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COMPARATIVE ANALYSIS OF LUBRICATION AND COOLING OF SOLUBLE CUTTING FLUIDS USING TRIBOLOGICAL METHODS AND MILLING MACHINING OF 7050 - T7451 ALUMINUM ALLOY

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Abstract. *The cutting fluid can be given in liquid, solid or gaseous state. In the metalworking industry, the lubricant solution has the function of facilitating the cutting operation, improving lubrication, cooling, removal of waste and minimization of corrosive actions on the machine tool and the workpiece. Thus, this article will address the lubrication and refrigeration performance of two soluble vegetable-based cutting fluids (type A and type B), at the same concentration, by means of tribological tests (Reichert and Pin-on-Disk tests) and machining test using HSM milling. The experiment was divided into two stages: the first consisted of bench tests (tribological evaluation) and aimed to verify the efficiency of lubricity, detergency, coefficient of friction, suspended solids and types of wear. On the second, the machining experiments were conducted in a five-axes machine tool, in order to verify the efficiency of material removal for different combinations of cutting parameters, and thus verify whether the results obtained in bench tests are repeated in a real situation of production (machine tool). The soluble cutting fluid type A had higher wear in tribological tests (which characterized low lubricity) and shorter tool life when machining. Soluble cutting fluid B showed lower values of coefficient of friction, and consequently less wear on bench tests (tribological experiments) and higher performance in material removal during machining experiments (traditional test of cutting tool life). According to the results obtained, it can be seen that in general the soluble cutting fluid type B presented better performance. Finally it was found that, for both of the fluids assessed, the machining results were consistent with the results obtained in the bench experiments.*

Keywords: cutting fluid, lubrication, tribological test, machining

1. INTRODUCTION

In the metalworking industry, supplying the constant need for quality lubricating oil is increasingly difficult, since not all fluids present lubrication and cooling efficiency. In 2004 about 39 million tons of lubricants were used in the world, of which 12 million tons were destined for the industrial sector (Mang and Dresel, 2007; Silva *et al.*, 2006). The emulsifiable cutting fluid when sprinkled on the workpiece has the function of cooling, lubrication, protection against oxidation and removal of material, and depending on its chemical composition it can affect the surface finish of the machined material (Alves *et al.*, 2006). To evaluate the choice of a good emulsion, it is necessary to evaluate other properties such as detergency, coefficient of friction, wear area, quantity of suspended solids, track width, tool wear and chip form, properties which can compromise product performance, thus improving the performance of machining processes (Gonçalves, 2013).

Tribology brings together the knowledge acquired in Physics, Chemistry, Mechanics and Materials Science to explain and predict the behavior of physical systems applied in mechanical systems. Tribological studies are considered bench tests, because they allow to evaluate the context on a small scale (Sinatora, 2005; Diniz et al. 2000). New research groups have emerged to develop the study of the problems mentioned above. So were sought other possible improvements to the current processes of production required to replace traditional methods, so that one can obtain manufacturing conditions associated with lower environmental impact and which are technically and economically coherent (Sokovic et al., 2001). Therefore, this article was divided into two stages: the first stage with bench tests (Pin-on-Disk and Reichert Test) and the second stage with the tests on the machine tool.

Aiming to use smaller volumes of lubricating oils and not cause a halt in productivity, the article has the objective of studying the feasibility of using tribological tests as a pre-test before the application of machine tool use in the machining process.

2. METHODS

For the development of the research, the tests were conducted at the facilities of the Competence Centre in Manufacturing (CCM), a laboratory of the Aeronautics Institute of Technology (ITA). The study consisted in comparing the lubrication and cooling performance of two distinct vegetable-based emulsions. For this purpose, two kinds of tests were performed: tribological tests (Pin-on-Disk and Reichert Test), which are bench tests and require small volumes of emulsion; and machining tests, which require larger amounts of cutting fluid. The methodology of this process is presented in Figure 1.

