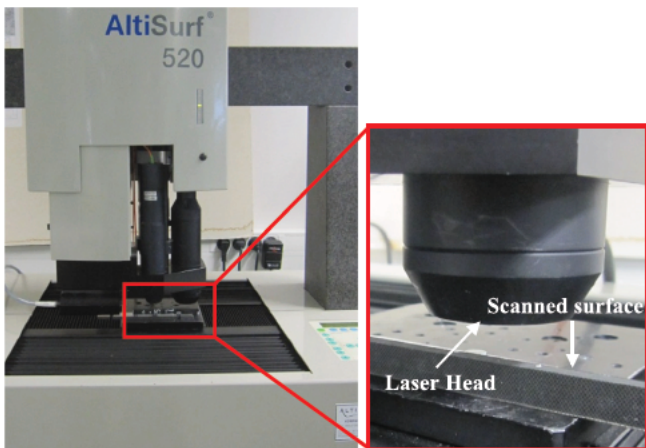


Fig. 5. X-ray tomography for analyzing specimens.

mechanisms in the heart thickness of the machined specimens, the X ray tomography was conducted using Micro Tomography Easy Tom 130 machine (Fig. 5) manufactured by RX Solutions France. The specimens, rotating through 360 °C, were placed at 20 cm from the X ray source. This technique gives 2D X ray images which can be reconstructed using extract software to obtain full scale 3D images.

### 3. Results and discussion

#### 3.1. Cutting forces analysis

The schematic diagram of trimming process is described in Fig. 6. Cutting forces are presented by Eq. (1) in which it is noticed that force component in Z direction is approximated zero due straight flute (helix angle ≈ 0°).

$$F_t = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

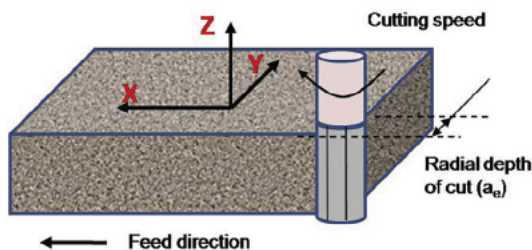


Fig. 6. Schema of the axes and the machining directions.

where:  $F_x$  and  $F_y$ ,  $F_z$  are the cutting force components in X (feed force), Y (normal force) and Z (thrust force) directions, respectively.

The evolution of cutting forces as a function of cutting parameters is illustrated in Fig. 7 at two cutting distances (0.28 m and 1.68 m). The choice of these two cutting distances, leads to analyse the results for the case where the tool is considered as new (for a distance of 0.28 m) and for the case where the tool is worn (for a distance of 1.68 m). It is important to mention that each point of the cutting force in Fig. 7 represents an average value of five measurements. From this figure it can be noticed that the amplitude of the cutting forces recorded for any cutting distance as well as cutting speed increases with the increasing of the feed speed, with an exception of the case of machining with 250 m/min and after a distance of 1.68 m. For example, when the tool is considered as new (distance of machining equal to 0.28 m) and when the trimming is conducted with a feed speed of 500 mm/min and a cutting speed of 150 m/min, the generated cutting force is 66% lower compared to the case of machining with a feed speed of 1500 mm/min (with the same cutting speed). This result can be explained by the fact that, with the increasing of the feed speed, the volume of the cut material increases too and this requires more force for the chip formation. If we refer to the literature work of [1,5], the influence of the cutting parameters (feed speed and cutting speed) on the cutting forces is directly related to the theoretical chip thickness. As a matter of fact, an increase in the feed speed or the decrease in the cutting speed favours the augmentation of the chip thickness. This can explain the reduction of the cutting forces with the augmentation of the cutting speed from 150 m/min to 250 m/min. For example, when trimming is conducted with a new cutting tool and with a cutting speed of 250 m/min (for a feed speed of 1500 mm/min), the cutting force is 25% lower compared to the case of trimming with a cutting speed of 150 m/min and for the same feed speed and the state of the tool. This result can be related, on the one side to the reduction of the theoretical chip thickness with the increasing of the cutting speed, and on the other side to the augmentation of the temperature of machining. In fact, with the augmentation of the temperature of machining favours the softening phenomenon of the epoxy matrix and the material can be easily cut. However, for the same conditions of machining (250 m/min) and after a distance of machining of 1.68 m, the variation of the cutting force in function of the feed speed is less evident compared to all other cases. This result can be related, on the one side to the theoretical chip thickness, and on the other side to nose radius of the cutting tool which is impacted by the wear phenomenon. In fact, with mentioned cutting speed and when the feed speed varies from 500 mm/min till 1500 mm/min the theoretical chip thickness varies from 2 μm to 6 μm. These theoretical values of the chip thickness are estimated based on the method proposed in [1]. In this case, the maximum and the minimum values of the chip thickness are inferior to the carbon fibres diameter (7 μm) and also inferior to the nose radius of the cutting tool after a distance of cutting of 1.68 m (Fig. 8). In this situation, it can be supposed that the mechanisms of chip formation, when helical tools or straight flutes tools are used, is more by pushing rather than cutting the matrix and the carbon fibres compared to the other cases. Similar results have been observed by Haddad et al. [5], Prakash et al. [15] and Wang et al. [38]. However, when the burr tools are used, Prakash et al. [15] have observed an augmentation of the cutting forces in function of the feed rates for any value of the cutting speeds.

From the Fig. 7, it can be also noticed that, the augmentation of the distance of machining has a non negligible impact on the augmentation of the cutting forces. This can be related by the fact that, due to the abrasive character of the carbon fibres, the wear of the tool occurs and with the augmentation of the machining distance the friction phenomenon and the cutting forces increase too.

