IMPACT OF THE ABRASIVE WATER JET MILLING PROCESS ON THE DAMAGE AND SURFACE CHARACTERISTICS OF CFRP COMPOSITE.

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Keywords: Abrasive Water Jet Milling, Machining Damage, Surface Topography

Abstract

Milling by Abrasive Water Jet (AWJ) is a novel process introduced recently, which can potentially be used for repairing composite structures. It is a promising technique when compared to conventional machining which has inherit problems like extensive damage and dust generation. Till now material integrity of the composite structures machined by AWJ process are not well investigated. In the present work, influence of AWJ milling parameters on the surface characteristics and size of damage (craters) are investigated for carbon/epoxy composite specimens using full experimental design. The surface quality was characterized by 2D Profilometry, 3D optical topography and Scanning Electron Microscopy (SEM) observation. In addition, surface topologies were analyzed to obtain roughness parameters and crater volume, which were correlated with machining parameters. SEM images reveal the presence of damages (in the form of craters, ridges, broken fibers and embedded abrasive particles in matrix) whose size is strongly influenced by the machining parameters. It is seen that the average crater volume increases by 350% when pressure varies from 80 MPa to 140MPa. ANOVA technique indicates that surface roughness and crater volume are highly influenced by jet pressure and formation of ridges is influenced by scan step compared to other parameters.

Excerpt from ISBN 978-3-00-053387-7

1. Introduction

Fibre Reinforced Plastics (FRPs) are a class of composite materials offering a very high strength-to-weight ratio / high modulus-to-weight ratio and corrosion resistance, it makes them a widely used material in aerospace, marine, robotics, construction, transportation, sporting goods, and defence applications. Usage of composites in any of these applications needs a specific shape, size, load bearing capacity, geometrical and damage tolerance. Hence, to obtain these attributes they undergo series of processing operations starting from mould curing to machining. Though they are manufactured to near net shape, secondary machining operations like trimming, milling, grinding and hole making is always required to produce the final functional component [1]. Machining is also required for repairing damaged sections of composite components in service which is usually done by milling out the damaged section and patching [2-3].

Milling of FRPs are practically difficult owing to their highly heterogeneous nature due to the presence of distinctive phases of fibre reinforcements and plastic matrix which have a huge variation in their mechanical, thermal and physical properties. This makes machining of composites a complex phenomenon where cutting tool interaction is unlike machining of metals. Research conducted on conventional milling of FRPs shows many kinds of damages like delamination, fibre pull-outs, matrix recession, inter-laminar cracks and thermal degradation whose nature, size and position chiefly depend on machining parameters and fibre orientation with respect to cutting direction [1]. Also conventional milling leads excessive and premature tool wear because of abrasive nature of the fibres and dangerous levels of dust generated affect the environment. All these limitations led to rapid advancement of machining FRPs by non- conventional techniques like abrasive water jet, laser, and electrical discharge machining. However several studies reports numerous defects delamination, matrix cracking, matrix degradation and burnout matrix recession, thermal damage in laser machining, defects like high thermal degradation, recast layer and delamination along the spark channel in electrical discharge machining and defects like delamination, grit embedment and striations in AWJ machining [1].

The AWJ machining is a well-established non-conventional machining process which is very effective for trimming a wide range of engineering materials including composites. Many studies have demonstrated effective approaches for trimming FRPs by AWJ [6-7]. In comparison with conventional machining, AWJ machining imposes minimal forces on the workpiece, does not require any tooling, does not produce any heat affected zones and in terms of impact on environment, abrasive water jet process is considered to be least harmful; these advantages encourage exploring more possibilities of using AWJ machining for composite materials. In last decade, AWJ machining has been used for turning and controlled depth milling of metals [8-9]. AWJ milling can be potentially developed as a superior technique for composites, especially for repairing damaged FRP structures by patching techniques. It requires cautious and selective material removal from damaged zones of the part [2-3].

