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Analysis of Wear after Machining of Fiber Reinforce 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.

On the other hand, FRP are manufactured with a shape very close to its final form, although this is not released for subsequent machining operations for suitability to the geometric requirements, which is not easy due to its complex behavior. High price of constituents and large degree on skilled lab our result in increased cost and low productivity, so that tool analysis when machining FRP is a topic of great importance in order to understand their behavior and therefore understand the factors that are determinant due to the industry's need to reduce fabrication costs. For this purpose it will be necessary to understand:

- What FRPs are their properties and on what properties depend.
- Usual machining operations of FRP.
- Machining quality factors.
- Tool wear and factors that are involved.
- Tool wears when machining FRP.

So that, tool wear analysis can be performed in order to evaluate which are the more relevant factors that are involved in wear mechanisms, since a greater understanding of them will allow a better work piece finishing, a longer tool life, and therefore an increased productivity and decreased costs. In order to achieve these goals, samples of aramid fiber reinforced polymer will have to be drilled.

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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.

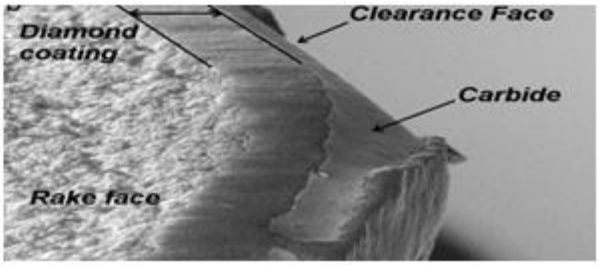

Figure 1: Diamond coating wear of 22691 Diager tool after 309 drillings. [3]

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).

Machinability of glass fiber reinforced plastic (GFRP) composite using alumina-based ceramic cutting tools [4]

This paper deals with the machining of GFRP fabricated in their laboratory using E-glass fiber with unsaturated polyester resin. Machining studies were carried out using two different alumina cutting tools: Ti[1] mixed alumina cutting tool and SiC whisker 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 [2]GFRP composite material.

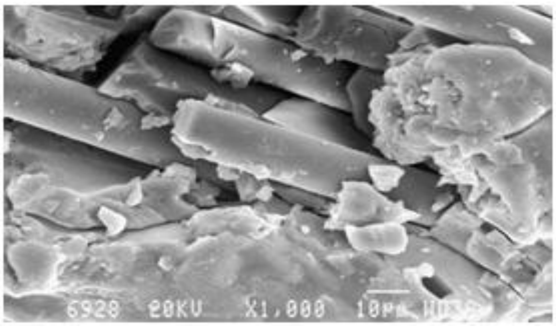

Figure 2: Machined surface during machining GFRP. [4]

The abrasive wear is quite smooth and less with the SiC whisker reinforced alumina cutting tool than with the Ti[3] mixed alumina cutting tool while machining GFRP composite material, which is due to the presence of highly abrasive [4]FIBRES. Variations in surface roughness values were noticed due to the inherent variation in the surface roughness of the matrix and the fibers[5].

Fibre Reinforced Polymer (FRP)

Once fibre reinforced composite properties are known, carbon, glass and aramid polymers will be explained in more detail. The following information is based on [1].

Polymer matrices

Polymer matrices exhibit inferior properties when compared to engineering metal alloys with regard to strength, stiffness, toughness and elevated temperature properties. Therefore, polymeric matrices are often considered the weak link in a composite material and their properties often dictate the operating temperatures of the composite parts and their machinability.

Polymers consist of chains of hydrogen and carbon atoms held together by primary or covalent bonds. Depending on the arrangement of hydrocarbon chains, different molecular configurations and hence different properties are obtained. There is a strong relationship between the configuration of a polymer and its macroscopic properties in the liquid and the solid states.

Machining

The machinability of materials refers to the ease or difficulty with which these materials can be machined. It is an assessment of the material's response to a system of machining, which includes, in addition to the work material itself, the cutting tool, machine tool, machining operation and cutting conditions. It is not easy to obtain quantitative and consistent measures of it but it has been mainly assessed by three parameters including tool wear or tool life, cutting forces or power consumption and surface finish. Therefore good machinability means less tool wear, low cutting forces and good surface finish. Machinability may also be assessed by the type of chips produced and the cutting temperatures, since there is a correlation between the type of chip produced and surface finish [1]. On the other hand, cutting temperatures, cutting forces and surface finish are directly or indirectly related to tool wear. Therefore, tool life tests are most commonly used to assess machinability.