These informations can be confirmed by the SEM images of cutting edge of tool before and after machining for different cutting condition of the feed speed and for a cutting speed of  $V_c = 150$  m/min (Fig. 8). Form this figure it is clear that the wear of tool in term of nose radius of

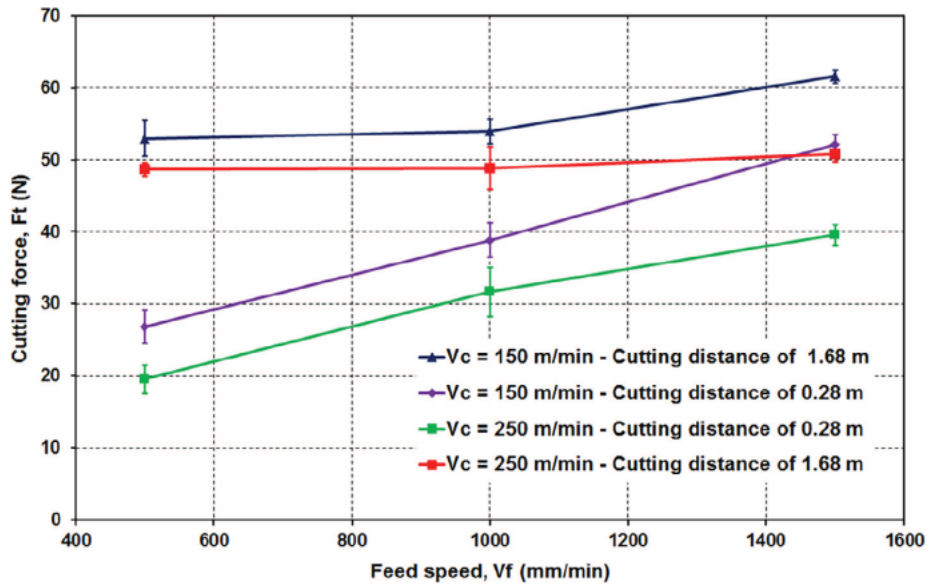


Fig. 7. Influence of cutting parameters and cutting distance on cutting forces.

the cutting edges is strongly impacted by the choice of the feed speed. From the Fig. 8 a and b, we can observe that, after trimming with a feed speed of 500 mm/min, the radius of the cutting edge has been strongly modified and is higher compared to the initial state (before machining). However, with the increasing of the feed speed, the variation of the local geometry of the radius of the cutting edge of the tool is less impacted (Fig. 8 c and d). This result can be explained by the fact, that when trimming is conducted with small feed speed, the machining time is more compared to the case when the feed speed is higher. Similar results have been observed by Cadorin et al. [4] during

drilling of 3D woven composite with the presence of the lubricant. Indeed, with the increase of the time of machining the distance covered by the cutting edge in contact with the CFRP is more important and the wear of the cutting edge is more highlighted. Based on the SEM images of the Fig. 8, the wear mechanism which occurs on the PCD cutting edge during the cutting process is mainly the abrasion.

The cartographies of the cutting edges for the different tools used are obtained thanks to microscopy leads to estimate the impact of the feed speed on the values of the nose radius of the cutting tools (Fig. 9). Based on these images and image processing technique, the value of the

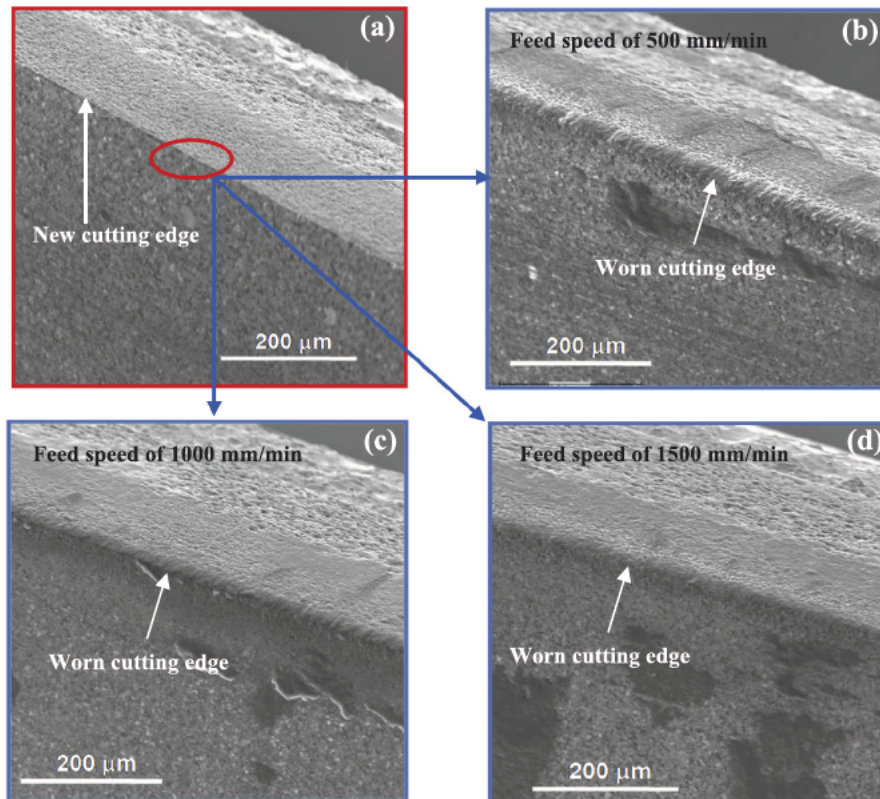


Fig. 8. SEM images of cutting edges of tools: magnified view of cutting edge of (a) unused tool and after cutting distance of 1.68 m for cutting speed of 150 m/min and with feed speed of (b) 500 mm/min, (c) 1000 mm/min and (d) 1500 mm/min.