Every machining technique has its own physics of material removal. The mechanism of material removal will impact the surface properties at the machined zone. The integrity of the machined surface can be inferior to that of initial surface if it contains micro cracks, damages and in some cases sub-surface damages [7]. Several studies have justified that these irregularities created due to machining will adversely affect the quality and mechanical behavior of the FRP components [10-11]. In order to predict the desired mechanical performance of the milled structures; it is important to adequately characterize the machined surfaces. However, if we refer to literature, the milling of composite materials is not yet mastered, especially for AWJ process. In addition, limited knowledge is available on the effect of AWJ milling process parameters on the nature and size of the damage, as well as their impact on the mechanical behavior of the machined part.

The scope of present work focuses on the influence of AWJ milling parameters (viz. jet traverse speed, jet pressure, scan step and stand-off distance) on surface characteristics and the extent of damage induced during material removal by milling for carbon/epoxy laminates. In order to understand the influence of different machining factors on milled depth, material removal rate (MRR), surface parameters (2D Roughness, 3D Roughness) and damage parameters (Crater Volume) a full experimental design is employed. The machining defects are examined by the Scanning Electron Microscopy (SEM) technique and the surface quality (Ra, Wq, Sa, Swa,) is characterized by 2D Profilometry and 3D optical topography. In addition, damage is quantified by analyzing surface topology and calculating the crater volume, thanks to the 3D contour processing.

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2. Materials and Methods

2.1 Composite material

Carbon fibers reinforced plastic (CFRP) laminates were made using unidirectional prepregs supplied by Hexcel Composite Company, referenced under Hexply T700-M21.

A unidirectional (UD) laminate with 16 plies and dimension of 300 x 300 mm was used for the tests. The laminate was prepared in a controlled atmosphere (white room) and compaction was carried out using a vacuum pump. A mold for the laminate was prepared and placed in a vacuum bag and evacuated to 0.7 bars. Curing was then conducted at 180°C for 120 min during which the pressure was maintained at 7 bars in an autoclave (as recommended by Hexcel Composite Company). With this process of manufacturing, the nominal fiber volume fraction is around 59% and the theoretical thickness of plate is around 4.2 mm. From the laminate, 12 coupons of size 280mm x 20mm were cut using AWJ and each coupon was used for 9 tests with different matching parameters where milled area for each set of parameters was 20mm x 20mm.

2.2 Abrasive water jet milling

The milling experiments were performed on the Abrasive Water Jet Machine manufactured by “Flow International Corporation”. Some machining parameters (Table 1) were kept constant for all experiments and full experimental design (with 108 experiments) was used for parameters jet pressure, jet traverse speed, scan step and standoff distance with different levels (Table 1).

Table 1. Fixed and Variable machining parameters.

Fixed Parameters		Variable Parameters	
Parameter	Value	Parameter	Levels
Nozzle Diameter	1.016mm	Jet Pressure (MPa)	80, 100, 120, 140
Focusing Tube Length	76cm	Jet Traverse Speed (m/min)	4, 8, 12
Orifice Diameter	0.3302mm	Scan Step (mm)	0.5, 1.0, 1.5
Type of Abrasive	Garnet Sand	Standoff Distance (mm)	50, 100, 150
Abrasive Flow Rate	0.34Kg/min		
Abrasive Grit Size	#120		

The raster scan pattern was considered for the milling path strategy, and direction of milling was maintained parallel to fiber orientation (Figure 1). The CFRP specimens were secured on wood plank to avoid movement during milling. The direction parallel to fiber orientation and milling path is considered longitudinal direction and direction perpendicular to it is taken as transverse direction.

