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ScienceDirect
Procedia Engineering 132 (2015) 693 – 700
Procedia Engineering
www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

SOM/SEM based characterization of internal delaminations of CFRP samples machined by AWJM

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Abstract

Linear Abrasive WaterJet Machining (AWJM) tests have been performed on Carbon Fiber Reinforced Plastic (CFRP) in order to have a first reference of the main defects developed onto the machined surface.
Delamination has been proved as one of the most critical defects when machining composites or layered materials. In this work this defect and the influence of cutting parameters in its formation have been studied. For this purpose, delamination morphology has been characterized using Scanning Optical Microscope and Scanning Electron Microscope. Additionally, a study of the influence of cutting conditions and material removal mechanisms involved has been achieved.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: CFRP; AWJ; SOM/SEM; characterization; delamination;

1. Introduction

Reinforced plastic and polymers were originally designed for improving the physicochemical properties and reducing the weight of the classic materials -mainly metallic alloys- commonly used in different industrial sectors. Particularly, among them, Carbon Fiber Reinforced Plastics (CFRP) are widely applied in sectors that require lightweight materials, ability to withstand great efforts, high stiffness and excellent conditions for fatigue [1]. These

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Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.549

characteristics -especially those related to its low density- makes CFRP materials highly attractive for being applied in aerospace engineering (wings of the Airbus A350 or Boeing 787), in the automotive industry (roof plastering) and motor racing (rear stabilizer in formula 1 cars), high stress resistance sport equipment (new frames for bicycles) and other high-strength/high-rigidity parts in transversal industrial applications, such as robot arms.

Notwithstanding, currently, due to changes in economic and political level at the global level, the production of CFRP has remained – it has even decreased in certain sectors - due to large cuts, mainly on defense. However, increased consumption intended for commercial applications has been able to compensate this loss. In addition, some producers expect an increase in demand by 2020 close to 75% in the industrial sector (excluding aerospace sector), highlighting the demand in sectors such as energy, transport and civil engineering [1].

All that commented in the previous paragraph must be joined to the development of technologies and associated tools for manufacturing parts in CFRP. Particularly, one of the manufacturing processes more widely used is machining.

Commonly, conventional machining processes (milling and drilling, mainly) are applied for manufacturing parts in CFPR. Nevertheless, this kind of processes involves dangerous defects on the machined surface. Some of the most prominent defects include cracking and fiber/matrix degradation, thermal defects or internal delaminations. These defects are responsible for rejection of components due to that minimal standards of functionality of the elements are insufficient. All this is further aggravated by the economic burden this implies. To get a machining where no defects or minimize its appearance becomes too complex.

A viable alternative technology to try to reduce the appearance of those defects can involve the use of non-conventional machining techniques. In this paper, Abrasive Water Jet Machining has been used for cutting CFRP sheets. This would also have an added advantage because no thermal damage occurs in the material or dust is produced by machining as occurs in conventional processes. Furthermore, tool wear is much lower than conventional machining [2,3]. However, other characteristic defects of this technology may appear as jet lag, taper angle or the appearance of delaminations mentioned previously. In this work, straights cuts employing AWJM technology with different parameters have been carried out on CFRP plane workpieces.

Delaminations using SOM/SEM techniques on the machining of CFRP have been characterized. To do this, 24 straights cuts employing AWJ technology with different parameters have been realized.

2. Experimental Procedure

CFRP plates with orientation of plies at 0° and 90°, stacked in thickness 4 mm with autoclave curing have been used as test pieces. The fiber netting used like reinforcement is plain weave type, where each longitudinal yarn and transverse thread passes over and under the next.

A MECÁnumeric MECAJET 2015 waterjet machine has been employed for cutting the composite, Figure 1. According to the collected in the literature [4,5], the performance of the machining process by abrasive water jet is dependent on different cutting parameters. Parameters used in this study have been included in Table 1, and they have been defined in order to study their influence on the machined workpiece quality. The rest of parameters of interest have been remained constant, Table 2. In addition, maximum water pressure has been employed to guarantee the maximum cutting power in the machine. Finally, it is important to note that the tests were carried out without delay of abrasive incorporation.