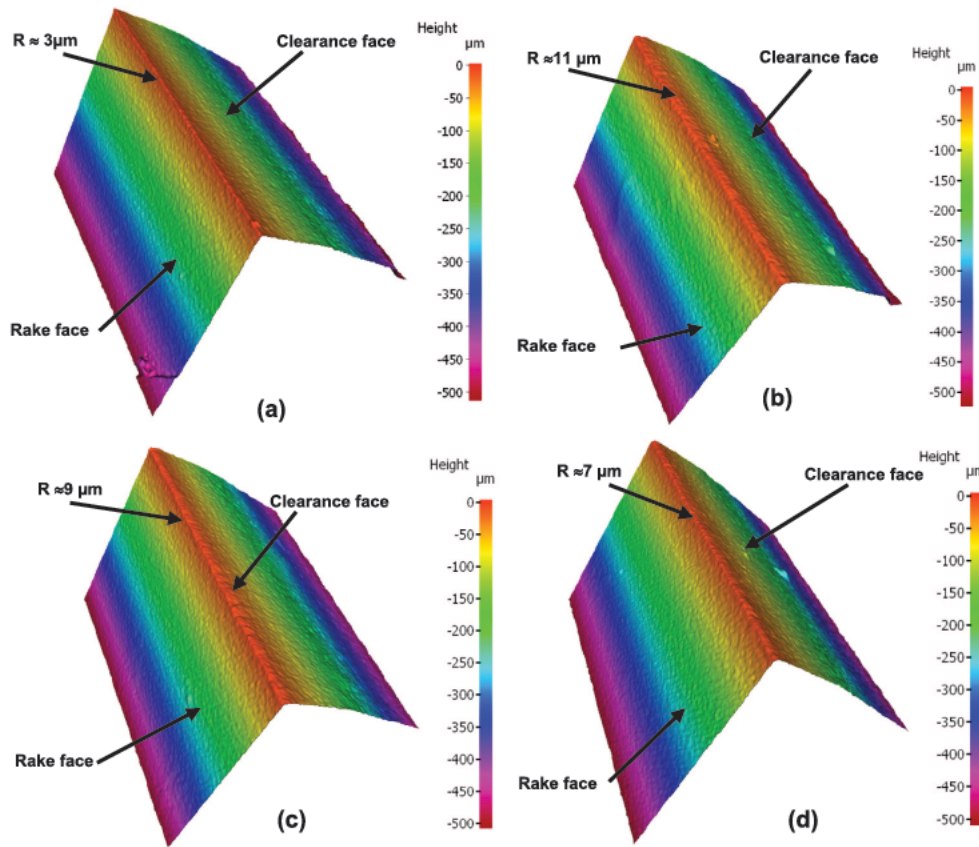


Fig. 9. Cartographies of the cutting edges of the tool in function of the machining parameters for cutting speed of 150 m/min. Before machining (a), and after machining ( $L_c = 1.68$  m) with (b)  $V_f = 500$  mm/min, (c)  $V_f = 1000$  mm/min and (d)  $V_f = 1500$  mm/min.

nose radius measured before machining on a new cutting tool is around 3  $\mu\text{m}$ . However, when trimming is conducted with feed speed of 1500 mm/min and a cutting speed of 150 m/min, the value of the nose radius reaches 7  $\mu\text{m}$  (Fig. 9 d). Moreover, with the reduction of the feed speed till 500 mm/min, the value of nose radius reaches 11  $\mu\text{m}$  (Fig. 9 b).

Compared to the case of trimming with a cutting tool made of tungsten carbide, the chipping phenomenon of the PCD edges is not observed as described in the work of Janardhan et al. [11]. In fact, the local modification of the cutting edge of the PCD tool due to the abrasion wear can impact, on one side the levels of the cutting forces, and on the other side the temperature of machining as well as the machining quality.

### 3.2. Analysis of machining temperature

In the Fig. 10, the influence of the feed speed and the machining distance on the maximum temperature generated during the trimming process captured on the surface by the Infrared (IR) camera is presented. From this figure it is clear that the levels of the machining temperature generated after a machining distance of 0.28 m is less than or equal to 103  $^{\circ}\text{C}$  for any feed speed tested. However, with the increasing of the machining distance (from 0.28 m to 1.68 m), the generated temperatures recorded by the IR camera are 25% superior to those measured after a machining distance of 0.28 m. In addition, the minimum value of the temperature recorded after a distance of machining of 1.68 m is superior to the maximum value recorded after a distance of machining of 0.28 m. For example, machining with a feed speed of 500 mm/min and with a new tool (distance of machining of 0.28 m), leads to generate a maximum temperature of 105  $^{\circ}\text{C}$ . However, when the tool is considered as worn (distance of machining of 1.68 m)

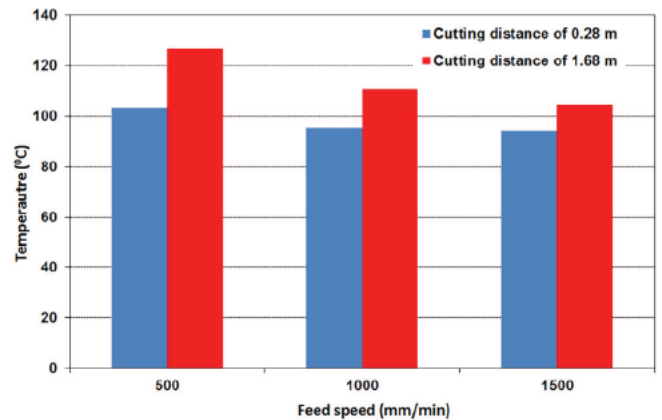


Fig. 10. Evolution of machining temperature versus feed speed and cutting distance for cutting speed of 150 m/min.

and with the same condition of trimming the maximum temperature recorded by the IR camera reaches its maximum value which is around 127  $^{\circ}\text{C}$ . In fact, this can be explained by the fact that, with the increase of the contacting distance between the active part of the cutting tool and the composite part, the wear of the tool is more pronounced and the geometry of the cutting edge is subjected to a local modification (Fig. 8). This information can be confirmed by the SEM observations of the cutting edge of the tool before and after machining for different machining distances and for different cutting conditions illustrated in the Fig. 8. From these SEM images, it is clear that the increase of the distance of machining, as well as the reduction of the feed speed, favors the raise of the nose radius of the cutting edge of the tool. It is important to mention that with the local modification of the nose radius of

the cutting edge, the friction phenomena increases and this can result, on the one side increase of the temperature of machining, and on the other side to the degradation of the machining quality.