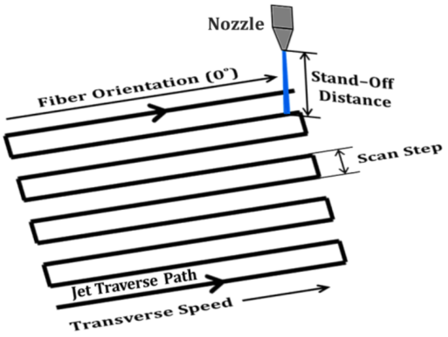

Figure 1. Schematic view of the water jet scan pattern with respect to the fiber orientation.

2.3 Characterization methods

The milled surfaces were subjected to profilometric and topographic studies. “Mitutoyo SJ 500” contact surface tester was used to obtain 2D roughness and waviness parameters in both transverse and longitudinal directions. Stylus with 2µm tip radius and 60° tip angle was used for the measurements. Topography of the milled surface was obtained using an extended field confocal microscope, “AltiSurf520”. For this an area of 6mm x 6mm at the center of the milled surface was considered and

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the scanning was performed at a resolution of 5µm. 3D roughness and waviness parameters were extracted from the topography using “Digitalsurf” software by applying Gaussian filter (cut-off = 0.8 mm) to isolate roughness and waviness. The topographies were analyzed to better characterize the size and volume of craters for different machining parameters. The obtained results were correlated with the SEM images.

3. Results and discussion

3.1 Influence of machining parameters on material removal

The mean effects of the machining parameters on the material removal properties namely, milled depth and material removal rate are presented in figure 2 and figure 3 respectively. It can be seen that the scan step, pressure and traverse speed highly influence the milled depth (Figure 2). For example, when the scan step varies from 1.5 mm to 0.5 mm (Figure 2-b), the milled depth increases by 190% (compared to mean value of 0.65 mm). Also, when machining is conducted with a pressure of 80 MPa (with: traverse speed of 8 m/min, standoff distance of 50 mm, scan step of 0.5 mm) the average milled depth is equal to 1.15 mm but with the same conditions if the pressure increases to 140 MPa the depth increases by 145% (Figure 2-a). These results are confirmed by the statistical method such as ANOVA, it reveals that scan step is most significant factor followed by the pressure and traverse speed. The percentages of contribution of these parameters are 41.5%, 30.3% and 24% respectively.

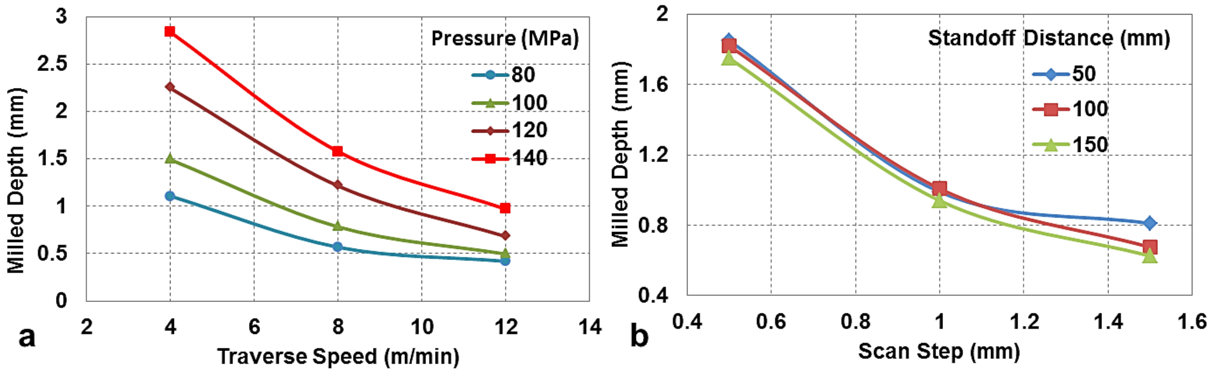

Figure 2. The mean effect of the machining parameters on the milled depth. With: (a) influence of the pressure & traverse speed and (b) influence of the scan step & standoff distance.