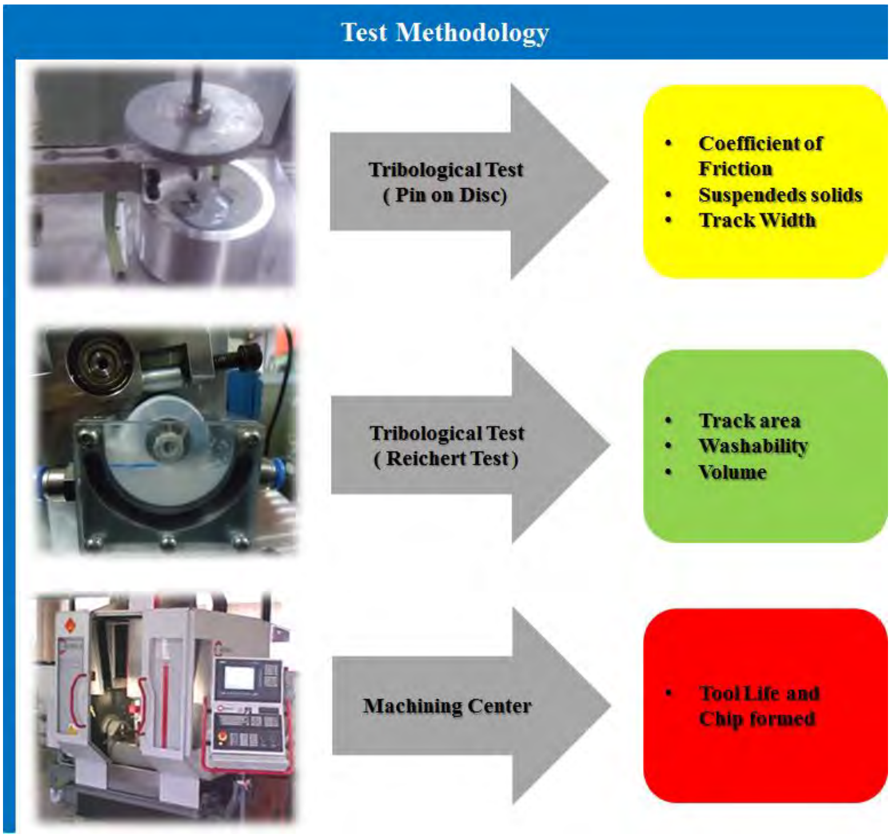

Figure 1. Flowchart of the test.

2.1 Cutting fluid

Two kinds of vegetable-based cutting fluid, Canola and Jatropha, A and B respectively, were used for tribology and machining analyses. The cutting fluids studied were prepared at a concentration of 8%, comprising approximately 95% water and 5% oil.

2.2 Tribology

2.2.1 Pin-on-Disk

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In the first phase of the research, Pin-on-Disk tests were performed by utilizing an equipment developed at the Competence Center in Manufacturing (CCM/ITA), shown in Figure 2. The test involves rubbing a sphere of silicon nitride on the specimen of aluminum alloy, making the friction between the two surfaces to cause wear on the test specimen. The tests were standardized with fixed weights on the load cell and about 120 mL of cutting fluid in the tank, allowing the study of the coefficient of friction. To ensure the standardization of the tests, the following variables were fixed: load (541.10 kg), speed (0.30 m/s), rotation (180.74 rpm), sphere radius (4 mm) and distance (1000 m), totaling 30,123.96 laps.

Figure 2. Apparatus used in the test.

2.2.1.1 Preparation of Test Specimens

The preparation of test specimens of aluminum alloy consisted of sanding using a polishing machine (Figure 3.a) with sandpaper of grain sizes 100, 220, 300, 500 and 600. After sanding, test specimens were verified using a profilometer (Figure 3.b), in order to ensure that the surface has an average roughness (Ra) of up to 0.8 µm, according to ASTM standard G 99-04. After verification of roughness, test specimens are able to be attached to the tribometer for friction testing.

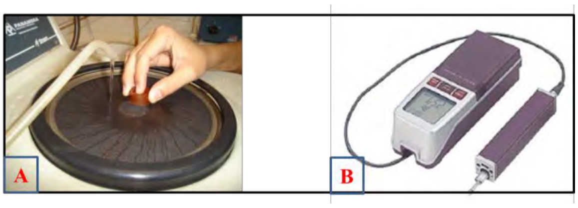

Figure 3. a) Polishing machine used for sanding of test specimens and b) Surface Roughness Tester used in the test.