If we refer to the work of Haddad et al. [17], which focuses on the trimming of the same CFRPs with burr tool made of tungsten carbide, the machining temperatures were found much higher compared to those obtained when trimming is conducted with PCD tool. In fact, the small values of cutting temperatures recorded in this study can be explained by the fact that, the PCD tools are characterized, on the one side by a high wear resistance, and on the other side by the small coefficient of friction in contact with the composite materials as well as high coefficient of thermal conduction. Indeed, with the small coefficient of friction and the high coefficient of thermal conduction the machining quality can be improved and in particular the thermal degradation induced by the physics of cutting can be reduced or removed. To confirm that, different technique of surface characterization has been conducted for the different specimens as it was mentioned above. The obtained results are presented in the next chapter.

### 3.3. Analysis of machining quality

#### 3.3.1. Machining surface analysis

In the Fig. 11 is presented the evolution of the roughness (Sa) as a function of the machining parameters as well as the cutting distance. From this figure it is clear that for a distance of machining of 0.28 m the values of the parameter Sa remain small and inferior to 3 μm. However with the increasing of the distance of machining important values of the parameter are recorded. For example, when trimming is conducted at small feed speed (500 mm/min) and high cutting speed the value of measured Sa after a distance of machining of 0.28 m is around 1.7 μm. However, with the increasing of the distance of machining (till 1.68 m), the recorded value of Sa reaches 5.5 μm. These differences can be related to the high values of the cutting forces recorded as well as the wear mechanisms observed when trimming is carried out at lower feed speed and high cutting speed. In fact, with the apparition of the wear phenomenon on the active part of the tool and in particular the augmentation of the radius cutting edge of the tool the machining quality can be impacted (Fig. 8 b). Trimming at high cutting speeds leads to accelerated tool wear phenomenon and especially when low feed speeds are combined with high cutting speeds. In fact, in this situation, the rate of tool wear and the temperature of machining is much higher compared to the case when the machining is conducted as high feed speeds. This phenomenon is also acknowledged by several authors and for different tool geometries as in Haddad et al. [5] and Prakash et al. [15]. It is important to notice that, when trimming is conducted with cutting speed of 250 m/min and low feed rate of 500 mm/min a high surface roughness is obtained (Fig. 11) after machining 1.68 m. This

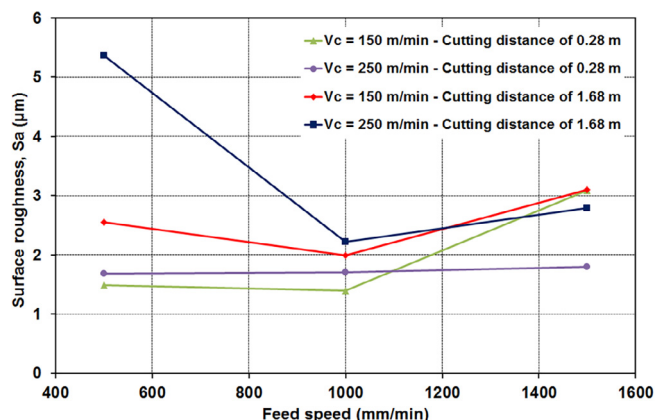


Fig. 11. Evolution of surface roughness, Sa, versus cutting parameters at two cutting distances.

combination of feed speed and cutting speed induces rapid tool wear, and after machining 1.68 m the nose radius of the tool is increased. This leads to increase in the cutting forces which favours the generation of the damages. These damages which have the form of crater and fibre pull outs (Fig. 14 and Fig. 15) have a real consequence on the augmentation of the surface roughness. To confirm that SEM images have been conducted for all the trimmed specimens.

The SEM images conducted on the different machined specimens after a distance of cutting of 0.28 m are illustrated in the Fig. 12. From these images it can be noticed that, when trimming is carried out with small feed speed (500 mm/min), the machining quality can be considered as good (Fig. 12 a). In fact, with this condition of machining the obtained surface is smooth and it is difficult to distinguish between the different plies of orientations of the laminates. However, with the raise of the feed speed (e.g. 1000 mm/min), it can be observed the evolution of small mechanical damage or mechanical degradation of the matrix on the machined surface. These damages are located mainly on the fibres oriented at +45°. It is important to mention that, with the configuration of trimming selected (down milling) the relative angle between the direction of the cutting speed and the plies oriented at +45°, is equal to 135° or -45°. In fact, in this machining configuration, the experimental tests of the orthogonal cutting conducted on unidirectional specimens by Zitoune et al. [10], reveals that with the raise of the depth of cut, macro cracks are generated on the free edge of the specimen and several zones of damages on the machined surface are observed. However, good machining qualities have been observed for the specimens oriented at 0° and +45°. In fact, these results have been explained by the physic of cutting which is strongly influenced by the relative angle measured between the ply orientation and the cutting speed direction.

The SEM images conducted after a distance of cutting of 1.68 m reveal that when the trimming is carried out with a feed speed superior or equal to 1000 mm/min, the augmentation of the cutting distance does not show a real impact on the machining quality (Figs. 12 c and 13 c). However, when the machining is conducted with small feed speed (500 mm/min), the SEM images of the Figs. 12 a and 13 a show the generation of important zones of craters and mechanical degradation of the matrix. This result can be clearly related to the wear phenomenon which impacted the local modification of the radius of the cutting edge of the tool.