The variations in these results can be explained by the fact that, the material is removed in the form of a channel along the jet traverse path. Scan step determines how close the 2 adjacent channels are, and the geometry of these channels depends on the jet diameter, pressure and traverse speed. If the scan step is smaller than the jet diameter then the two adjacent scanning paths overlap, thereby removing the material at the overlapping zone twice, this implies a higher milled depth. But when the scan step is high, there will be no overlapping of the channels, which accounts for lower milled depth. In addition, when the pressure increases, the kinetic energy of the water and the abrasive increase, which in turn increases the impact energy. With the increases of the impact energy, the material removal rate increases too. This can be confirmed by the figure 3, which depicts the mean effect of the machining parameters on the material removal rate (MRR). It is clear that, when the pressure varies from 80 MPa to 140 MPa, the mean MRR varies from 60 mm^3/sec to 150 mm^3/sec (for a transverse speed of 4 m/min). It can also be seen that there is critical value of speed for which MRR is the highest for the given set of parameters deviating from it will result in lower MRR (Figure 3-a). However, the rise in the scan step for a standoff distance inferior or equal to 100 mm, induces a small variation in the MRR. In the case of standoff distance superior to 100 mm a non-negligible reduction of the MMR is recorded.

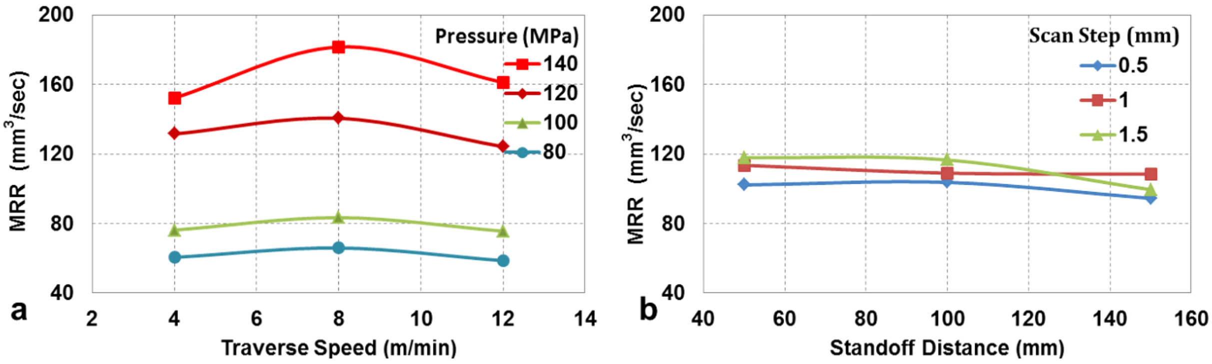

Figure 3. The mean effect of the machining parameters on the material removal rate (MRR). With: (a) Influence of the pressure & traverse speed and (b) Influence of the scan step & standoff distance.

3.2 Influence of machining parameters on machined surface quality

The mean effect of the machining parameters on the surface quality characteristics viz. average surface roughness (Ra) and root mean square waviness (Wq) along the longitudinal and transverse direction is represented in the figure 4 and figure 5 respectively. The surface roughness in the transverse direction of milling is highly influenced by the jet pressure and traverse speed (Figure 4-a). High pressure increases the energy available to the abrasive particles due to which localized material removal will be vigorous there by creating a rugged surface with high roughness compared to the surface milled with lower pressure. This can be confirmed by SEM observation that broken fibres are found in abundance on the surface milled with high pressure (Figure 6) compared to low pressure milled surface. Also, influence of scan step on Ra along transverse direction is prominent, where increase in scan step contributes to higher surface roughness (Figure 4-b). The mean effect of the jet pressure, traverse speed and stand off distance on the surface roughness along the longitudinal direction follows the similar trend as in transverse direction, but the role of scan step is negligible in longitudinal direction.

