STUDY OF THE OPTIMIZED COOLING TECHNIQUE ON THE SURFACE GRINDING OF CARBON FIBER REINFORCED PLASTIC COMPOSITES

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Abstract. *Composite materials are becoming essential and widely used in modern industry, mainly in aeronautics, aerospace and naval sectors. The reason for its increasing use it is their structural composition, which comes from the combination of two different materials, resulting into a low weight, extremely rigid and resistant matrix. Due to the material anisotropy, it tends to present, at the end of its manufacturing, residual stresses or structural distortions. This way, it is difficult to control effectively the geometry and tolerances of the pieces. Recent researches show that the finishing machining process called grinding is the most recommended to eliminate these structural problems. When they are subject to grinding, it becomes necessary a great amount of cutting fluid (conventional cooling), and the surface wear is high. The abusive application of these fluids has become a factor of concern for the modern industries, due to the issues related to occupational health and environmental hazard, because of its toxic compounds. In reference to these concerns, arises a new method of application called optimized cooling, a technique which aims to reduce substantially the amount of fluid used in grinding, and also tends to improve its performance in comparison to the conventional cooling. This way, this work intended to analyze the behavior of the surface grinding of carbon fiber reinforced plastic (CFRP) composites using optimized cooling, as an alternative to the conventional cooling. This assessment was done trough the analysis of the following output variables: tangential cutting force and G ratio. With the results obtained, it was intended to evaluate the process, aiming to insert it into the modern industry context and to contribute with the literature about grinding composite materials, which is very scarce.*

Keywords: *Composite materials, grinding, cutting fluid, optimized cooling, carbon fiber.*

1. INTRODUCTION

According to Lee et al. (2000), in the last decades it has been observed a significant increase on the application of composite materials, as alternatives to conventional materials (steels, ceramics, polymers, etc.). The reasons for this ever increasing use rely on its excellent properties, such as high specific modulus, high specific strength, good damping properties and low thermal expansion coefficient.

Zhong (2003) emphasize the fact that carbon fiber reinforced plastic (FRPC) composites are becoming widely used due to their excellent mechanical and physical properties. On its use as responsibility parts, it is usually necessary to undergo some machining processes, in order to obtain dimensional and geometric precision, such as in holes or fittings. After this primary machining operation, if it is necessary to achieve better surface quality, it is recommended to apply the grinding process, which is a process considered as the only one viable to reduce the surface roughness.

As reported by Hu and Zhang (2006), due to the recent increase of the demand for composite materials, many research has been conducted concerning the properties of unidirectional carbon fiber reinforced plastic composites, under conventional cutting processes such as turning and milling. However, many studies are still needed in relation to multidirectional reinforcements, as well as studies assessing the grindability of the material.

In grinding, during chip formation, great portion of generated energy is converted to heat, increasing the temperature of the cutting zone, which can thermally damage the parts and compromise its surface integrity, with the emergence of cracks, distortions and residual stresses. The application of cutting fluids in grinding thus becomes indispensable. According to Kovacevic and Mohan (1995), besides the functions of lubrication and cooling, the cutting fluid removes the machined chips, protects the machine and parts against oxidation, and others.

Bianchi et al. (2010) showed that the absence of fluids could cause a loss on the wheel efficiency, due to the increase of the process temperature, deteriorating the geometric and dimensional qualities, as well as the surface finishing, without mention the wheel clogging. On the other side, some legal requirements concerning environmental impact due to fluid disposal allowed new forms of application to be developed, in order to optimize the lubri-cooling, with reduction of the amounts of cutting fluid spent during the process. One technique which has been successfully employed is the optimized cooling method, which directs a high pressurized fluid flow straight into the cutting zone.

The present work aims to study the optimized cooling, which can corroborate to diminish the environmental impact of cutting fluids, when grinding carbon fiber reinforced plastic composites. It also seeks to evaluate the viability of this cooling method on grinding plastic composites, aiming to contribute with the modern manufacturing processes. Beyond that, this study will also collaborate with the present literature concerning composites grinding, which is very scarce.

