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# Analysis of Wear after Machining of Fiber Reinforced Polymers

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## Abstract

***Fiber Reinforced Polymers (FRPs) are composed of a continuous constituent, which is called matrix, and also fibers which are the reinforcement phase. FRPs are characterized compared with metals by high specific strength and stiffness, good corrosion resistance, fatigue resistance, thermal insulation, conductivity and acoustic insulation.***

***However, the FRPs present marked anisotropy because of fibers, which results in high cost, low productivity and not always good finishing. Therefore, to understand their behavior throughout machining process and to analyze the influence of tool wear, they are necessary in order to achieve cost reductions required by the industry. This paper summarizes the theory necessary to understand the nature of FRP materials and presents the conclusions of tool wear when drilling Aramid Fiber Reinforced Polymer (AFRP).***

## Introduction

Fiber Reinforced Polymer (FRP) materials are characterized by their lightness compared with metals; however its specific strength and stiffness generally outperform metals because of the reinforcement fibers. In addition to improving structural properties, they are also in many cases better in corrosion resistance, fatigue resistance, thermal insulation, conductivity, and acoustic insulation than metals. Because of those properties, FRPs have become relevant for many applications, including aerospace, aircraft, automotive, construction, marine, commodity and sports.

## Technique state

This section describes the latest research related to the machining of FRP, both machine ability and wear, in order to get an overview over the existing trends.

### Wear resistance and induced cutting damage of aeronautical FRP components obtained by machining [2]

A 2D-finite-element progressive failure analysis has been developed to investigate the chip formation process and induced damage when machining unidirectional fibre reinforced polymer composites. The model is an approach which predicts the macro-chip formation process without imposing any trajectory of fracture and/or the order of the various fractures.

It shows that the primary fracture occurred by fibers rupture ahead of the tool nose on a plane which is not often consistent with the flank plane. Direction and level of the primary fracture plane was mainly fibre orientation dependent. The secondary fracture plane occurred at the fibre/matrix interface was found to be always consistent with the reinforcement orientation. The cutting induced damage versus the fibre orientation has also been predicted.

### Modeling and tool wear in drilling of CFRP [3]

This paper presents the prediction and evaluation of thrust force in drilling of carbon composite material. The experimental results indicate that the feed rate, the cutting speed and the tool wear are the most significant factors affecting the thrust force.

**Figure 1: Diamond coating wear of 22691 Diager tool after 309 drillings. [3]**

A phenomenological model of axial load, taking into account the tool wear, has been proposed to predict the parallel evolution of axial load and wear with different drilling sequences during the tool life. Moreover, the study has also pointed out the beneficial effect of the presence of a diamond coating on the carbide drill leading to tool life 10 to 12 times the tool life of the uncoated carbide drill for cutting speeds 3 times higher (170 m/min instead of 56 m/min).

Reinforced alumina cutting tool. The machining process was performed at different cutting speeds at constant feed rate and depth of cut. The performance of the alumina cutting tools was evaluated by measuring the flank wear and surface roughness of the machined GFRP composite material.

**Figure 2: Machined surface during machining GFRP. [4]**

The abrasive wear is quite smooth and less with the SiC whisker reinforced alumina cutting tool than with the Ti[C, N] mixed alumina cutting tool while machining GFRP composite material, which is due to the presence of highly abrasive FIBRES. Variations in surface roughness values were noticed due to the inherent variation in the surface roughness of the matrix and the fibers.

### Characterization of friction properties at the work material/cutting tool interface during machining of randomly structured carbon fibers reinforced polymer with carbide tools under dry conditions [5]

More work needs to be done on on-the-fly methods for multi-scale simulations of composite machining. 2-D and 3-D finite element models introduced in this paper explain the chip formation process, tool–particle interaction, prediction of cutting forces, cutting temperatures and the sub-surface damage and are in good agreement with experimental measurements. A numerical model must be selected to assist in selecting machining parameters: tool geometry and cutting conditions to improve the mach inability of metal matrix composites.

### Hole drilling in ceramics/Kevlar fibre reinforced plastics double-plate composite armor using diamond core drill [7]

In this work, an experimental study of drilling the ceramics/KFRP double-plate composite armor by using a special sintering diamond core drill has been carried out on a general-purpose drilling machine. This tool is shown in "Figure 4".

**Figure 4: The sintering diamond core drill. [7]**

Machining mode, drilling sequence, and machining efficiency have been discussed based on drilling experiments. According to the discussed experimental results, machining using manual step feed, drilling the KFRP backboard firstly, and selecting the reasonable technical parameters could greatly facilitate the hole drilling in the ceramics/KFRP double-plate composite armor. The results achieved show that the machining method presented in this work is applicable for small order production.

