EVALUATION OF THE TOOL WEAR AND TOOL LIFE IN HIGH SPEED MILLING OF CARBON FIBER REINFORCED PLASTICS

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Abstract.

The use of composite materials has been growing in the substantial form. These materials and their manufacturing methods are more popular and they are now being increasingly used in applications such as aerospace, commercial aircrafts, ships, automobiles, machine tool and sports equipments. A distinct advantage of composites, over other materials, is the ability to use many combinations of resins and reinforcements. Composite materials such as carbon fiber reinforced plastics (CFRP) are important materials for structural components owing to their excellent properties such as high specific strength, high specific stiffness, high damping, low thermal expansion and good dimensional stability. Due to their anisotropy, CFRP poses problems in machining such as fiber breakage, matrix cracking, fiber/matrix debonding, fiber pullout, thermal degradation, and delamination. The purpose of this work is to evaluate the tool wear mechanism and tool life in high speed milling of CFRP. With an 8 mm diameter, six flute milling cutter ISO K10 hardmetal, the CFRP in plate 4 mm thick were machined at speed spindle ranging from 4000 to 24000 rpm and federate ranging from 1790 to 10740 mm/min. After all the tests carriedout the main conclusion was that the abrasion is the basic tool wear mechanism.

Keywords: *Carbon fiber reinforced plastic, high speed milling, tool wear*

1. INTRODUCTION

The discovery of carbon fiber in 1964 was a major contribution to adoption of composite materials in aircraft structures. These new composites materials began to be applied on military aircraft. With increasing application and experience of their use came better fibers and matrix materials resulting in carbon fiber reinforced plastics composites with improved mechanical properties. Refinements in fiber process technology over the past 20 years have led to considerable improvements in tensile strength and in strain to fracture for PAN-based fibers. These can now be supplied in three basic forms, high modulus (HM, 380 GPa), intermediate modulus (IM, 290 GPa) and high strength (HS, with a modulus of around 230 GPa and tensile strength of 4.5 GPa). High strength, high modulus carbon fibers have about 5–6 μm in diameter and consist of small crystallites of 'turbostratic' graphite, one of the allotropic forms of carbon (Soutis, 2005).

Fiber-reinforced plastics (FRPs) are light construction materials. They are characterized by high strength and stiffness and simultaneously low weight, and, hence, are superior to metallic materials in many cases. Therefore, FRPs have replaced conventional materials in various fields of application such as aeronautical and space engineering, traffic engineering, mechanical and plant engineering, as well as in other industries (Jahanmir, 1999).

Carbon Fiber-Reinforced Plastics (CFRP) one kind of composite materials, have been widely used in aircraft and spacecraft structures, and their use is being extended to sports and leisure products and automotive parts due to their high specific modulus (E/ρ), high specific strength (S/ρ), high damping capacity and low coefficient of thermal expansion in the fiber direction . Recently carbon fiber epoxy composite materials have been used in precise mechanical elements such as rollers for thin film processing, machine tool spindles and power-transmission shafts of aircraft, ships and cars for energy saving, easy maintenance and portability in the working space . When carbon fiber epoxy composite materials are employed in the structures of precise mechanical machines, the surfaces of composite structures frequently require several machining processes such as drilling, cutting and grinding after molding in an autoclave (Lee, 2000).

1.1. - Machining

Manufacturing technologies associated with machining can be categorized by cutting with geometrically defined cutting edges, cutting with geometrically undefined cutting edges, and unconventional machining. During cutting, the shaping of the workpiece is done by a defined relative motion between tool and workpiece and by transformation of the cutting edge geometry of the tool to the workpiece. The dividing technologies are separated under the effects of cropping and cutting tools. In contrast to unconventional machining technologies such as laser beam and water-jet cutting, which operate with wear-free tools and use of high mechanical and thermal active energies, tool wear occurs during cutting with geometrically defined and undefined cutting edges. Although the cutting of FRP parts is rarely desired, it can seldom be avoided for the production of final geometry, surface quality, and form accuracy of conventionally produced parts (Jahanmir, 1999).