Machining FRPs

FRPs are inhomogeneous materials that consist of distinctly different phases, so that their machining is characterized by uncontrolled intermittent fibre fracture causing oscillating cutting forces. The machinability of FRPs is primarily determined by the physical and mechanical properties of the fibre and matrix, fibre content and fibre orientation. Tool wear is greatly influenced by the type and volume fraction of the FIBRES.

Tool wear

Tool wear monitoring becomes important in order to prevent any hazards occurring to the machine or deterioration of the surface finish. Cutting tools may fail due to the plastic deformation, mechanical breakage, cutting edge blunting, tool brittle fracture or rise in the interface temperatures [1]. Optimising cutting process in terms of improving quality, increasing productivity and lowering cost has technical and economic importance.

Tool wear influences cutting power, machining quality, tool life and machining cost. When tool wear reaches a certain value, increasing cutting force, vibration and cutting temperature cause surface integrity deteriorated and dimension error greater than tolerance, so the cutting tool must be replaced or ground. The cost and time for tool replacement and adjusting machine tool increases cost and decreases the productivity.

The prediction of tool wear is performed by calculating tool life according to experiment and empirical tool life equations such as Taylor's equation, although gives no information about the wear mechanism, moreover when tool geometry is changed, new equation must be established by making experiment.

Tool wear phenomena

Cutting tools are subjected to an extremely severe rubbing process. They are in contact, between the chip and work piece, under conditions of very high stress at high temperature, especially near the tool surface. During cutting, tools remove the material from the component to achieve the required shape, dimension and finish. However, wear is occurring during the cutting action, and it will result in the failure of the cutting tool and has to be replaced to guarantee the ordinary cutting action.

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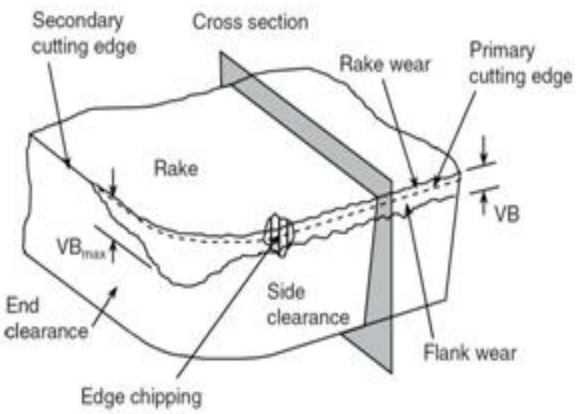

Figure 3: Types of Tool Wear. [1]

Under high temperature, high pressure, high sliding velocity and mechanical or thermal shock in cutting area, cutting tool has normally complex wear appearance, which consists of some basic wear types such as crater wear, flank wear, thermal crack, brittle crack, fatigue crack, insert breakage, plastic deformation and build-up edge (Fig.28). The dominating basic wear types vary with the change of cutting conditions, although crater and flank wear are the most common ones.

Crater wear

In continuous cutting crater wear normally forms on rake face. It conforms to the chip shape underside and reaches the maximum depth at a distance away from the cutting edge where highest temperature occurs. At high cutting speed, crater wear is often the factor that determines the life of the cutting tool. Crater wear is improved by selecting suitable cutting parameters and using coated tool or ultra-hard material tool.

Flank wear

It is caused by the friction between the newly machined work piece surface and the tool flank face. It is responsible for a poor surface finish, a decrease in the dimension accuracy of the tool and an increase in cutting force, temperature and vibration. So that, the width of the flank wear (VB in Fig.28), is usually taken as a measure of the amount of wear and a threshold value of it is defined as tool reshape criterion, although it may present different behaviours of flank wear (Fig.29).

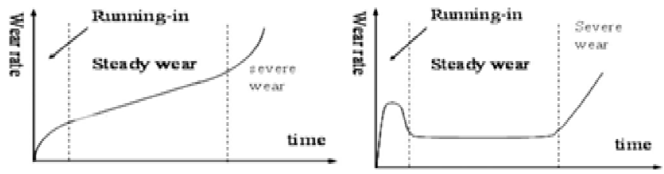

Figure 4: Different behaviours of flank wear.

Wear mechanism

Tool wear is not formed by a unique tool wear mechanism but a combination of several of them, including: abrasive wear, adhesive wear, delamination wear, diffusion wear, oxidation wear, electrochemical wear, etc. Among them, abrasive wear, adhesive wear, diffusion wear and oxidation wear are the most important.

Abrasive wear

It is mainly caused by the impurities within the work piece material, such as carbon, nitride and oxide compounds, as well as the built-up fragments. It is a mechanical wear and the main cause of the tool wear at low cutting speed.