During the research it has been observed that most papers deal with characterization of parameters with the help of finite element models. Moreover, delamination analysis has been found to be quite usual, what make sense since it is one of the main problems when machining FRPs. On the other hand, altough surface roughness has been shown that reveal little about the true surface characteristics of the composite [1], several papers about it have been also found. The materials used for the researches are most often carbon and glass fibre reinforced, while the most common maching operation is drilling followed by turning.

### Fiber Reinforcement Composites

In order to understand tool wear not only tool properties are important, also the material that is going to be mechanized is relevant. That is because wear is related to interactions between surfaces, so a better understanding of the properties and behavior of the mechanized material will result in a better analysis of the involved factors. At the present point main characteristics and properties will be explained based on [1].

### Glass FIBRES

Glass fibre is widely used because of the combination of low cost, corrosion resistance, and ease of manufacturing. Moreover, it has relatively low stiffness, high elongation, and moderate strength and weight, and generally lower cost relative to other FIBRES. On the other hand, their use is limited in high-performance applications because of their relatively low stiffness, low fatigue endurance, and rapid degradation in properties with exposure to moisture. Some chopped glass FIBRES are shown in the following figure (Fig.8).

**Figure 8: Chopped glass fibre.**

Glass FIBRES are produced by drawing a molten mixture of silica ($SiO_2$) and other oxides through small holes in a platinum-alloy bushing. A protective coating, or size, is applied to the FIBRES to protect their surface and to enhance their bonding to the polymer matrix. Fibre diameters for composites applications are in the range from 10 to 20μm.

### Carbon FIBRES

Carbon FIBRES offer stiffness and strength combined with low density, that is high stiffness-to-weight and high strength-toweight ratios, and intermediate cost. Another characteristic property of carbon FIBRES is their negative CTE in the longitudinal direction. This property allows the design of structures with zero-dimensional variation over a wide range of temperatures.

Carbon FIBRES typically have a diameter in the order of 5–8μm. Because of this small size, the FIBRES are grouped into tows or yarns consisting of from 2 to 48000. Carbon FIBRES are anisotropic (transversely isotropic) and their properties are mainly affected by the degree of orientation of the graphite layers with respect to the fibre axis. In the following figure, disposal of carbon FIBRES in a layer is shown.

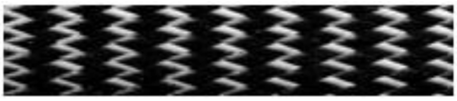


**Figure 9: Carbon fibre layer.**

During machining the FIBRES' dust is abrasive and may cause wear in machine guides and moving surfaces. Carbon reinforcement may also cause galvanic corrosion of metal inserts because of their electrical conductivity [1].

### Aramid FIBRES

Aramid FIBRES or also called Kevlar are organic FIBRES manufactured from aromatic polyamides (aramids) by solution spinning. Polymer solution in sulfuric acid is extruded by spinning through small holes into FIBRES in which the molecules are aligned with the direction of shear. Further alignment of the FIBRES may be achieved by heat treatment under tension [1]. In the following figure an aramid fibre layer is shown.

**Figure 10: Aramid fibre layer.**

Aramid FIBRES offer higher strength and stiffness relative to glass coupled with lightweight and high tensile strength but lower compressive strength. Aramid also exhibits an outstanding toughness and damage tolerance, so that it tends to respond under impact in a ductile manner, as opposed to carbon fibre, which tends to fail in a more brittle manner. This outstanding toughness of aramid FIBRES also creates a problem during machining. The FIBRES are very difficult to cut and special tooling and techniques are required [1].

## Other FIBRES

Oriented polyethylene or *Spectra* fibre, which is also manufactured by spinning, exhibits similar properties to aramid in terms of strength and stiffness. But because of their extremely lightweight (specific gravity of 0.97) its specific strength and modulus are higher and comparable to that of carbon fibre. On the other hand it has a very low range of temperature usage so that obtaining adhesion to matrix materials is difficult. It is being used as a hybrid with carbon fibre in certain applications, in an attempt to combine the lightweight and toughness of the Spectra fibre with the stiffness of carbon fibre. Other FIBRES used for polymer reinforcement include boron and silicon carbide for high-temperature applications, although their use is a very small fraction of the use of glass, carbon, and aramid FIBRES [1].

## Core material

Core material is used to support lateral loads on a composite sandwich structure. The most common core materials are wood, honeycomb, corrugated, and expanded polymer foams. Honeycomb core has a hexagonal cellular structure similar to the beeswax honeycomb. Among the many materials used to manufacture honeycomb cores are unreinforced and fibre-reinforced polymers, metals and paper.