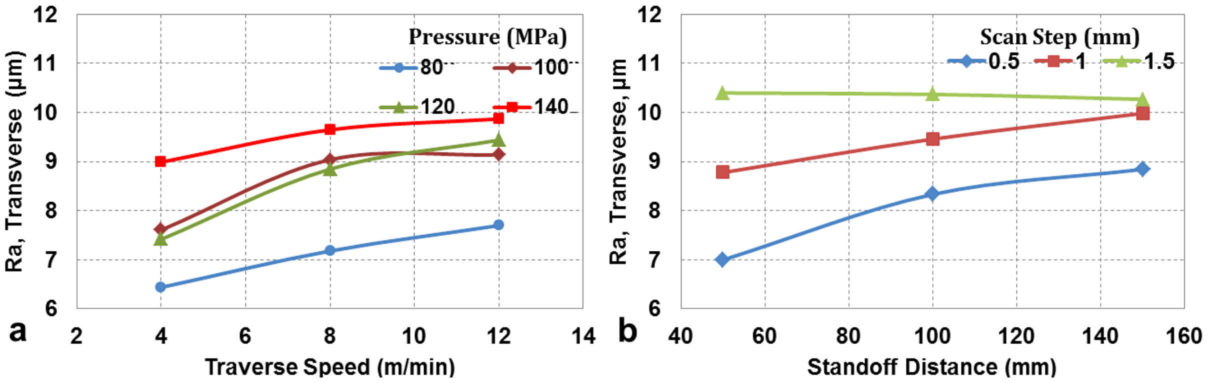

Figure 4. The mean effect of the machining parameters (a) Pressure & traverse speed on roughness in transverse direction, (b) Scan step & standoff distance on surface roughness in transverse direction.

The mean effect of root mean square surface waviness (Wq) along the transverse and longitudinal direction is highly influenced by scan step and standoff distance respectively (Figure 5). The evolution of surface waviness (Wq) along the transverse direction demonstrates a critical behavior with respect to scan step (Figure 5-a). Here, the waviness decreases to the lower most value when scan step is 1 mm, which is equivalent to the nozzle diameter. This phenomenon suggests that over lapping or separation of scan paths will generate surface waviness. ANOVA acknowledges this fact by showing

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that scan step alone accounts to 52.11% of the total variance for waviness along the transverse direction. It is interesting to note that standoff distance does not play a significant role in material removal where as it happens to be an important parameter when surface characteristics are considered (Figure 5).

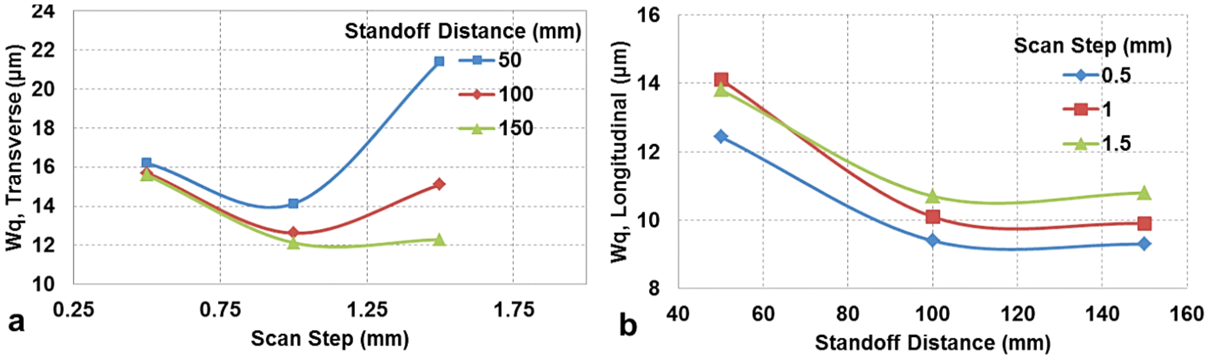

Figure 5. The mean effect of machining parameters (a) Scan step & standoff distance on waviness in transverse direction (b) Scan Step & standoff distance with on waviness in longitudinal direction.