Thanks to the surface characterization by confocal microscope, measurements conducted on the different trimmed specimens reveal that, with the augmentation of the cutting distance the maximum depth of the damaged zone measured after a distance of machining of 1.68 m can be three times superior to the one measured after a distance of machining of 0.28 m. For example, when trimming is conducted with a feed speed of 500 mm/min and cutting speed of 250 m/min, the maximum damage depth measured by the confocal microscope is around 50 μm after a distance of machining of 0.28 m. However, with the same condition of machining and after a distance of machining of 1.68 m, the maximum damage depth recorded is around 160 μm. Based on these images the volume of the craters generated by the process of cutting have been quantified in function of the machining parameters (Fig. 14).

It is important to mention that the confocal microscope allows giving surface information and the measured values of the depths of the damage (craters) as well as the roughness parameters, Sa, can be distorted by the presence of the fibres pull out or by the micro cracks. Indeed, to overcome this problem, the use of the X ray tomography technique, to predict the internal depth and form of the damage (craters and cracks), seems to be the ideal technique of measurement.

#### 3.3.2. Depth damage analysis by X ray tomography

The X ray tomography has been conducted on all the machined specimens and for two different distances of cutting. The selected distances are 0.28 m and 1.68 m. The reference image is the first image which characterize the machined surface and corresponds to the plane



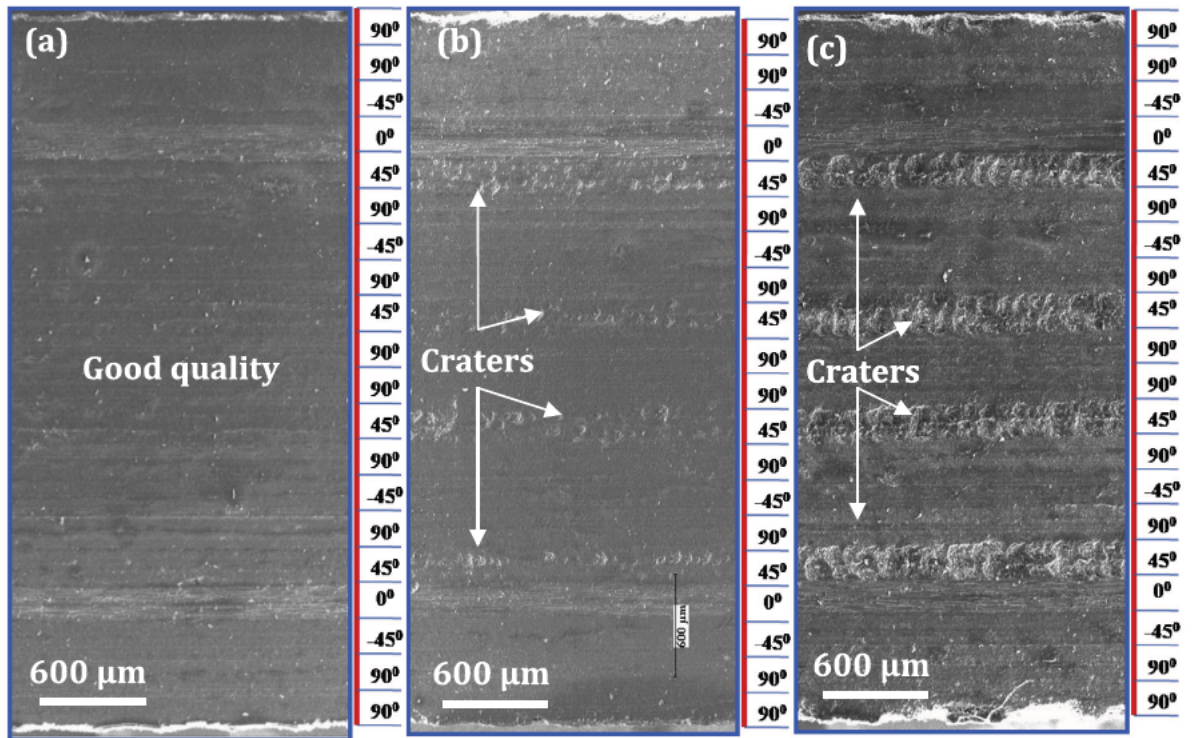


Fig. 12. SEM images conducted on specimens trimmed with a cutting speed of 150 m/min and after a cutting distance of 0.28 m with a feed speed of (a) 500 mm/min, (b) 1000 mm/min and (c) 1500 mm/min.

“Y = 0” or to the Depth of Scanning (DoS) equal to 0 (Fig. 16). In fact, the damage depth is visualized in the Y direction as described schematically in the Fig. 16 and is measured using the “Volume Viewer” Plugin of ImageJ software.

tomography on specimen after trimming with a cutting speed of 150 m/min, feed speed of 500 mm/min and distance of cutting of 0.28 m. From these images we notice the presence of small craters located in the area where the plies are oriented at  $-45^\circ$  (Fig. 17 a) and the machining quality is considered as good. In fact, with the increasing of the depth of