2.2.1.2 Suspended solids

After completion of the tribological test (Pin-on-Disk), the samples of cutting fluid emulsions A and B were stored for the quantification study of the mass of suspended solids. For this purpose, two filter papers were placed in the laboratory oven (Figure 4.a) at 50 °C for 30 minutes in order to ensure the mass measurement without humidity. After weighing the filter papers (Figure 4.b), they were used for filtering the cutting fluid samples A and B used in the Pin-on-Disk tests. Then the filters with the suspended solids were placed back in the oven for a period of 3 hours to ensure the evaporation of the cutting fluid, thus enabling the weighing of the filter with the particulate material. Based on the methodology of Souza *et al*. (2012), the presence of suspended solids was calculated.

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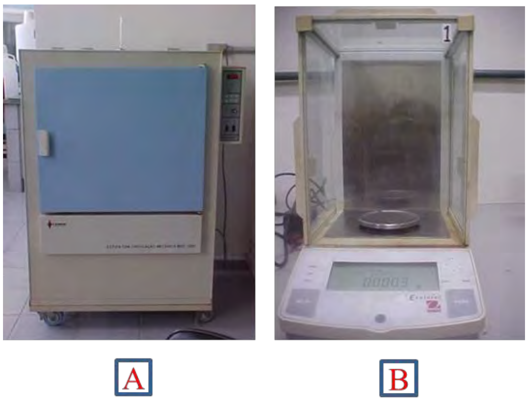

Figure 4. a) laboratory oven model 320E and b) precision analytical balance brand OHAUS.

2.2.2 Reichert test

The study consists of rubbing a cemented carbide cylindrical rotary track over an aluminum alloy pin, so that about one-third of the track is immersed in the studied solution. The equipment must be connected 30 minutes before the start of the tests for stabilization. In order to ensure the stabilization of the rotational speed of the tribometer, the machine is turned on 30 seconds before the start of the friction between the pin and the disk. Then, the test specimen is lowered, the friction occurring over a period of one minute. After the tests, it is examined whether the worn surface is dirty or not, which is intended to evaluate the detergency capability of the oil. Subsequently the elliptical worn area of the pin is measured to study the lubricity. The smaller the area, the better the lubricity of the oil, since it is able to form a thicker protective surface between tool and workpiece. The dirtier the test specimen is, the worse the detergency power of the oil will be.

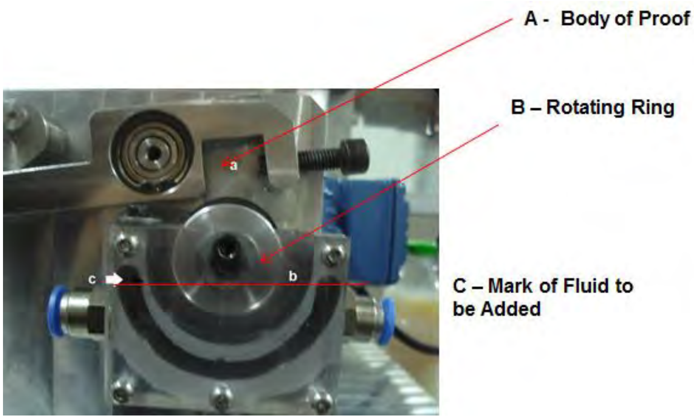

Figure 5. Reichert Test Tribometer.

2.3 Machine Tool

2.3.1 Machining Center

Scientific experiments were conducted in the HERMLE C600U machining center at high speeds, Figure 6. The machine tool has a maximum speed of 16,000 rpm and power of 15 kW, with a rotating and tilting table, featuring five motion axes: three translational performed by the head and two rotational performed by the table. Its base is made of synthetic granite and its positioning accuracy is 4 µm. In addition, the machine tool has a cooling system for adduction outside the tool using either compressed air or cutting fluid, with a 200 L tank, air extractor, magazine with a capacity of thirty tools, laser measuring system (preset) of length and diameter of tools, and probe with ruby tip to reference the workpiece in the machine workspace. The coupling of the tool to the spindle is of type HSK 63.

To evaluate the performance of the vegetable base cutting fluids A and B, three combinations of cutting parameters for milling tests of aluminum alloy 7050 T7451 were analyzed, Table 1.