3.3 Scanning Electron Microscopy and damage

Scanning electron microscope (SEM) imaging done on the milled surface reveled different kinds of damages in the form of craters, ridges, broken fibers and sparing amount of embedded abrasive particles. Craters were the most common damage observed across all specimens, however, their magnitude varied with machining parameters. Inspection of the SEM images affirmed that the jet pressure and standoff distance were the most influential parameters in deciding the form of the crater whereas scan step was influential in defining the nature of ridges. Figure 6 shows a section of surface machined with high jet pressure of 140 MPa, where craters are clearly visible.

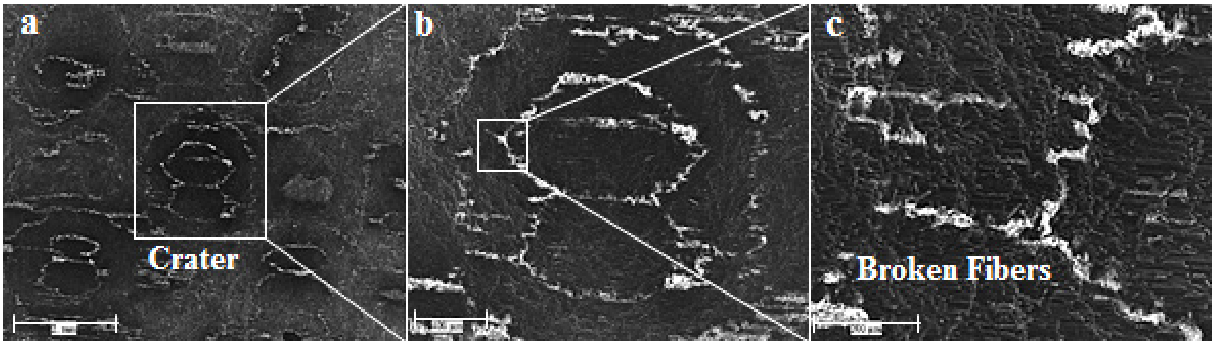

Figure 6. SEM Images showing the nature of damage observed after machining with: pressure = 120MPa, standoff distance = 50mm, scan step = 0.5mm and traverse speed = 4mm/min. (a): global view of the machined surface showing craters (in a specific pattern), (b) zoom on the highlighted zone of the figure (a), and (c): zoom on the highlighted zone of the figure (b) showing broken fibers.

Noticeably, craters placed periodically were found in specimens milled with least scan step (0.5 mm) and least standoff distance (50 mm) and their magnitude increased with increasing pressure. Craters were also found in other specimens but the size was not as significant when compare to high pressure milled specimens and they were randomly distributed. Presence of broken fibers (Figure 6-c) was wide

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spread across the milled surface and was common to all types of specimens which is also a vital damage causing a huge impact on the material integrity of the machined component.

3.4 Topography Analysis

The topography profiles provide the information on the dimensions of the damage features observed in SEM images. The depth, area and volume of the craters calculated gives clear indication that their magnitudes were influenced by machining parameters. The figure 7 show the topologies of surface machined at pressure 140 MPa, standoff distance 50 mm and scan step 0.5 mm (Figure 7-a) and 1.5 mm (Figure 7-b). The presence of craters and ridges are very clear. A specific pattern is observed in the crater and ridge formation as seen from both SEM images (Figure 6-a) and topography contours, this pattern is direct implication of the surface waviness. As discussed previously in section 3.2 the waviness in transverse direction increases with scan step and pressure whereas in longitudinal direction it increases with pressure which is confirmed from topography analysis. The craters on the machined surface were quantified by their volume, figure 7-c shows the scheme of crater volume measurement for specimen machined with pressure = 120MPa, standoff distance = 50mm, scan step = 0.5mm and traverse speed = 4mm/min. The effect of jet pressure and scan step on the crater volume is shown in figure 7-b, it is very clear that jet pressure increases the crater volume. It is also seen that increase in scan step increases the crater volume however the evolution is random at values of high pressure. (Figure 7-b).