Fig. 1. Detail cutting machine using water jet machining a CFRP plate

Table 1. Parameters range

	Levels			
Parameters	1	2	3	4
Feedrate (m/min)	300	900	1500	2100
Stand-off distance (mm)	1,5	3	4,5	
Abrasive flow rate (gr/min)	300	600		

Table 2. Constant parameters during cutting

Orifice diameter	Nozzle diameter	Nozzle lenght	Abrasive size	Abrasive type	Water Pressure
0,3048 mm	0,8mm	94,7 mm	80 mesh size || 120μm	Garnet	450MPa

Finally, the test pieces have been inspected by combining Stereoscopic Optical Microscopy (SOM) and Scanning Electron Microscopy (SEM) techniques. SOM observations were achieved using a Nikon SMZ 800 Stereoscopic Optical Microscope, Figure 2 (a). On the other hand, SEM analysis was carried out in a Phillips Quanta 200 Scanning Electron Microscope, Figure 2 (b).

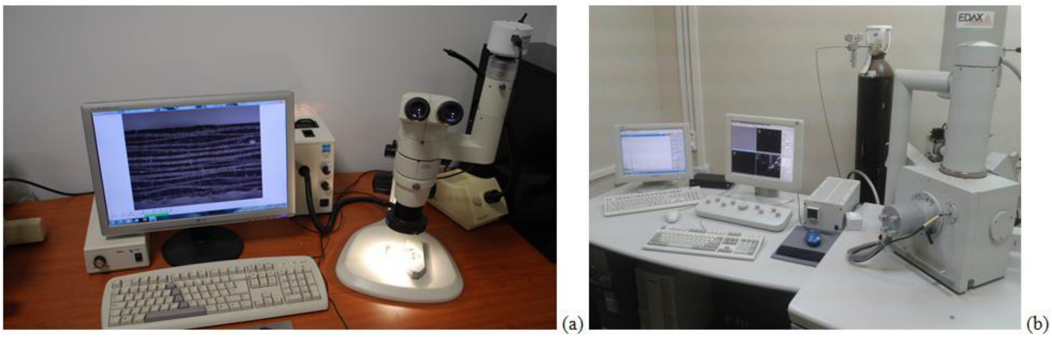


Fig. 2. Microscopes used in the experimental study: (a) Nikon SMZ 800 and (b) Quanta 200

3. Results and Discussion

As it has been aforementioned, delamination is one of the most relevant defects that can take place when CFRP plates are machined. In the case of AWJM, it can be caused by different cusses involved in the cutting process. On one hand, it occurs due to the effect of wave produced when the jet hits at high speed on the material surface. In this respect, water is only used as a means for transferring a moment to the abrasive particles giving rise to the erosion process through which part of the removal of material takes place [6]. On the other hand, it is necessary to consider some variables related to the process, as if there is delay on incorporating abrasive after starting the cutting process, the flow rate thereof, the pressure, traverse feed rate or stand-off distance.

Subsequently, during the cutting process, cracks give rise to spaces between the layers that hold the composite. Then, abrasive particles can penetrate in these spaces causing more defects between layers because they still possess sufficient cutting energy. Finally, the particles are housed inside the space, as shown in Figure 3.

The process of forming the delamination begins with the generation of internal cracks (fracture mechanics mode I) with the first impact of the jet on the composite because the material is unable to withstand the shock wave [6], as it has been commented in previous paragraphs. Subsequently, during the cutting process, the cracks increase their size creating spaces between the layers of the composite.

Table 3 contains SOM images of kerf wall of each probe machined. The images were taken with the same magnification at the same cutting position (machining length).

In a first observation of Table 3, it can be appreciated how the test specimens machined to a higher flow rate (600 g/min) reported lower formation of gaps regardless of other parameters. Indeed, the influence of the abrasive is higher when it is compared with other variables in the formation of delaminations. Moreover, the formation of delaminations depends not only on the flow, but also on the size of the abrasive. If the size of the abrasive is larger the cutting power is increased.