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Centro de Usinagem 5-eixos Hermle C 600 U

	Fuso	
Velocidade	20 rpm	16000
Potência	15 kW	a partir de
Torque	Até 1100 rpm 130 Nm	16000 9 N
	Eixos	
Força de avanço	6000N	
Avanço máximo	35 m/min	
	Curso Máximo de Deslocamento das Guia	
X	**Y**	**Z**
600 mm	450 mm	450 r
	Limites de Rotação e Velocidades dos Eixos A	
A		**C**
-110°	+110°	360° (ser
10 rpm		15 rp
	Mesa Giratória (Eixo C)	
Capacidades	280 mm	200

Figure 6. Machine tool used in the test.

Table 1. Cutting parameters for milling tests.

Cutting parameters	Cutting speed (m/min)	Depth of cut (mm)	Advance (mm/rot)
Condition 1	1884	2.88	0.05
Condition 2	1884	2.88	0.15
Condition 3	1884	2.88	0.30

2.3.1.1 Workpiece and cutting tool

The workpiece used in the milling process was aluminum alloy 7050 T7451, employed in the aviation industry, whose dimensions are 200x90x120mm. The cutting tool used was the cemented carbide cutting tool LNAR1106 – PN – N – P, square end, 50 mm in diameter and 4 teeth.

2.3.1.2 Surface Roughness Measurement

The same profilometer (Figure 3b) SJ-201P Model was used for measuring the surface quality of the workpieces machined with cutting parameters stated on Table 1. The values of average roughness (Ra) obtained were analyzed according to the values stipulated by the aviation industry.

2.4 Chromatic Aberration Confocal Microscopy

In order to acquire images of the test specimen from Reicher test, a chromatic aberration confocal microscope brand Cyber CT100 was utilized, Figure 7.

This device provides bi- and three-dimensional analyses of surfaces (2D and 3D parameters), such as:

- Profile projection (2D) – roughness analysis;
- Spatial (3D) – analysis of volume of material removed.

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Figure 7. Chromatic aberration confocal microscope

3. RESULTS

3.1 Measuring roughness on Pin-on-Disk test

In Figure 8, one can observe how the measurement of surface roughness of test specimens was performed prior to Pin-on-Disk tests, and Table 2 shows the values of average roughness (Ra).

Figure 8. Roughness measurement on Pin-on-Disk test.

Table 2. Surface roughness values.

Fluid	Ra (µm)
A	0.18
	0.22
	0.17
B	0.17
	0.14
	0.15

Considering ASTM G 99-04 standard and surface roughness values measured, it was observed that the average roughness (Ra) of test specimens A (0.19 µm) and B (0.15 µm) are within the amount stipulated, less than 0.8 µm.

3.2 Coefficient of friction

Figure 9 contains graphs of the coefficient of friction for Pin-on-Disk tribological tests of vegetable fluids A and B.

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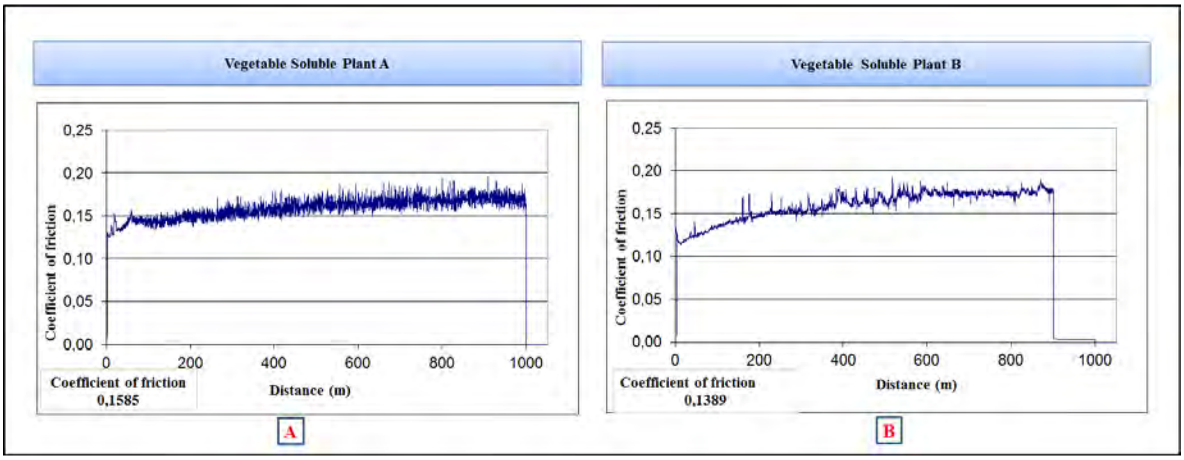


Figure 9. Coefficient of friction along the 1000 m distance of fluids (A) and (B).