Analytically (Bhatnacar, 1995) it is possible to calculate the values of shear strength for different fiber angles by using the transformation matrix but the estimation of the cutting forces should take certain concerns on the validity of the model because:

- Machinability of FRP is strongly dependent on the machining direction i.e. the chip formation phenomenon differs for the same fiber angle if the machining direction reverses (Figure 1).
- The measurement of shear plan angle in FRP is difficult and there is no standard technique to measure it. Besides, except for 0 ° fiber angle, the chips are generally of powdered form and it is extremely difficult to measure the chip thickness so as to calculate the "shear angle" by the well established relations of metal machining.
- It is somewhat doubtful whether the mean angle of friction between the chip and the tool remains the same for all fiber angles. As such, calculation of the cutting forces by using just one value of mean angle of friction for different fiber angles may not be correct.

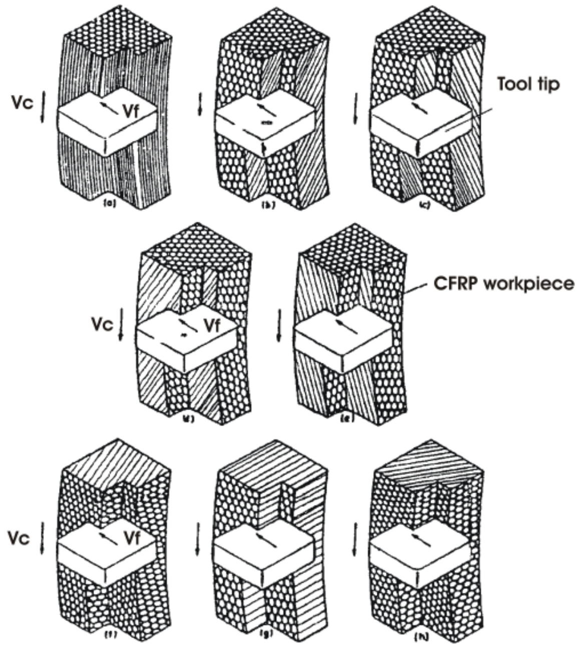

Figure 1. Fiber orientation in machining cutting.

The production of FRP parts from thermoplastics is typically achieved with conventional machining technologies. However, finish machining or secondary machining is often necessary. The reasons for that can include the manufacturing of highly precise function and joint areas, unfavorable part geometries, high dimensional accuracy of finished parts, flexibility during production of small numbers of pieces and high production costs for tooling. The specific properties of the anisotropic, inhomogeneous material must be considered during cutting of FRPs. The following have to be emphasized:

- Different thermal expansion coefficients of matrix and fiber lead to "frozen" stress after the curing process, which may be released during mechanical machining. Deformations and part damages may occur.

- The low interlaminar strength permits damage during machining such as delamination and chip-off of boundary layers. For unidirectional materials this danger is bigger than for multidirectional laminates, because their mechanical carrying capacity is low vertical to the grain.
- The heterogeneous structure combined with the high cohesive resistance particularly of carbon and glass fibers also leads to excessive tool wear during cutting.
- If chip dust and machining by-products are not carried off by a cooling lubricant, they have to be removed using a vacuum. Graphite dusts are conductive and thus endanger the control and drives of electrical machines.
- During application of coolants, moisture absorption by the matrix may occur. Form and dimensional accuracy as well as the mechanical properties of the part suffer.

1.2. - Drilling

About 100.000 holes are made for a small single engine aircraft; in a large transport aircraft millions of holes are made mainly for fasteners such as rivets, bolts and nuts. Almost 50% of the total airframe production cost is in airframe assembly. The quality of the drilled holes, such as waviness/roughness of its wall surface, axial straightness, and roundness of the cross-section, can cause high stresses on the rivets that lead to their failure. The composites are produced to near-net-shape, but additional machining operation such as drilling is often required. Unfortunately the cutting tool action during machining can damage the work material surface increasing substantially the risk of mechanical failures. Delamination (figure 2) is one of the principal damages observed after drilling composite materials and for this reason delamination can often be a limiting factor in the use of composite materials for structural applications (Davim, 2007). Delamination is a major problem associated with drilling fiber-reinforced composite materials. It causes poor assembly tolerance, reduces the structural integrity of the material, and has the potential for long-term performance deterioration. In the aircraft industry, for example, drilling associated delamination accounts for 60% of all part rejections during final assembly of an aircraft. The economic impact of this is significant considering the value associated with the part when it reaches the assembly stage. Two mechanisms of delamination are observed in drilling polymeric composite materials: peel-up and push-out. Peel-up occurs as the drill enters the laminate, while push-out exists as the drill exits the laminate. In drilling polymeric composite materials, the thrust force has been cited as the main cause of delamination. The most commonly used method for reducing the push-out delamination at the drill exit is to have a support under the work piece (Seif, 2007).