2. LITERATURE REVIEW

2.1 Composite materials

According to Strong (1989), composite materials are a combination of a reinforcement material (in forms of particles or fibers) in a matrix, which holds together the first. The matrix also protects the reinforcement from environmental effects, while the latter is responsible for supporting stresses. These materials can be divided into two categories: carbon fiber reinforced plastic composites (CFRP), and carbon fiber reinforced carbon composites (CFRC). Besides that, the reinforcement fibers can be molded unidirectional or multidirectionally. Figure 1 illustrates some possible arranges of multidirectional composite fibers.

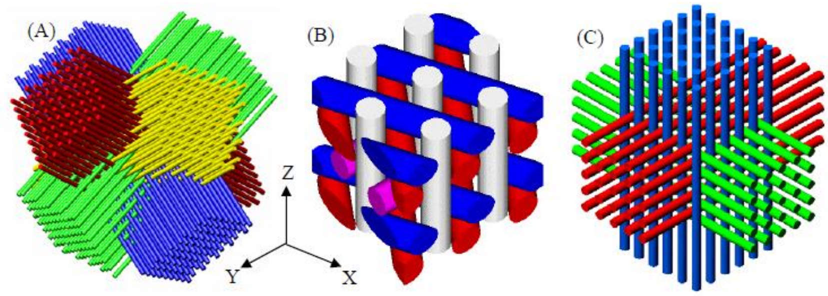

Figure 1. Multidirectional preforms used in composite manufacturing. (A) Tetradirectional - Pyramidal, (B) Tetradirectional - Planar, (C) Tridirectional - Orthogonal (Pardini & Gonçalves, 2009).

2.2 Grinding of composites

Zhong and Hung (2000) reported that, composite materials, which have been attracting increasing interest to researchers, in relation to its machining, are known as advanced materials due to their high specific strength, high wear resistance and remarkable low weight. Manufacture methods, and studies related to its mechanical properties have become popular on the last years. These materials are used mainly on aeronautic, aerospace, naval, military and automotive industries.

According to Takeshita (1985), lately, with the increasing frequency of use and application of composite materials (CFRP and CFRC) and, analyzing its early manufacturing, it can be seen the need for employing machining processes, since the dimensions and tolerances cannot be always achieved with conventional processes, in order to fulfill the product specifications.

Martins (1999) and Ferreira (1997) state that the characteristics of the composites vary from part to part. Thus, to know the material behavior under machining is of great importance when manufacturing mechanical elements. Composite machining can be accomplished by the most conventional tools. According to Di Ilio and Paoletti (1999), grinding provided better results when using conventional abrasives, specifically silicon carbide (SiC) wheels.

2.4 Optimized cooling method

The marked growth of industrial productivity and utilization of grinding has made necessary the use of great amounts of cutting fluids. Special care must be taken mainly due to the application of water-based fluids, which have very low density, and thus make the fluid jet less coherent (when using conventional nozzles). It is necessary, then, to employ huge reservoirs, fluid cooling units and high power pumps. However, using the optimized method, it is expected to reduce the amount of cutting fluids, as well as the costs with application, storage and disposal of the fluids. (Webster, 1999).

Conventional cutting fluid application systems are relatively inefficient in grinding, particularly under severe machining conditions. The energy stored in the fluid jet during the application is insufficient, on the most cases, to overcome the centrifugal forces of the wheel, and the air barrier formed due to the tool rotation (Catai et al., 2008).

According to Webster et al. (1995), a fluid jet directed straight to the cutting zone is capable of reducing significantly the local temperature; however, high fluid jet velocities are required for effective penetration on this contact zone. Through the application of a circular nozzle properly designed, it was noticed the temperature reduction on the cutting zone, when comparing to the conventional fluid jet.

Webster et al. (1995) also states that the cutting fluid jet velocity should minimize the possible impacts between fluid and tool. This can be verified when the fluid jet velocity is equal to the peripheral velocity of the wheel. On this case, the fluid tends to penetrate the cutting region with the same velocity as the abrasive grains, eliminating thus significant interferences, as well as disrupting the air barrier around the rotating wheel.

The nozzle geometry, its inlet and outlet surfaces, as well as its internal surfaces, should be taken into account during design. The concave surfaces present better results, because they tend to approximate the fluid layers which are formed inside the nozzle. This reduces the turbulence effect, unlike the convex surface, which tends to separate these layers, thus increasing turbulence.

Figure 2 illustrates the nozzle (geometry and dimensions) used by Webster et al. (1995), and a conventional nozzle.