Fig. 17 represents the different images obtained by the X ray

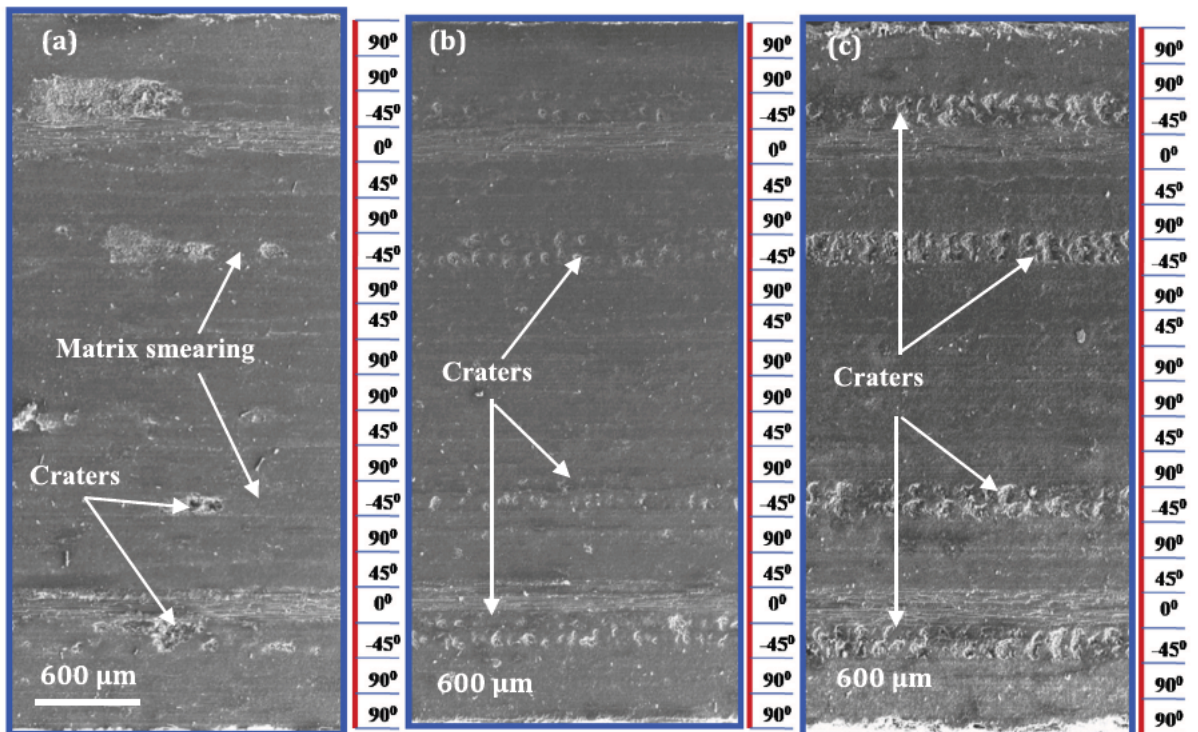


Fig. 13. SEM images conducted on specimens trimmed with a cutting speed of 150 m/min and after a cutting distance of 1.68 m with a feed speed of (a) 500 mm/min, (b) 1000 mm/min and (c) 1500 mm/min.



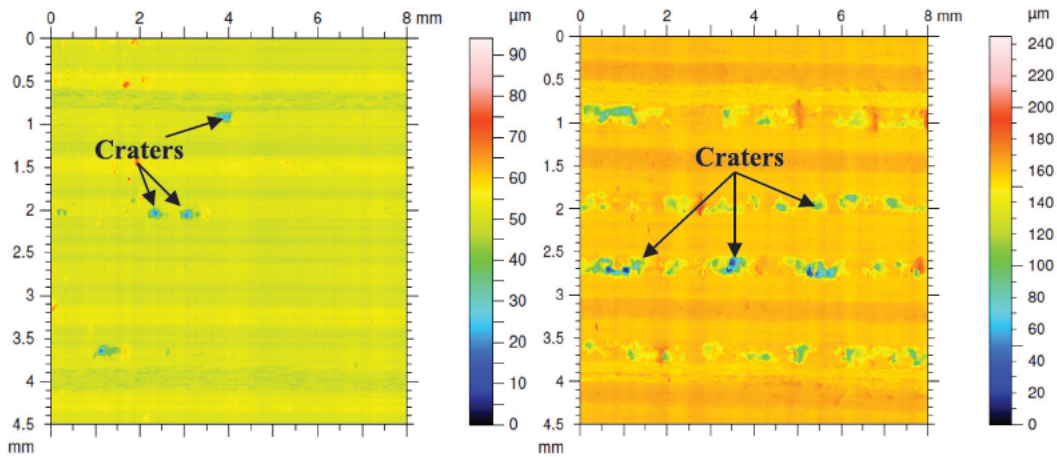


Fig. 14. Topography profiles showing the appearances of craters on the machined surface for the cutting condition of 500 mm/min feed speed and 250 m/min cutting speed for cutting distance of (a) 0.28 m and (b) 1.68 m.

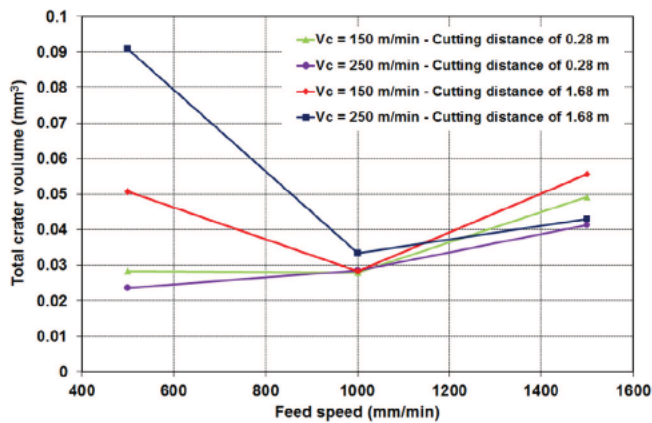


Fig. 15. Evolution of crater volume versus cutting parameters at two cutting distances.

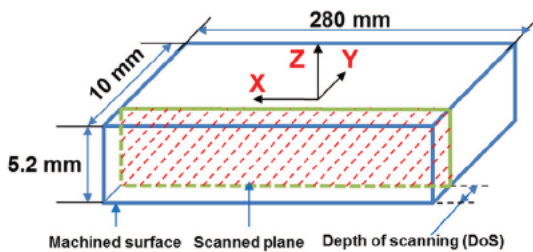


Fig. 16. Schematic view of the depth of machining damage.

scanning the images of the Fig. 17 b and c reveal that, the maximum depth of the observed craters is less or equal to 24  $\mu\text{m}$ . However, with the same machining parameters and when the distance of machining reaches 1.68 m, several zones of damage (with form of craters) are observed (Fig. 18 a). Based on the images of the Fig. 18, it can be mentioned that the form and the size of damage are different from those observed when the cutting distance is around 0.28 m. In addition, when the distance of cutting is around 1.68 m, the maximum depth of the damage reaches 140  $\mu\text{m}$ .