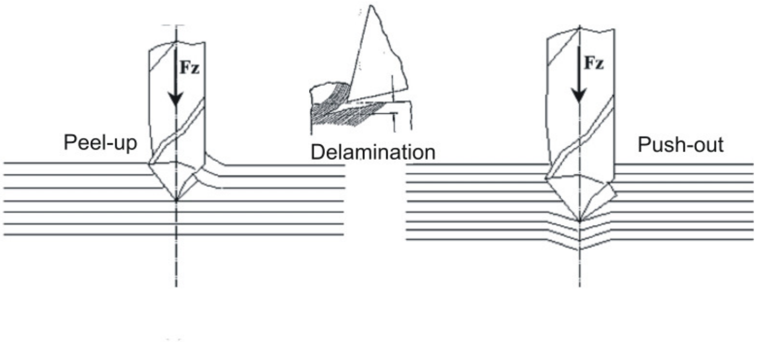

Figure 2 Fiber delamination

In order to overcome these difficulties it is necessary to develop procedures to select appropriate cutting parameters, due to the fact that an unsuitable choice could lead to unacceptable work material degradation. The factors such as cutting parameters and tool geometry and material must be careful selected aiming to obtain best performance on the drilling operation, i.e., best hole quality, which represents minimal damage to the machined component and satisfactory machined surface (Abrão, 2007).

1.3. - Milling

Milling is the machining operation most frequently used in manufacturing parts of fiber-reinforced plastics, because components made of composite materials are commonly produced by net-shape that often require the removal of excess material to control tolerances, and milling is used as a corrective operation to produce a well defined and high quality surfaces. The machinability of fiber-reinforced plastics is strongly influenced by the type of fiber embedded in the composite and by its properties (figure 3). Mechanical and thermal properties have an extremely importance on machining FRP. The fiber used in the composites has a greater influence in the selection of cutting tools (cutting edge material and geometry) and machining parameters. It is fundamental to ensure that the tool selected is suitable for the material. The knowledge of cutting mechanisms is indispensable in view of cutting mechanics and machinability assessment in milling.

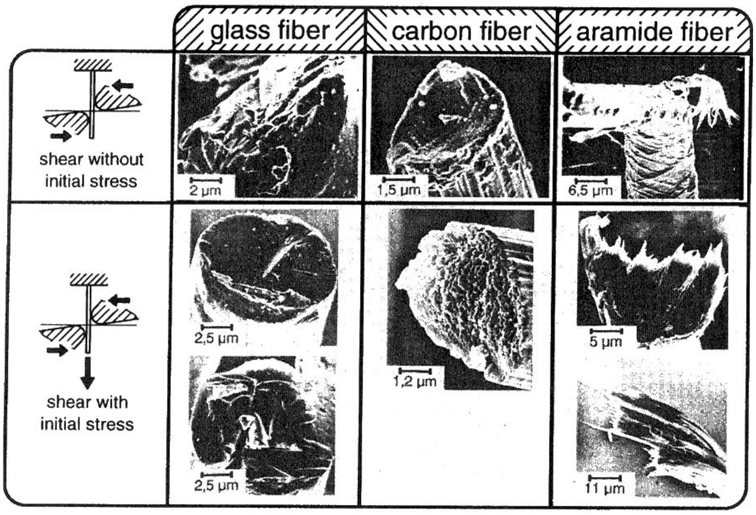

Figure 3. Failure mechanism of composite fiber material

The works of a number of authors, when reporting on milling of FRP, have shown that the type and orientation of the fiber, cutting parameters and tool geometry have an essential paper on the machinability. The principal cutting mechanisms on machining of polymeric composites correlates strongly to fiber arrangement and tool geometry. It can be realized that the value of Ra increases with feed rate and decreases with the cutting speed, i.e. with a higher cutting speed and a lower feed rate it is possible obtain a better surface finish (Davim, 2005). In summary, it can be noticed that the works carried out on the machinability of FRP, are basically related on the wear of cutting tools and the quality on the surfaces, as a function of the cutting conditions, the distribution of staple fibers in the polymeric matrix and the angle of inclination of staple fibers.

1.4. - Surface Quality

Surface roughness is a parameter that has a greater influence on dimensional precision, performance of mechanical pieces and on production costs. For these reasons, research developments have been carried out with the purpose of optimizing the cutting conditions to reach a specific surface roughness. For achieving the desired quality of the machined surface, it is necessary to understand the mechanisms of material removal, the kinetics of machining processes affecting the performance of the cutting tools.