Furthermore, the conditions in which the abrasive is supplied are crucial in the formation of delaminations. Some authors [4,5,7] have shown different discussion ways about the formation of delamination using pure water or abrasive delay, obtaining that the employment of abrasive since the beginning of machining raises the cutting power as it favors the phenomenon of erosion during cutting, reducing the appearance of delaminations.

Fig. 3. Detail of embedded particles in fiber delamination

In connection with the last considerations, the material removal mechanism that acts during the machining of CFRP using AWJ consists in a combination of erosion, micromachining and shearing [8].

According to [9-12], these materials exhibit brittle behavior when the abrasive particles of the water jet impacts their surface. Thus, the maximum erosion rate is reached when the angle of impact of the jet is normal to the surface.

In accordance with the aforementioned, the stages that characterize the phenomenon of erosion in CFRP are:

- Firstly, the particles impact the surface material and begin the deterioration of the matrix because it is the element that surrounds the fibers and is of lower hardness.
- Subsequently, when the fibers are exposed, the particles are introduced at the interface between the fibers and the adjacent area of resin. Furthermore, cracks perpendicular progressively to the longitudinal direction of the fiber are formed. This effect, not only propagates the crack, but it is able to flex the remaining fibers and to bend them due to the absence of the matrix to sustain it.
- Finally, the process of erosion is still again when the particles impact a new layer of material.

Likewise, there are different factors to be taken into account as the fiber/matrix percentage and the adhesion between the two phases. So, furthermore, composites with a lower porosity rate are more resistant to erosion process.

Other variables whose influence is crucial in the formation of delaminations are the jet pressure and the thickness of plate [5]. Indeed, the possible machining thickness increases linearly with the increase of pressure P, but this rate decreases above a certain pressure P'. It could be caused due to fragmentation of particles when colliding due to the high pressures. Furthermore, also the cutting depth capability increases when the abrasive flow is increased because the density of particles hitting the surface the same time increasing. However, an excessive abrasive flow rate causes that the particles to collide with each other resulting in a loss of performance of the process. One way to correct the high density of abrasive impact on the material is increasing the speed, but it can affect the appearance of other defects, such as jet lag, depending on the thickness of the machined test piece.