Based on this new technique of measurement and characterization of the damage due the machining process, in the Fig. 19 is represented the influence of the feed speed and the distance of cutting on the maximum depth recorded after trimming with a cutting speed of 150 m/min. From this figure it is clear that the minimum internal depth of damage is observed when trimming is conducted with a feed speeds

less or equal to 1000 mm/min and with a distance of machining of 0.28 m. With this condition of trimming the depth of the internal damage is inferior to 40  $\mu\text{m}$ . However, with the increasing of the distance of machining and due to the mechanisms of wear and the local modification of the cutting edge of the tool, the maximum depth of the internal damage is superior to 40  $\mu\text{m}$  and can reach 140  $\mu\text{m}$  when the feed speed used is 500 mm/min.

#### 4. Conclusion

The experimental study of trimming of multidirectional laminate made of CFRP material is presented in this study. The effects of cutting parameters (cutting speed, feed speed) and the distance of machining on cutting forces, tool wear, machining temperatures and machining quality are investigated. From the analysis of the machining quality, new proposed parameters, such as volume of crater and depth of the internal damages, are proposed. Based on this study the following conclusions can be drawn:

- The main parameters that affect the cutting forces measured during trimming are the cutting distance, feed speed and the cutting speed. In fact, it was observed that a decrease in the cutting distance or in the feed speed as well as the increase in cutting speed induce an important reduction in the cutting forces. However, with the augmentation of the wear of the tool and for high cutting speed, the variation in the cutting forces as a function of the feed rates is less evident and this results was found to be in good agreement with the results obtained by Haddad et al. [5] and Prakash et al. [15].
- Machining temperatures recorded by the infrared camera reveals that for any condition of cutting tested the obtained temperatures were inferior to the glass transition temperature ( $T_g$ ) of the machined material. In addition, the machining temperatures increase with the reduction of the feed speed and with the increase of the cutting distance. In fact, when trimming at low feed speed favors the increasing in the time of machining or the contact time (between the cutting tool and the CFRP part). In this case, the machining temperatures due to the frictional phenomenon are higher compared to the case of machining with high feed speed. In comparison with the results of Haddad et al. [5], it was found that, when trimming the same CFRP with burr tools and with the same machining condition, the recorded temperature was found superior to those measured when cutting with PCD straight or helical flute tool.
- Feed speed is the key parameter which influences the damage levels after performing cutting for some distance. The quantification of machining damage gives a better insight to tool wear phenomenon

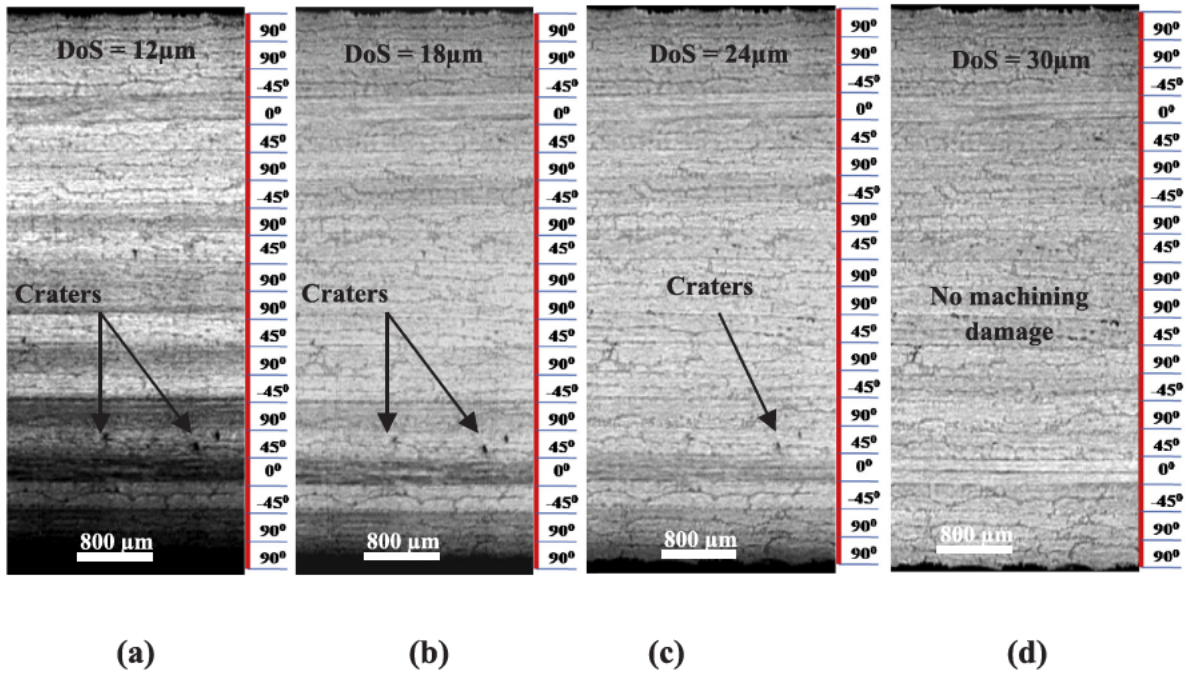


Fig. 17. X-ray tomography images showing machining damage for cutting speed of 150 m/min and feed speed of 500 mm/min at cutting distance of 0.28 m with various depth of scanning of (a) 12  $\mu\text{m}$ , (b) 18  $\mu\text{m}$ , (c) 24  $\mu\text{m}$  and (d) 30  $\mu\text{m}$ .