Typical phenomena of damage such as matrix chipping and delamination are to be expected during machining of fiber-reinforced plastics. The surface quality is in principle related to fiber orientation. The elastic recovery occurs in the cutting of fibers that possess angles bigger than 90° in relation to the cutting direction (figure 4). Thus, the surface topography, e.g., for the machining of uni and multidirectional laminates is characterized by small holes, fiber chippings, cracks, and blurs of the matrix material.

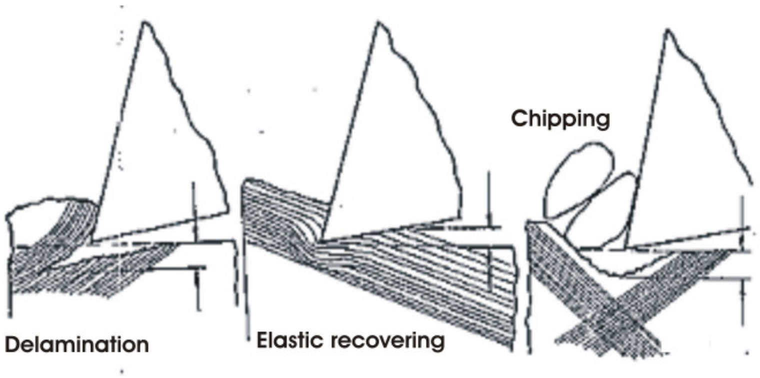

Figure 4 Typical damage of CFRP machined surface

The most significant difference between the cutting of a heterogeneous material with fibrous reinforcement elements and a homogeneous material is the fiber orientation and angle of fiber orientation influence on the surface quality and marginal zone of the workpiece. The surface quality is not only influenced by the direction of fibers, but also by the type of fiber. While glass and carbon fibers show brittle fraction, aramide fibers are tough. As a result, delaminations on the surface and increased tool wear frequently occur during machining of aramide fibers. In contrast, carbon fibers mostly break as bundles, with the length of fiber breaks being related to fiber orientation. Some of the broken fibers settle on the already machined surface. The matrix blur diminishes with decreasing fiber orientation. In most cases, the degree of matrix damage increases with increasing fiber orientation angle. The matrix blur reduces the surface roughness.

The degree of tool wear also influences the surface quality. In addition to the roughness, which results from the transferring of the cutting edge corner on the workpiece surface in relation to feed and tool geometry, rising values of roughness occur with increasing width of flank wear land. Cutting temperatures have to be considered specifically; too, with regard to the analysis of machining quality. The high cutting temperature can lead to local combustions due to the bad heat conductivity of thermosets and in the case of thermoplastics melting can happen. Both phenomena result in part damages and surface deteriorations.

Surface topography and marginal zone damage represent a major quality criterion for the analysis of the workpiece. Due to the magnitude of cutting forces, the adhesion strength between fiber and matrix can be exceeded, so that fibers either peel (delamination) or are removed by the expansion of matrix parts. Tool wear and unsuitable cutting parameters cause thermomechanical damage that can lead to various damage phenomena in relation to the type of matrix.

2. EXPERIMENTAL SET-UP

This work was planned to identify the tool life, measuring the flank tool wear in high speed milling of CFRP. The tool used was an 8 mm diameter, with six straight flute. The cutting tool material was abrasion resistant solid micrograin carbide K10. The geometry of cutting tool showed on figure 5 A, B and C has center cutting in one flute for plunging and neutral helix to minimize delamination. The commercial code of the tool is GSR-D-0800 from Composite Cutting Tools Ltd and the amounts of tools samples were restricting to six units.

Figure 5. Cutting tool geometry and machine tool

The high speed milling tests had been carried out in a high speed machining center FIDIA D165 equipped the Fidia C1 compact high-performance numerical control (figure 5 D). The dust suction unit is essential when machining graphite or resins (figure 5 E) was attached to the machine table. The high capacity suction device equipped with self cleaning filters were mounted outside the lab. These filters offer a high degree of filtration (figure 5 F) and are able to operate in the presence of dust and smoke that came from CFRP milling. The main spindle power motor had 18 kW and maximum spindle speed of 24000 rpm with HSK63a tool holder type. The three axles are set in motion at freely programmable speed up to 30000 mm/min.