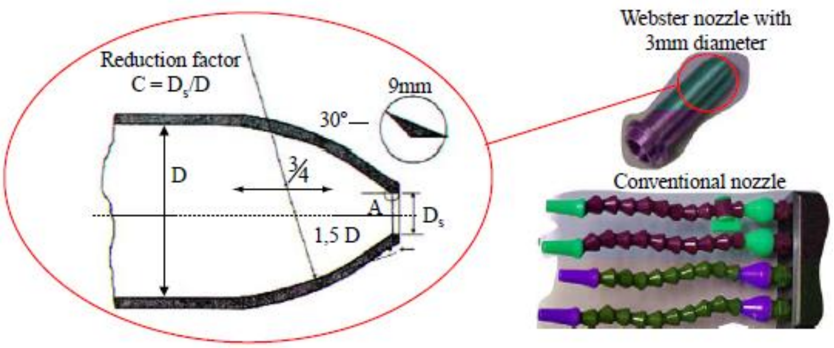

Figure 2. Cooling nozzles.

3. MATERIAL AND METHODS

The tests were conducted on a Sulmecânica 1055E surface grinding machine.

The workpieces, donated by Centro Técnico Aeroespacial (CTA), consisted of carbon fiber reinforced plastic composite plates, with the respective dimensions: 650 mm x 100 mm x 5 mm. The reinforcement fibers are multidirectional, alternating between 0°, 45° and 90° every three layers. The plates were cut perpendicularly, obtaining smaller workpieces with dimensions of: 200 mm x 100 mm x 5 mm, which were the workpieces actually used on the tests. From the cutting of the original plates, it was also obtained smaller parts (100 mm x 1000 mm x 5 mm) used to imprint the wheel wear.

The tool used was a conventional silicon carbide (SiC) wheel, having 355 mm external diameter, 127 mm internal diameter, and 25mm width. The bond is vitrified and the wheel specification is 39C 60 K VK. It was manufactured and donated by Saint Gobain Abrasives Ltd. The tool was dressed every two tests (due to the fact that the great wheel width could perform two tests for each dressing), with a multigranular dresser, which is composed of diamond tips in a metallic matrix. The cutting fluid used was an emulsion (2.5 % in water) of Tapmatic ME-1 semi-synthetic soluble oil. According to the manufacturer, this fluid also has, on its composition, anticorrosion compounds, biocides, fungicides, alkalinizers, antifoam, non-ionic sufcactants, alcanolamides, besides others.

The optimized cooling system used the same fluid as the conventional cooling, but it was used a more powerful pump, a flow meter, and a special nozzle designed specifically to this purpose (shown in Figure 2).

The tangential cutting force was measured by determining the consumed power by the electric motor which drives the wheel, monitoring its tension and electric current. An electronic module is used to convert the electric current and tension values into compatible tension values, and send them to a data acquisition board, in order to be manipulated by LabView 7.1 ®, from National Instruments ®. With this obtained data, it was obtained the tangential cutting force graphs after some manipulation and filtering with Matlab ® 9.0.

Before each dressing operation (except the initial one), the tool wear was measured by an average value (from 5 measurements) of the wheel profile impressed perpendicularly on the workpiece. With a Surtronic 3+ rugosimeter, it was possible to map the workpiece profile, indirectly measuring the wheel wear. After that, some graphs were plotted on Talymap®, and then it was possible to calculate the G ratio, which is defined as the quotient between the volume of material removed (Z_w) and the corresponding volume of grinding wheel used (Z_s) (both in mm^3), in each condition.

For the experiments, it was established the following machining parameters: cutting velocity (V_s) of 33.5 m/s, workpiece velocity (V_w) of 0.08 m/s, optimized cooling outlet fluid jet velocity of 26.3 m/s, conventional cooling outlet fluid jet flow of 0.000458 m^3/s and optimized cooling fluid jet flow of 0.000342 m^3/s.

Three depths of cut were used for each lubri-cooling method, and the tests were repeated two times, resulting in 18 workpieces and tests in total. The depths of cut chosen were: 100 μm, 300 μm and 600 μm. Thus, the three equivalent cutting thicknesses are: $h_{eq1} = 0.267$ μm, $h_{eq2} = 0.8$ μm e $h_{eq3} = 1.6$ μm.