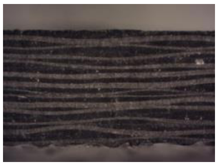
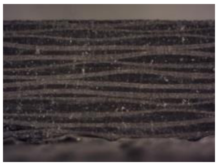
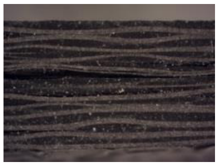
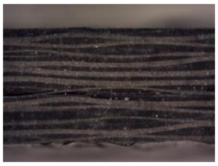
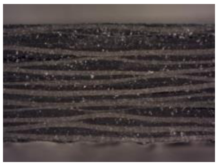
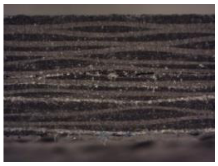
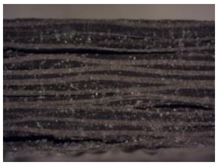
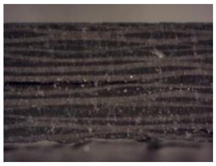
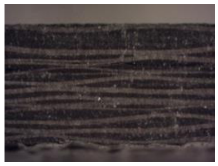
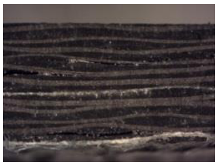
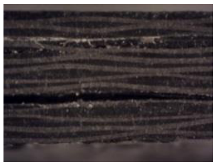
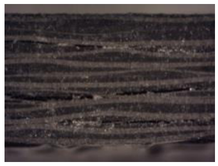
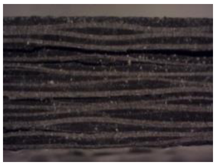
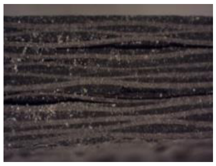
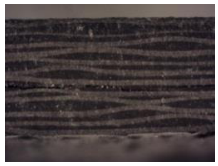
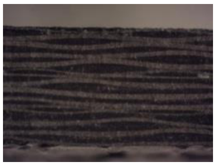
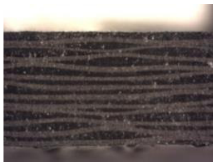
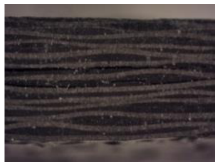
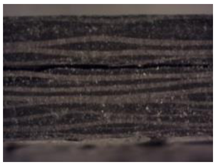
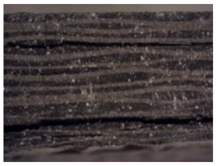
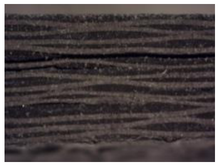
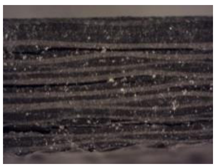
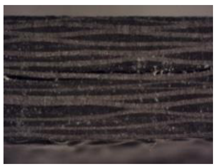
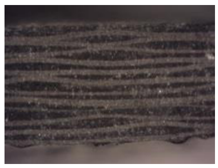
According to that, it must be stated that a decrease in pressure can be an advantage because -although not avoid the formation of delaminations at a given depth of kerf- less energy cut prevent abrasive is introduced into the space created between the layers further increasing material defects (Figure 3).

On the other hand, the influence of the cutting speed has been previously mentioned. An increase in cutting speed favors the appearance of jet lag. In this case, this defect was not observed due to reduced plate thickness, except lightly when the maximum traverse feed rate (2100 mm/min) is applied, Table 3. However, an excessive speed reduction may lead to the phenomenon described above due to the large number of particles that impact the material simultaneously. Thus, it is necessary to arrive at an appropriate speed depending on the characteristics of the material that is intended to cut. In this case, it appears that the cuts made in a range of intermediate speeds reduce the occurrence of defects.

As for the ratio of the stand-off distance, the SOM characterization does not seem enough to relate directly the distance with the appearance of delaminations. This indicates the need for a deeper analysis of the variables involved in the cutting process. T

o analyze in more detail as described above, some of the samples using SEM have been characterized. Thus, in Figure 4 different images contrast with what is discussed above. Figure 4 show in detail the area affected by erosion at the entrance of the jet area and the different delaminations that has suffered the specimen during the cutting process. It also shows in detail the entrance area affected by erosion which highlights the multiple fractures and morphological defects as well as the occurrence of abrasive embedded between the fibers [3]. It also allows appreciating the orientation of the reinforcement as composite material with layers.

Table 3. SOM images of kerf wall in workpieces machined at the indicated cutting parameters

		1,5 mm	3,0 mm	4,5 mm
300 (mm/min)	300 (g/min)			
	600 (g/min)			
900 (mm/min)	300 (g/min)			
	600 (g/min)			
1500 (mm/min)	300 (g/min)			
	600 (g/min)			
2100 (mm/min)	300 (g/min)			
	600 (g/min)			