The size of workpiece was 4mm thick, 630 mm wide and 900 mm length. The figure 6 shows how the woven fibers were disposed in layers in the workpiece thickness. The CFRP was built with ten layers of carbon fiber, one layer of fine copper wire, two layers of carbon fiber and finally one layer of glass fiber.

The cutting parameters for tool life test were federate of 0,075 mm/rpm and cutting speed of 100, 200, 300, 400, 500 and 600 m/min. The spindle speed and the feed in a cnc program are showed in table 1. The tool traveled 50 mm in air at full spindle speed and feedrate before reached the workpiece to avoid the influence of machine acceleration.

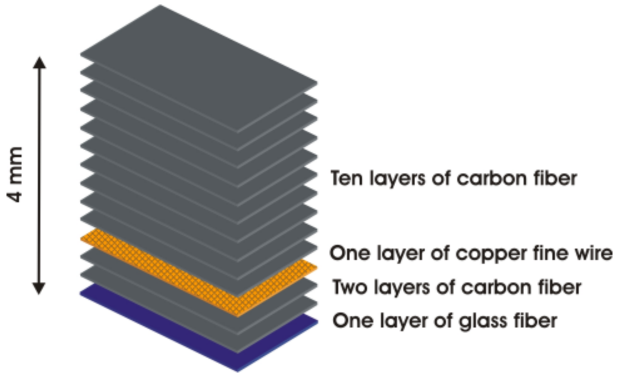

Figure 6. Workpiece sketch for drilling tool life test.

Table 1. Tool life test parameters

Test number	v_c (m/min)	f_z (mm/tooth)	a_e (mm)	a_p (mm)	n (rpm)	vf (m/min)
1	100	0.075	8	4	3978	1790
2	200	0.075	8	4	7957	3580
3	300	0.075	8	4	11936	5371
4	400	0,075	8	4	15915	7161
5	500	0.075	8	4	19894	8952
6	600	0,075	8	4	23873	10742

3. RESULTS AND DISCUSSION

The results obtained from the tool life tests are presented and discussed in this section.

3.1. - The mill tool wear

The miling test began at cutting speed of 100 m/min and feedrate of 1790 mm/min. The procedure of test consisted of positioning tool 50 mm before the workpiece, start the spindle and federate. The tool traveled 1000 mm, 50 mm in air, 900 mm milling the CFRP and 50 mm in air. Then tool was positioned at start point and the cnc program ended. After the dust were removed by a vacuum cleaner the workpiece was repositioned and the cnc program started again. After the eighth tool path the main cutting edge was then analyzed in a stereomicroscopic to measure the tool wear land and identify the tool wear mechanism. When the tool wear land reached 0,3 mm the cutting test was finished.

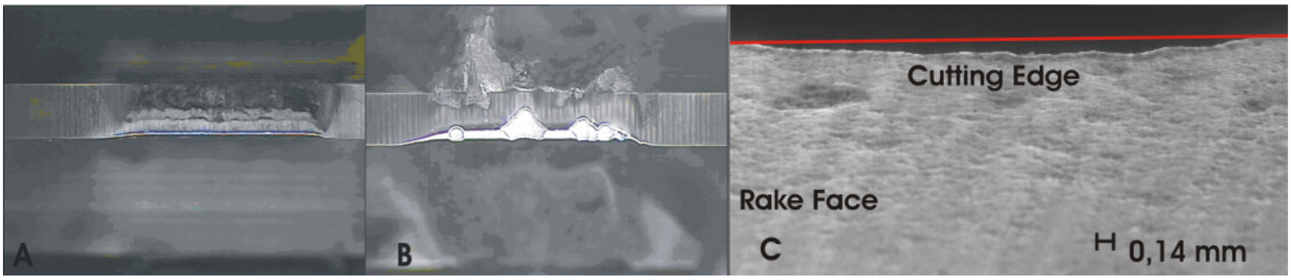

Figure 7: Wear of main cutting edge

The figure 7A shows the typical land wear of main cutting edge. This kind of wear happened at cutting speed of 100, 200, 300, 400 e 600 m/min. It was impossible to notice any difference in main cutting edge provoked by the fine wire copper layer or the glass fiber layer. The wear was the same in all length of cutting edge engaged on cutting CFRP.