## Experimental work

In this section all the information concerning the measurement of the tools for further analysis is collected. This includes a glimpse of the main manufacturers, material machining tests information, equipment used for measurement and data obtained by performing the measurements of the tools.

## Tool manufacturers for machining FRPs

We proceed to explain the leading manufacturers of tools for machining of FRP, which have provided tools for the tests.

## Van Hoorn Carbide [40]

They offer optimised resistance against mechanical abrasion, less friction and minimized cutting edge roundness: better tool life, excellent surface finish and higher productivity. On the other hand, they told that diamond tipped vs. PCD provides: 2 to 5 times more tool life, more accuracy and a better surface finish and higher machine efficiency. Their single flute end mills for glass and carbon fibre reinforced materials are told to get superior surface finish and high productivity, through low radial forces, sharp and pre-balanced cutting geometry. An example of tool parameters for machining GFRP is shown in "Figure 65".

| | Van Hoorn | Competitor |
|---|---|---|
| $v_c$ | 94 m/min | 94 m/min |
| n | 15.000 -/min | 15.000 -/min |
| $F_z$ | 0.05 mm/t | 0.05 mm/t |
| $v_f$ | 900 mm/min | 7500 mm/min |

| | Van Hoorn | Competitor |
|---|---|---|
| $a_p$ | 2 mm | 1 mm |
| $a_e$ | 2 mm | 2 mm |
| Q | 3600 mm$^3$/min | 1500 mm$^3$/min |

**Figure 65: Van Hoorn Carbide tool parameters for machining glass fibre. [40]**

## Hufschmied [44]

It is structured in the range of high performance tools for the mould and the industry as well as milling cutters for machining plastics. They told that their cutting tools perform through quality, tool life and cutting behaviour regarding best cutting quality, helping to boost productivity and increase profitability. They have a fibre-line that understands the needs of glass and carbon fibre materials as well as fibre-reinforced materials (Fig. 67).

**Figure 67: Hufschmied tools. [44]**

## Tool

The tool that is going to be used for drilling is "*Solid carbide slot drill 6 mm GARANT*" (Fig.68). High performance tooth geometry for efficient machining of aramid fibre reinforced composites to roughing standards. The geometry prevents delamination of woven FIBRES and textile-based fibre structures. [46]

Figure 68: Tool used for drilling aramide. [46]

It should be noted that this tool has been selected because of being one of the few that are designed specifically for the machining of aramid. It is suitable for 110 m/min cutting speed ($v_c$) in polyaramide fibre composites. Its modulus of elasticity is 59000 N/mm$^2$. Moreover, it is applicable for dry machining and for use with compressed air feed [46]. Tool parameters provided by *Garant* are shown in "Figure 69"

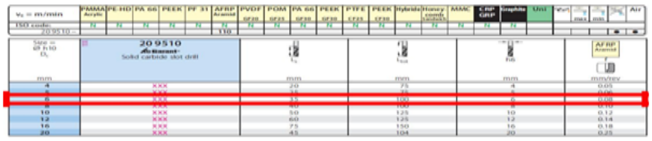


Figure 69: Tool parameters. [46]

### Wear measurement

On the other hand, for the wear analysis a measurement of the tool edges is necessary. The measurement device that has been used is the *Alicona IF-Edgemaster* (Fig.72). The *IF-EdgeMaster* is an optical 3D measurement device to measure automatically cutting tools regardless of type, size, material or surface finish.

- Serial number: 019022002911
- Measuring principle: Focus variation

Figure 72: Alicona IF-Edgemaster. [51]

### Process setup

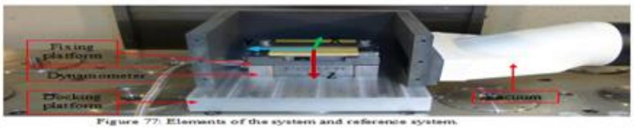
The process followed for the preparation of the necessary equipment for drilling and measurement of forces and torque is as follows:

Placement of the dynamometer in the machining centre (Fig.74).

Figure 74: Dynamometer.

Connecting the devices necessary for the collection of data obtained from the dynamometer (Fig.75).

Coupling the particles suction system (Fig.77). Aramid FIBRES can be split forming fibre diameter in the respirable range, so that a vacuum system has to be used. Although industrial monitoring shows that level of fibrils in air is low in typical operations, so it is advisable to use mask. On the other hand, elements involved in the drilling process and the reference system used are shown in the following figure (Fig.77).



Assembling of the lid in order to improve the extraction by suction.