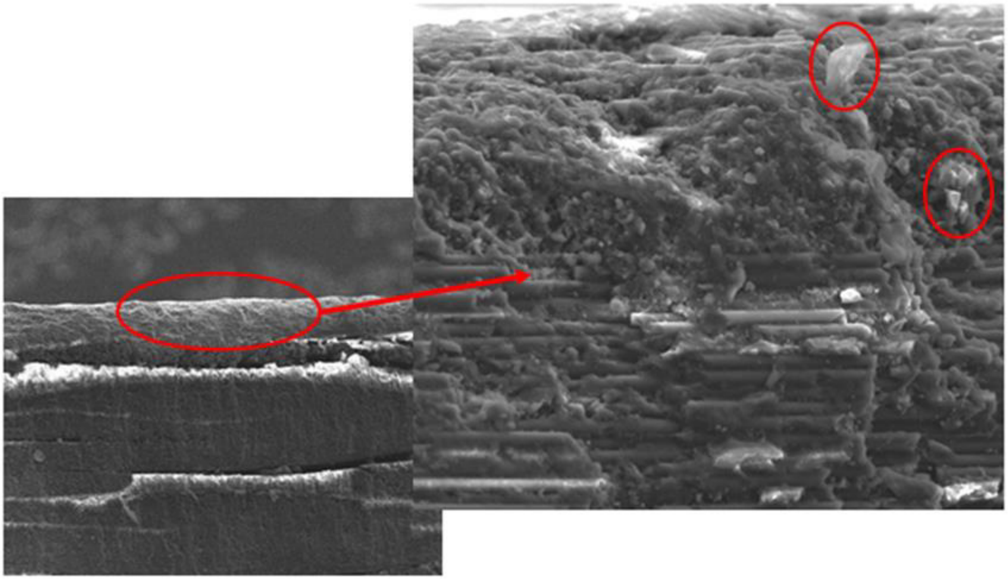


Fig. 4. SEM image of a workpiece machined with a traverse feed rate of 900 m/min, 600g/min of abrasive mass flow rate and stand-off distance of de 4, 5 mm. Detail of erosion affected zone.

On the other hand, Figure 5 enlarges a detail of Figure 3. In this case, it can be seen as the abrasive particles are housed within the delaminated space created between the material layers with different orientation contributing to further expand the space. Moreover, it can be observed the appearance of fibers without resin due the phenomenon described above in the removal of material from the effects of erosion.

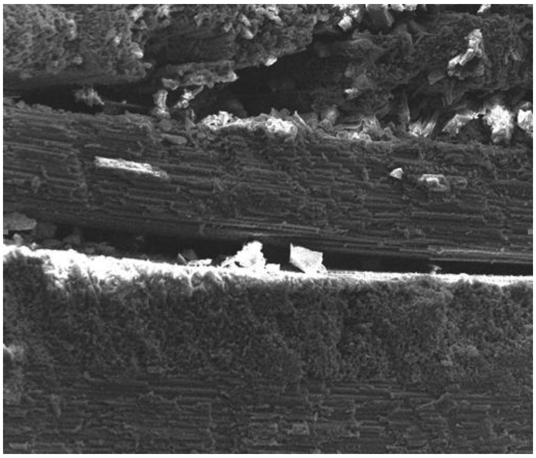


Fig. 5. SEM image of a workpiece machined with a traverse feed rate of 1500 m/min, 300g/min of abrasive mass flow rate and stand-off distance of de 3 mm. Detail of delamination showing abrasive particles between the layers.

4. Conclusions

A preliminary study to determine the influence of cutting parameters on the formation of delaminations in AWJ machining of CFRP plates has been performed on the basis of straight cuts. For this purpose, combined SOM and SEM technologies have been employed. Starting from the obtained results, it can be formulated the following conclusions:

1) SOM-SEM analysis of the machined workpieces can help to identify the mechanism of formation of delaminations.

2) The abrasive is the most influential parameter in the formation of delaminations. The importance of flow, size of abrasive or delays in the incorporation of abrasive in the jet is necessary to know the combined material removal mechanisms and its relation to defects characterized.

3) The influence of pressure and its relation to the plate thickness have been studied. Higher pressures allow machining materials of a higher thickness.

4) The employment of a range of intermediate speeds and greater abrasive flow allows minoring the studied defects. On the other hand, the stand-off distance requires further study to values their influence.

Acknowledgements

This work has received financial support from the Spanish Government (Project DPI2011-29019), from the European Union and from the Andalusian Government (PAIDI). Authors thank to the École Nationale Supérieure d'Arts et Métiers (ENSAM) from Bordeaux for its support in the experimental stage of this parameter

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