4. RESULTS AND DISCUSSION

4.1 Tangential cutting force

With the data obtained from the acquisition board, after some filtering and manipulation, Fig. 3 was plotted, on which it can be observed the average tangential cutting force of each condition. According to Hu and Zhang (2006), the cutting forces during grinding carbon fiber reinforced plastic (CFRP) composites can reach high values, due to the multidirectional structure of the reinforcements. This makes the reinforcement fibers (which have different orientations) intertwine, making the grinding of the workpiece more difficult and increasing thus the cutting forces.

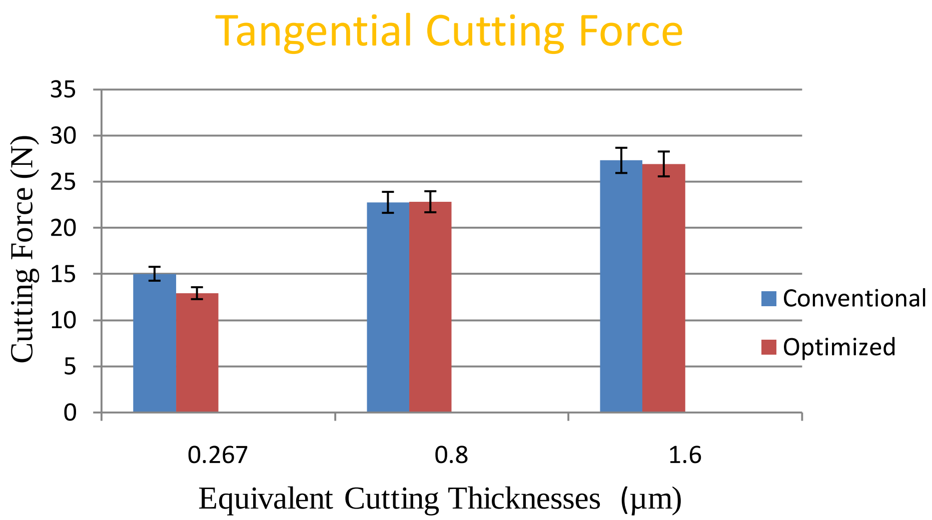

Figure 3. Results of tangential cutting force obtained.

From the figure above, it can be verified that the behavior of the tangential cutting force tended to increase, when using higher depths of cut. This increases also the contact area between the grinding wheel and the workpiece. Thus, there are more abrasive grains in contact, besides the higher cutting forcers per grain and higher dissipative energies (heat, acoustic emission, deformations, and others), for a higher material removal rate.

For the cooling methods studied, the values of tangential cutting force remained close to the three equivalent cutting thicknesses. However, the optimized cooling method provided lower values, when using the equivalent cutting thicknesses of 0.267 µm. These results can be explained by the fact that the conventional cooling method provided abundant fluid flow, without higher pressure, which is not enough to reach effectively the cutting zone. This way, the friction between grain and piece increases, increasing also the cutting forces. The fact that the optimized method provided better results relies on the following reasons: the optimized cooling method uses a specially designed nozzle, and the fluid jet velocity is higher, closer as the wheel peripheral velocity. This causes better fluid jet penetration, and provides better lubrication and cooling, as well as chip removal. However, these values cannot be the only criteria to disqualify any of the lubri-cooling methods presented.

The fact that the fluid flows effectively, removing the chips generated during cutting, minimizes wheel clogging. On these cases, the abrasive grains remain attached to the tool cutting surface, wearing the cutting edges, and not providing total rupture of the grains, which causes and justifies the increase of the tangential cutting forces.

4.2 G Ratio

As stated before, the G Ratio is defined by the quotient between the volume of material removed (Z_w) and the corresponding volume of grinding wheel used (Z_s). The volume of material removed (Z_w) was set at 12000 mm^3, corresponding to the height of material removed from workpiece, times the length times the width. The volume of worn grinding wheel is given according to Eq. 1:

$$Z_s = \frac{\pi}{4}\left((355)^2 - (355 - D)^2\right)5 \quad (1)$$

In this respect, 355 is the wheel diameter, in mm, 5 is the width of the workpiece, in mm, and D is the wear of the wheel, also in mm. The former was obtained through the wear profiles of the thinner workpieces, and subsequent manipulation by Talymap.