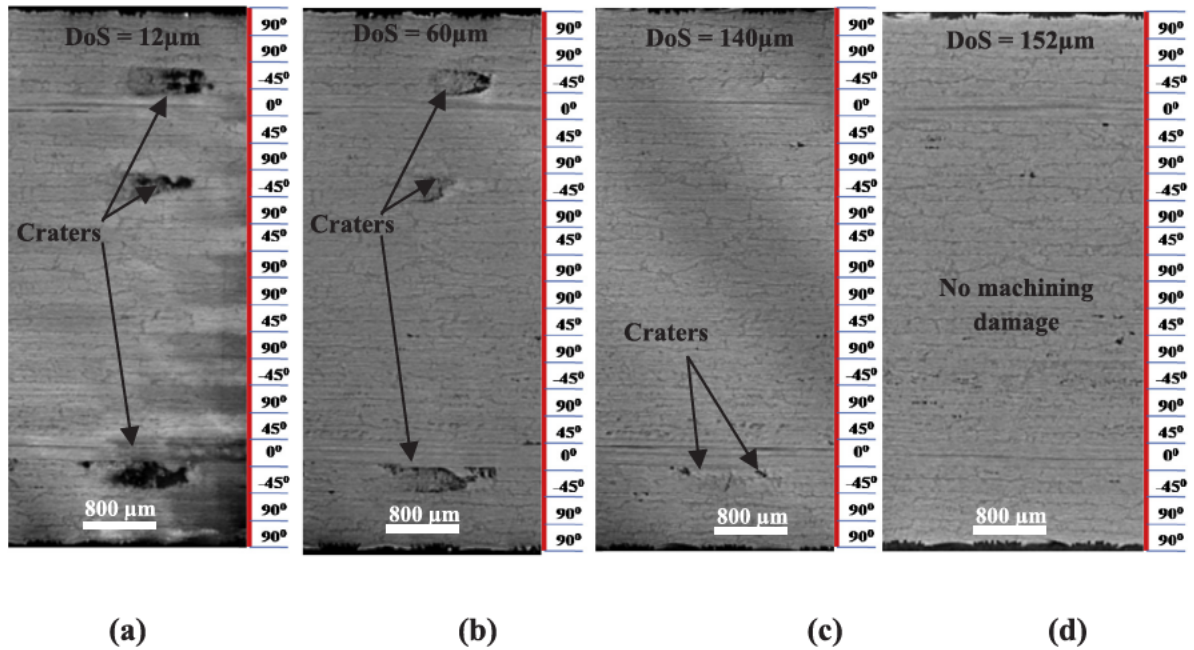


Fig. 18. X-ray tomography images showing machining damage for cutting speed of 150 m/min and feed speed of 500 mm/min at cutting distance of 1.68 m with various depth of scanning of (a) 12  $\mu\text{m}$ , (b) 60  $\mu\text{m}$ , (c) 140  $\mu\text{m}$  and (d) 152  $\mu\text{m}$ .

in comparison with roughness criterion, thanks to multi scale characterization. As the cutting distance increases, the augmentation of damage levels are more pronounced especially when trimming with low feed speed (500 mm/min). This phenomenon is directly due to the consequence of tool wear which increases the cutting edge nose radius. However, damage levels remain almost stable and no internal damages are seen when higher feed speeds (1000 mm/min and 1500 mm/min) are used. This suggests that higher feed speeds must be preferred for better machining quality.

- For the first time, a new parameter, the Crater volume ( $C_v$ ), that characterizes the surface quality and quantifies the machining

damage, was used. This parameter was seen to be more representative of the damage generated due to machining. It was noticed that, feed speed and cutting distance (tool wear) have strong influence on  $C_v$ , where low feed speed has the most influence on the augmentation of  $C_v$ . In fact,  $C_v$  increased by 112% when feed speed was decreased from 1500 mm/min to 500 mm/min at cutting speed of 250 m/min and also  $C_v$  increased by 284% when cutting distance varies from 0.28 m to 1.68 m, when trimming was conducted at a feed speed of 500 mm/min and cutting speed of 250 m/min.

- The machining damage was also quantified using another parameter, the Depth of Scanning (DoS) damage parameter, thanks to



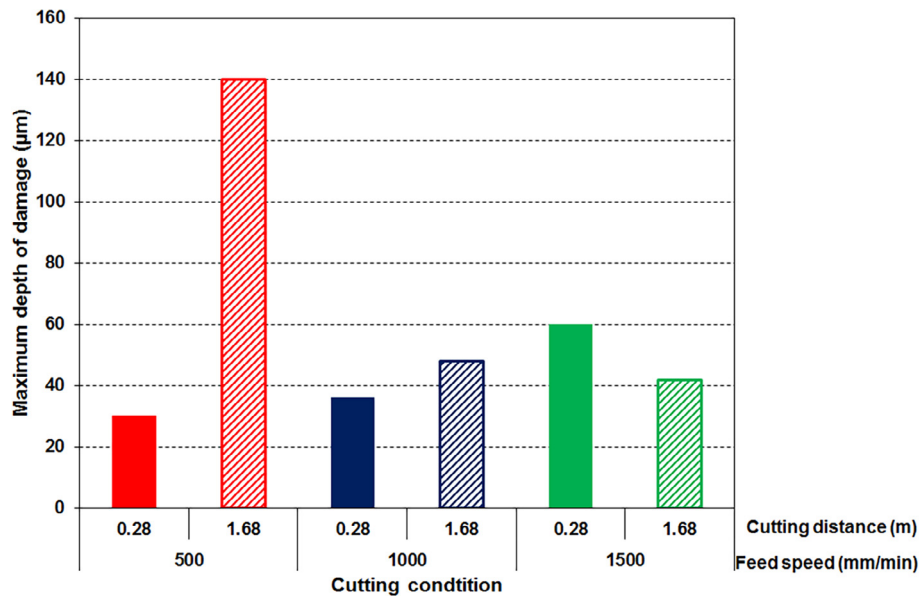


Fig. 19. Influence of the feed speed and the cutting distance on the depth of the machining damage when trimming is conducted with a cutting speed of 150 m/min.

the X ray tomography technique. As seen in the case of Cv, DoS damage also increased with decreasing feed speed and increasing cutting distance. In fact, it was observed that, the DoS damage varied from 28 µm to 140 µm with the increase of the cutting distance from 0.28 m to 1.68 m when trimming was conducted at 500 mm/min.

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