At 500 mm/min cutting speed the cutting became unstable and the tool started to chipping before the tool life criteria was reached. The figure 7B shows the chipping of the main cutting edge on the clearance surface. The chipping wasn't provoked by a fine wire copper layer because it happened at middle edge and at beginning and at the end. The copper layer was in the bottom of CFRP close to surface of workpiece. At a full spindle speed all the vibrations that happened at 500 m/min disappeared. One possible explanation for this could be that the chattering was happening at 19849 rpm. At maximum spindle speed all the vibration that provoked the chipping of the tool ended and the material was cut smoothly. The mechanism of tool wear returned to abrasion. The figure 7C shows the main cutting edge viewed from the rake surface. The red line shows the original positions of main cutting edge when the tool was new. The same trend of the main cutting edge deformation was observed at all cutting speeds. As the land wear started to grow a small step in straight format could be noted on main cutting edge. The length of step was the same of CFRP workpice thickness. After ended all the tests, the graphic of tool wear (figure 8) could be built.

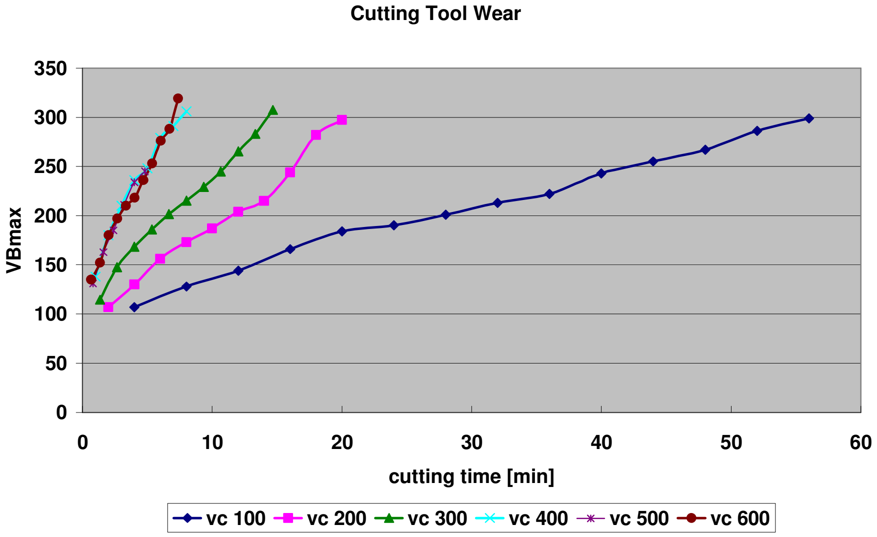

Figure 8 Tool wear at six different cutting speeds.

The figure 8 shows that the cutting speed has a strong influence in tool wear and the tool wear rate is lower when cutting speed is lower. At higher cutting speed the tool wear rates becomes higher. The vibration that appears at 19849 rpm spindle speed could not be noted and the values of tool wear at that speed are mixed with tool wear values at 600 m/min. It means that the vibration accelerates tool wear. The tool wear values at 400 m/min and 600 m/min are so closed because the scale factor is the same for all cutting speeds.

The figure 9 shows four photos of SEM analysis of the tool. After the tool life test ended, the six tools were cleaned with compressed air and analyzed with SEM to identify the dominant tool wear mechanism. The figure 9A shows the cutting edge of the tool viewed from the clearance face. The white line shows the original position of the main cutting edge when the tool was new. The difference between the cutting of a composite material with carbon and glass fiber reinforcement elements and a homogeneous metallic material is the type and orientation of the fiber. The principal cutting mechanisms on machining of polymeric composites correlates strongly to fiber arrangement and fiber elastic recovery. It occurs in the cutting of fibers that possess angles bigger than 90° in relation to the cutting direction and increases the abrasion wear (see figure 4). The abrasive action of the fiber helps to round the main cutting edge. The figure 9B shows the same tool from the rake face. The gap between the white line helps to understand the abrasive action of the carbon fiber that rounds the main cutting edge. The dust form of the chips practically does not interact with the rake face of the tool. The figure 9C and 9D are the amplification of the small chipping that appeared on figure 9A. Inside of the chipping the dust form of CFRP chips are trapped there. This chipping happened at all spindle speeds and become catastrophic only at 500 m/min. The chipping that is viewed from the clearance face wasn't wider than the land wear (figure 9C).