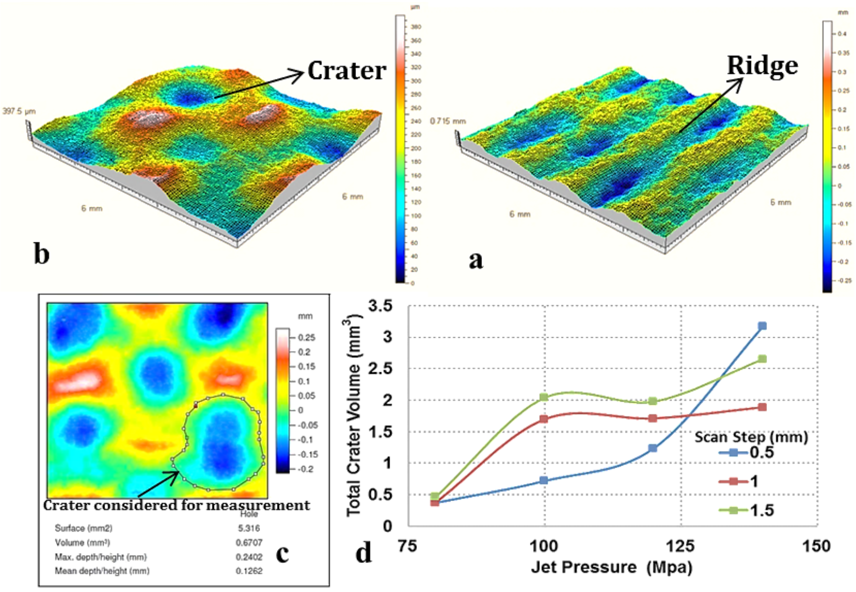

Figure 7. Topography of the machined surface obtained by optical profilometer system after machining with: pressure = 120MPa, traverse speed = 4mm/min, standoff distance = 50mm, (a) Scan Step = 0.5mm, (b) Scan Step = 1.5mm, (c) Measurement of crater volume (d) Evolution of total crater volume in the scanned region with respect to jet pressure and scan step.

4. Conclusions

This paper presents the experimental study on AWJ milling of unidirectional CFRP composite. The influence of machining parameters (jet traverse speed, jet pressure, scan step and stand-off distance) on the surface quality and damage is demonstrated. Machining damage in the form of craters was quantified by calculating the volume of the craters which was a novel attempt and proved to be effective. The following critical observations can be drawn:

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- The milled depth is strongly influenced by scan step, jet pressure and jet traverse speed in the increasing order of significance. In addition, jet pressure and traverse speed are the crucial factors in the case of material removal rate. Whereas standoff distance is an insignificant parameter for both milled depth and material removal rate.
- The jet pressure is most influential factor for 2D surface roughness (Ra) in both transverse and longitudinal directions. However, traverse speed and scan step are next in the order of significance. Also it is to be noted that scan step has minimal influence in evolution of surface roughness in transverse direction.
- Surface waviness (Wq) in transverse direction is influenced by scan step, jet pressure and standoff distance in the order of significance and jet traverse speed is insignificant. It should be noted that surface waviness along transverse direction has the least value for scan step of 1.0mm which is close to the nozzle diameter (1.016 mm). In longitudinal direction the order of significant factors is jet pressure and standoff distance. However, Wq along the longitudinal direction reaches high value at medium traverse speed (8 m/min). It should be noted that waviness is the outcome of periodic pattern of crater formation. Hence, jet pressure, scan step and standoff distance are factors aiding the crater formation.
- Craters and ridges were the most significant form of damage. For the first time, the damage in the form of crater associated with the broken fibers was quantified by introducing crater volume measurement. It was found that the crater volume increases with increase in jet pressure and scan step.

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