Adhesive wear

Due to the high pressure and temperature, welding occurs between the fresh surface of the chip and rake face. Severe wear is characterized by considerable welding and tearing of the softer rubbing surface at high wear rate, and the formation of relatively large wear particles (Fig.30). Adhesion wear occurs mainly at low machining temperatures on tool rake face. Under mild wear conditions, the surface finish of the sliding surfaces improves.

Diffusion wear

Wear is a process of atomic transfer at contacting asperities. There are several ways in which the wear may be dependent on the diffusion mechanism.

Gross softening of the tool

Diffusion of carbon in a relatively deep surface layer of the tool may cause softening and subsequent plastic flow of the tool. This flow may produce major changes in the tool geometry, which result in high forces and a sudden complete failure of the tool.

Diffusion of major tool constituents into the work

The tool matrix or a major strengthening constituent may be dissolved into the work and chip surfaces as they pass the tool. In cast alloy, carbide or ceramic tools, this may be the prime wear phenomenon. Diamond tool cutting iron and steel is the typical example of diffusion wear.

Diffusion of a work-material component into the tool

A constituent of the work material diffusing into the tool may alter the physical properties of a surface layer of the tool. This may produce a thin brittle surface layer, that can be removed by fracture or chipping (Fig. 30).

Figure 5: Abrasive, adhesive and diffusion wear respectively. [47]

Oxidation wear

A slight oxidation of tool face is helpful to reduce the tool wear. It reduces adhesion, diffusion and current by isolating the tool and the work piece. But at high temperature soft oxide layers, for example Co_3O_4, WO_3 or TiO_2 are formed rapidly and then taken away by the chip and the work piece. That results in a rapid tool material loss (Fig. 31).

Chemical wear

Corrosive wear is due to chemical attack of the surface (Fig. 31).

Fatigue wear

It is often a thermo-mechanical combination. Temperature fluctuations and the loading and unloading of cutting forces can lead to cutting edge cracking and breaking (Fig. 31). Intermittent cutting action leads to continual generation of heat and cooling as well as shocks of cutting edge engagement.

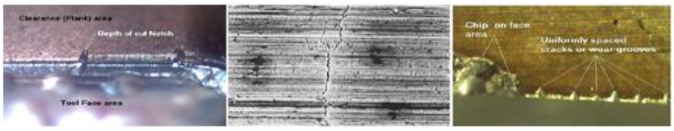

Figure 6: Oxidation, chemical and fatigue wear, respectively. [47]

Under different cutting conditions dominating wear mechanisms are different. For a certain combination of cutting tool and workpiece, the dominating wear mechanisms vary

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

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		Van Hoorn	Competitor
v_c	94 m/min	94 m/min	a_p	2 mm	1 mm
n	15.000 -/min	15.000 -/min	a_e	2 mm	2 mm
F_z	0.05 mm/t	0.05 mm/t	Q	3600 mm³/min	1500 mm³/min
v_f	900 mm/min	7500 mm/min			

Figure 7: Van Hoorn Carbide tool parameters for machining glass fibre.

Sandvik

The Company was founded in 1862, the manufacturing of stainless steel began in 1921 and production of cemented-carbide tools was begun in the 1950s.

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Guhring

They provide tools with PCD and CBN for difficult-to-machine, highly abrasive materials. They offer long tool life, highest surface quality (Fig. 66), optimal process reliability and repeatability and economic efficiency. Their PCD tools do not display the typical initial wear, but guarantee no delamination tendencies during the machining process thanks to the extremely resilient diamond cutting edge. However, in order to take full advantage the customer has to apply the tools on rigid and vibration-free machines as well as highly accurate spindle bearings or slide ways respectively.

Once checked that it fits, first hole is going to be analysed. The glass transition temperature of the matrix is about 100°C, temperature which can be achieved easily while machining. That means that the time that is spent on changing the plate (some minutes) is enough to cool the chips that are in the tool, solidifying and remaining attached to it, so the tool is clogged (Fig. 90). After the plate replacement the process starts again, requiring a greater force during the machining of the first hole in order to remove these bonded chips. In addition, the tool is still cold, so the matrix softening is not in such a way as it will happen in the next holes, likewise necessitating a greater force for drilling.

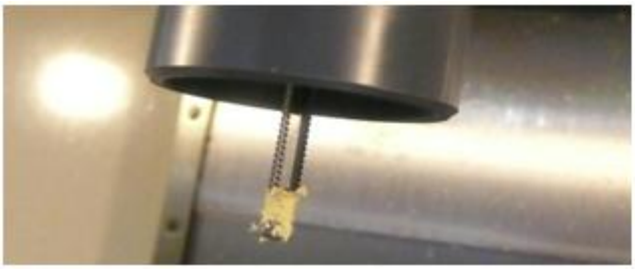

Figure 8: Clogged tool.