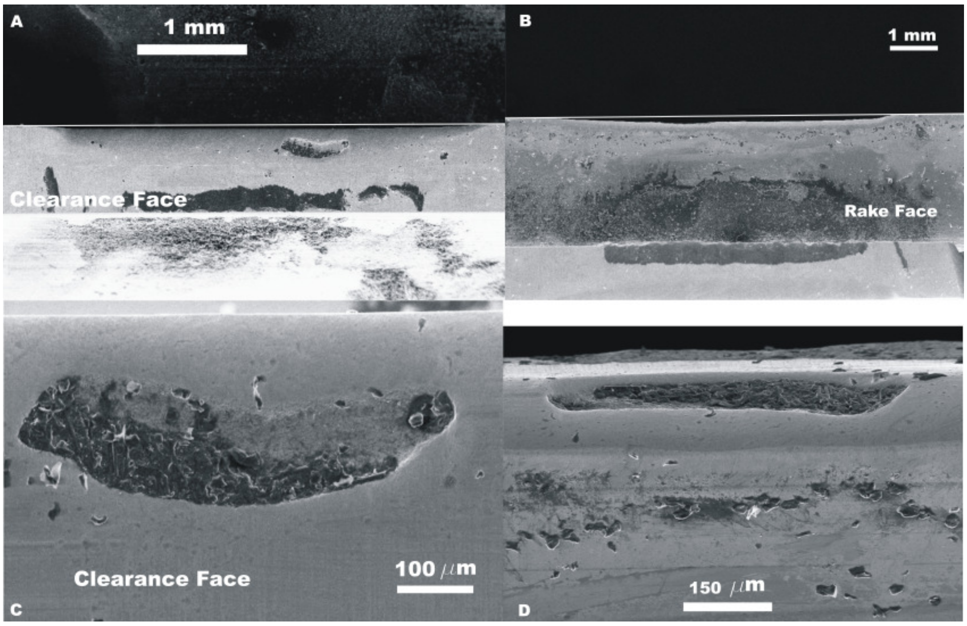

Figure 9. The SEM analysis of the main cutting edge.

3.2. - The mill tool life

The cutting edge life of a 8 mm milling tool solid micro grain carbide K10 can be expressed by the constants n and C in the Taylor equation (equation 1)

$$VT^n=C \quad (1)$$

The data of the tool wear test located in a graph of figure 8 are the key to found the n constant in the Taylor equation. The tool life criteria was VBmax = 0,3 mm and the cutting parameters are showed on table 1. The n value can be found using the data available on figure 10. Each point on the graphic (figure 0) was built through the logarithmic of cutting time to reach the tool life criteria and the logarithmic of respective cutting speed. The line equation was get from the least squares technique. The n and C constants from Taylor equation are then 0,86 and 3013. The figure 10 shows that the correlation data of the straight line are very close showing that the experimental error during the tool life test was very small.

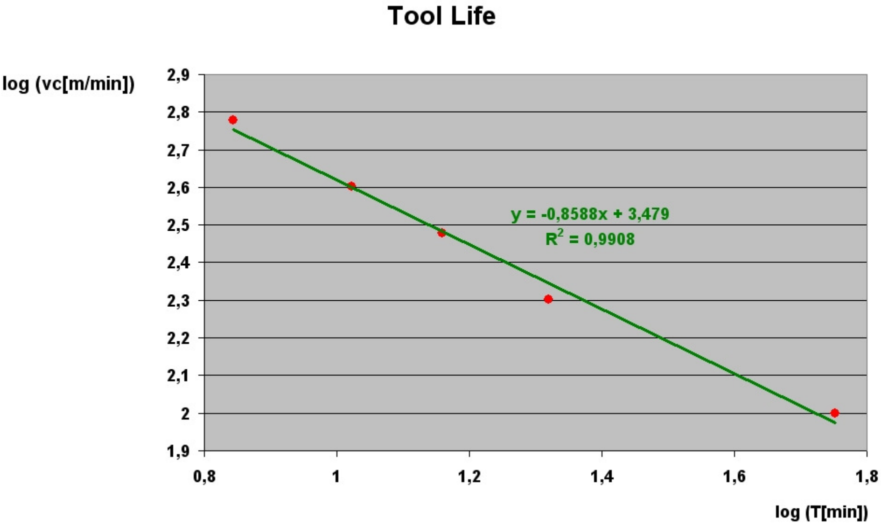

Figure 10. Taylor tool life

The cutting speeds that wer accounting for building the graphic of figure 10 were 100, 200, 300, 400 and 600 m/min. The cutting speed of 500 m/min was not taken in account because the tool wear mechanism was affected by vibration. As can be seen on figure 7B the chipping was present on main cutting edge at cutting speed of 500 m/min.