Drilling the four holes (Fig.78).

Figure 78: Drilling.

Removing the lid and taking away the plate.

If another plate has to be drilled, it has to be fixed and the lid assembled.

Moreover, every time the tool is taken away for wear measurement it should be recalibrated.

## RESULTS AND ANALYSIS OF THE PROCESS

Once properties of the tool, samples, equipment to be used and setup have been described, an analysis of the results is carried out. For this purpose it is strictly necessary to analyze what happens during the machining process of a plate, then subsequently analyze the general case including all samples machined and finally the tool wear and its influence on the machining process. The values of the parameters used for testing are the ones specified by the manufacturer (Table 12). These parameters are feed per revolution (*f*) and cutting speed ($v_c$).

| | |
|---|---|
| $v_c$ [m/min] | 110 |
| *f* [mm/rev] | 0.08 |

**Table 12: Parameters used for testing.**

## Plate pattern

In order to analyze more precisely these variables different charts will be presented, starting from the one regarding the force, as it is the most representative variable of the process. The main force is that of the “z” axis direction, which makes sense since the machining operation is drilling. Focusing on Fz, it can be clearly differentiated each one of the four holes that are machined in every single plate (Fig.80).

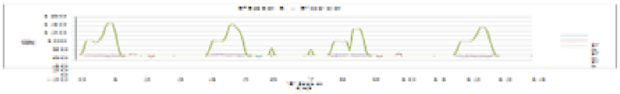


**Figure 79: Plate 1 - Fx, Fy, Fz, Mx, My and Mz.**

There are two peaks that attract attention between the machining of the third and fourth hole, so it will have to be analysed if it is a casual event or whether it shows some event. Besides it can be appreciated, in general terms, two steps in the drilling process. That is due to the fact that the first step is when the drill point is working, and later the whole drill is involved. This kind of tool geometry is used in order to reduce the thrust force and therefore it avoids delamination damage. In order to analyse this phenomenon in more detail, the "z" forces are going to be superimposed (Fig. 81).

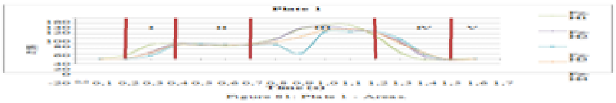


**Figure 81: Plate 1 - Areas.**

So that, the distance from the upper layer of the sample can be determined (Table 13). From other point of view, this distance is also the length of the tool which is machining.

| Area | Start (s) | End (s) | Depth (mm) |
|---|---|---|---|
| I-II | 0.2 | 0.4 | 0-1.56 |
| II-III | 0.4 | 0.7 | 1.56-3.89 |
| III-IV | 0.7 | 1.2 | 3.89-7.78 |
| IV-V | 1.2 | 1.5 | 7.78-10.12 |

**Table 13: Correspondence of areas.**

In order to analyse the force graph more easily, the correspondence of these areas on the tool is shown in the following figure (Fig. 82).

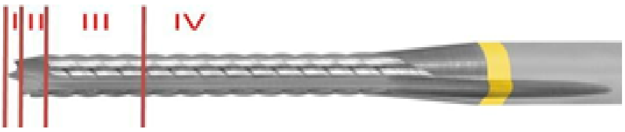


**Figure 82: Tool areas.**

**Figure 83: Plate 1 - Fx and Mx.**

At the beginning of the drilling process, the force Fx and its concomitant torque are quite similar, that is due to the peak that performs the main work (Fig.83). After that, the torque increases. It is due to the fact that the flute edges are in the tool periphery, so the moment is higher than the force since it is proportional to the radius.

Finally, the effect of wear on the finishing could not be analyzed during the tests, since high level of wear have not been met. Although the design of the drill point, which is candle stick, is supposed to produce low delamination damage, high quality finish has not been achieved. It may be recalled that the worst finishing is found in the second hole because the vacuum was not enough to chip disposal. This pattern has been repeated throughout the machining of the forty-five plates (Table 15).

## Conclusions

Fibre Reinforced Polymer materials are characterized by their lightness and higher specific strength and stiffness compared with metals. Besides they are in many cases better in corrosion resistance, fatigue resistance, thermal insulation, conductivity and acoustic insulation. Because of those properties, in recent years, FRPs have become relevant in all fields of engineering. Although these materials are manufactured with a very close shape to their final one, subsequent machining is usually required. Due to its complex behaviour, machining results in high cost and low productivity. So it is necessary to understand the factors that define this behaviour in order to improve the processes and its development, through less tool wear, low cutting forces and good surface finish, satisfying the need of the industry to reduce fabrication costs.

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