Finally, the second hole, whose values are lower than the ones found in the first hole but higher than the quite similar third and fourth ones, is going to be analysed. The tool used for the machining is a straight flute cutter. This tool geometry provides versatility but its ability of chip disposal is not high [1]. In the following figure (Fig. 91) it can be observed that the first and the fourth hole are the closest to the suction system, being the second and the third the farthest from it.

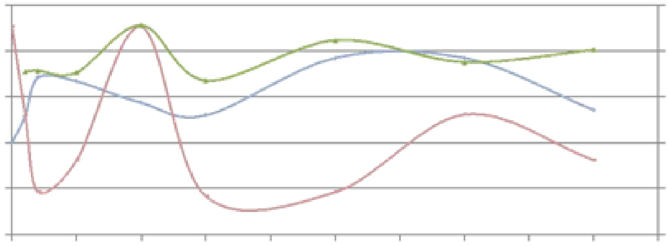

Figure 9: Radius vs. Fxy.

In contrast, a higher value of the force Fxy of plate 35 would make sense to the following force. This suggests some kind of anomaly in the measurement of the force of the 35th. plate, so what happens with force in "z" direction is going to be analysed for further information about this behaviour (Fig. 98).

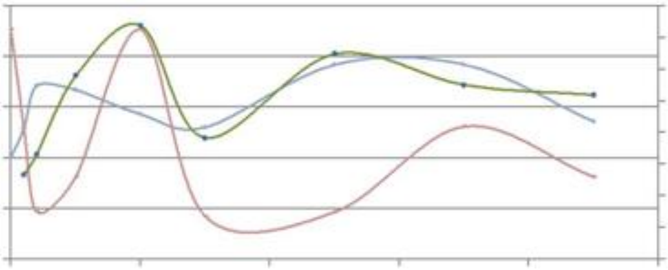

Figure 10: Radius vs. Fz.

This time, the relation between the force in the vertical direction and the sharpness of the major cutting edge seems to be narrower. When the edge is sharper less force is required which makes sense. However this suggests that the forces should be slightly higher. The value of the radius of the major cutting edge for plates 25 and 35 is the same, so a hypothetical value of force for the plate 35 (Fx35´) is assumed, whose value is equal to the force of the plate 25, in order to check how its tendency could be.

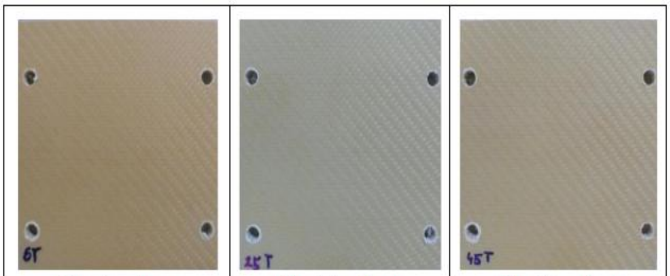

Plate 6: top layer	Plate 25: top layer	Plate 45: top layer

Table 11: Top layer of plates 6, 25 and 45.

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Besides push-out delamination has been found in each one of the holes in all the machined samples (Table 16). The level of push-out delamination has been very similar in all cases.

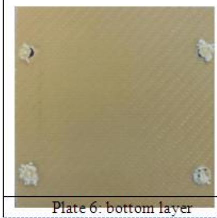		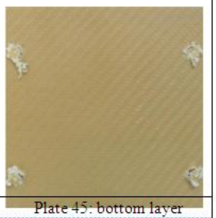
Plate 6: bottom layer	Plate 25: bottom layer	Plate 45: bottom layer

Table 12: Bottom layer of plates 6, 25 and 45.

Process improvement and future development

It has been checked that clogging has led to an increase in force required. Although the ability of chip disposal of the tool is not high because of being a straight flute, the softening of the matrix due to high temperature has also been evident. Moreover, it has been noted in the second hole that the lack of airflow led to clogging and also in compression of the surface layer and poor surface finish in the top layer. Therefore the use of compressed air (which is allowed for this tool) and adjustment of process parameters to reduce the chip thickness (increasing the cutting speed and decreasing the feed rate), should help to reduce the clogging problem and to improve the surface quality. Improvement of the chip suction system that has been used would also suppose a way to reduce the clogging problem, although compressed air could be more suitable. Other possible solutions aimed at solving the problems with the first hole, could be the search for a continuous machining process or heating the tool while performing the change of plate, both of them in order to prevent the material to cool down and to adhere to the tool.

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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