3.3. - The surface quality.

During the tool life tests small samples of the machined workpiece had been collected for SEM analysis. All machined samples presented the same pattern showed in figure 10. At the top of surface, indicated by number one, the figure 10 shows the glass fiber layer. The region indicated by number two shows the brightest spots equally spaced bellow the surface. These spots are the cross section of the fine copper wire layer. The bulk material identified on region three is the CFRP and the small white spots that are found there (number four) were identified by EDS analysis as glass fiber.

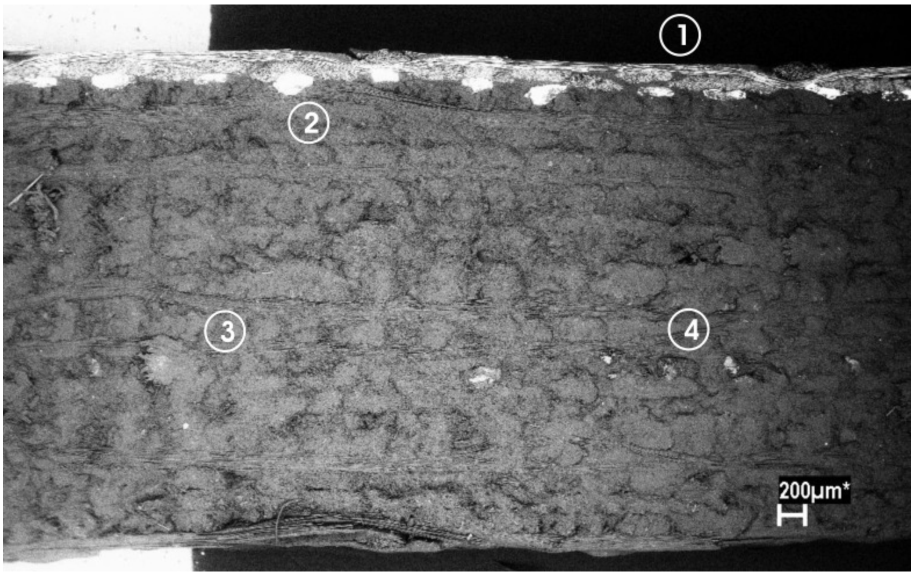

Figure 10. Typical milled surface

The milled workpiece showed the typical damage found during machining of fiber-reinforced plastics. The delamination was found close to surface in the opposite side of fine wire copper layer. The figure 11A shows delamination that happened at cutting speed of 200 m/min. Delamination was present too at 400 m/min close to glass fiber surface as showed by figure 11B.

The matrix chipping in the milled surface only could be found at higher magnifying rate. The figure 11C shows the matrix chipping in milling surface at 600 m/min.

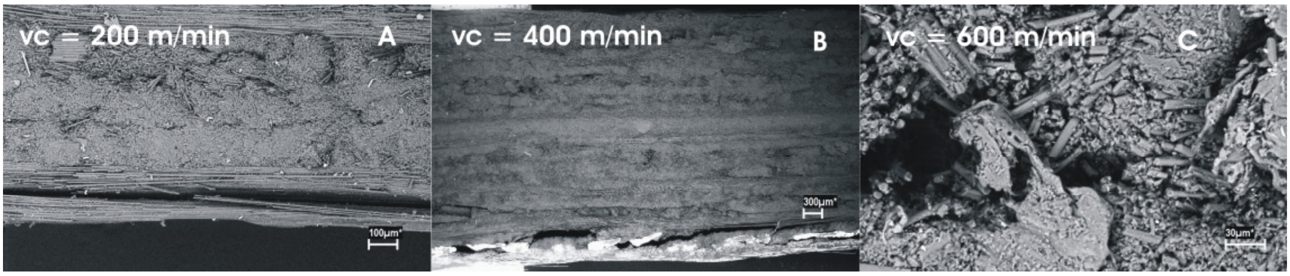

Figure 11. Typical damage of CFRP milled surface

4. CONCLUSION

The dominant tool wear mechanism in high speed milling of CFRP is abrasion.

The fine copper wire as interlayer and glass fiber interlayer doesn't change the main cutting wear mechanism.

The correlation factor found in tool life test shows that the Taylor concepts of tool life are applicable in machining CFRP.

The typical surface damages found during machining of fiber-reinforced plastics are present at high speed milling of CFRP

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