Then it was possible to generate the column graphs (Fig. 4) which relates the G ratio to the equivalent cutting thicknesses (in µm) used on the tests.

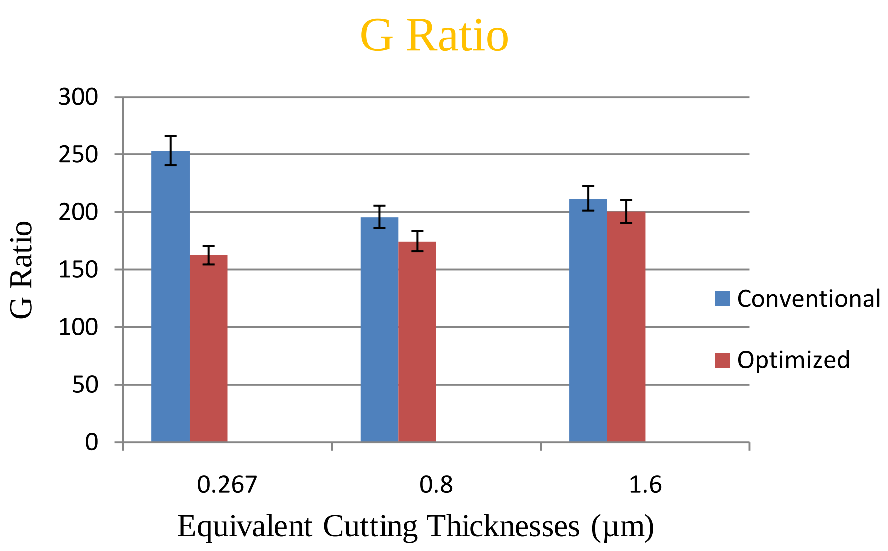

Figure 4. Values of G Ratio obtained.

At first, analyzing generally the variable in question, for the same material volume removed, it can be concluded that a high value of G ratio indicates a wheel of high cutting capacity, capable of removing this volume with lower tool wear. On the other hand, a low value of G ratio indicates a wheel which suffers more wear when removing the same volume of material.

Di Ilio and Paoletti (1999) studied composite grinding, and observed that the main cause of wheel wear is the obstruction of its pores by the fine composite matrix.

The values obtained in G ratio for the optimized and conventional lubri-cooling methods can be considered high. That happens probably due to the chip removal from the cutting zone, which makes the grain fracture predominant over the whole grain removal (self-sharpening). Thus, the wheel is less worn, which provides higher values for the G ratio.

Besides that, the values for the G ratio were kept close for both methods, considering the values for the equivalent cutting thickness of 0.8 µm and 1.6 µm, with better results when using the conventional cooling. For the equivalent cutting thickness of 0.267 µm, it was obtained the best value for the conventional cooling, and the worst for optimized cooling. That occurs due to the conventional cooling applies an abundant flow on the workpiece, which provides lower stresses, and, consequently, less tool wear.

5. CONCLUSIONS

From the results obtained, using two different cooling methods (conventional and optimized), it can be concluded that, for the surface grinding of carbon fiber reinforced plastic (CFRP) composites:

- For the tangential cutting forces, the best results were obtained for the equivalent cutting thickness of 0.267 µm, and the optimized cooling method showed itself always equal or better than the conventional cooling. Still for this equivalent cutting thickness, it was possible to obtain a reduction of 17% (obtained by the comparison of the numerical result of both methods), when applying the optimized method.
- When observing the values for the G ratio, it can be noticed that the best results were obtained for the equivalent cutting thickness of 0.267 µm, providing an increase of 56% (obtained by the comparison of the numerical result of both methods) on the value of this variable, when using the optimized method.
- Each lubri-cooling method analyzed has its own advantages and disadvantages. The conventional method showed itself more efficient when concerning tool wear, but was incapable of providing lower values in relation to the tangential cutting force. The optimized cooling method, however, provided better results for the tangential cutting force.

- When analyzing the machining outputs provided both methods used on this study, it can be concluded that the conventional cooling method is indicated when aiming for less tool wear. When aiming for lower cutting forces, the optimized method is more suitable.
- The results for conventional and optimized cooling were similar, and, considering that the fluid flow for the optimized can be up to 12,5% in relation to the conventional, that could be a promising alternative to reduce the use of cutting fluids.

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