It was observed that both cutting fluids tested did not show a steady state in the coefficient of friction, however the cutting fluid A had a better performance when compared with the fluid B. The oscillations and instability can be due to the presence of suspended solids in the fluid, whereas the larger the presence of suspended solids in the lubricant fluid, the higher its average coefficient of friction resulting in greater wear.

Table 3 presents the data obtained on Pin-on-Disk about mass differences of suspended solids present in the emulsions A and B.

Table 3. Mass differences of suspended solids.

Cutting fluid	Mass of suspended solids at the beginning of the test (g)	Mass of suspended solids at the end of the test (g)	Mass Differences (g)
A	0.4936	0.5738	0.0820
B	0.5074	0.5554	0.0480

Cutting fluid B had a smaller mass, indicating a smaller amount of suspended solids in its emulsion.

3.3 Track width

The images obtained with chromatic aberration confocal microscope, Figure 10, clearly show the difference of wear between the fluids A and B.

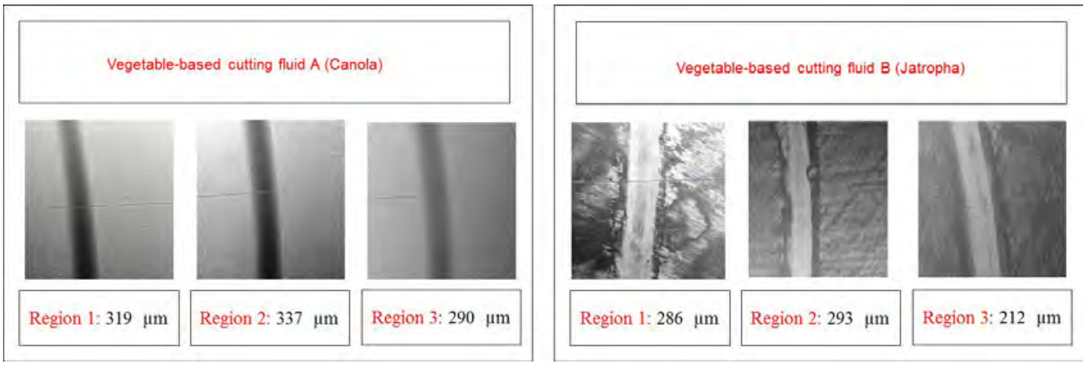
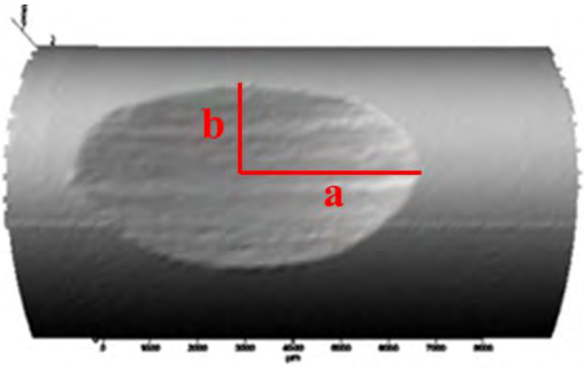


Figure 10. Track width calculated using chromatic aberration confocal microscope.

It was noted a correlation of the worn track width with the amount of suspended solid on the cutting fluids. The vegetable-based cutting fluid A presented a greater track width and a greater amount of suspended solids whilst the vegetable-based cutting fluid B resulted in smaller worn track width and fewer suspended solids.

3.4 Lubricity, Detergency and Wear Area

Figure 11 shows the equation and the dimensions used for calculating the wear area. Table 4 contains the analysis performed in the Reichert Test.



$$A = \pi ab$$

A = Area of the ellipse;
a = Larger radius;
b = smaller radius.

Figure 11. Dimensions of wear and the equation for calculating the elliptical wear area.

Table 4. Analyses carried out in Reichert Test

Cutting Fluid	Sample (beginning and end)	Calculation of Track Area	Summary
Vegetable Base Canola – A			Larger diameter (2a) = 3.513 mm Smaller diameter (2b) = 1.982 mm Wear area = 5.466 mm ^{2} Detergency = Bad
Vegetable Base Jatropha - B			Larger diameter (2a) = 2.638 mm Smaller diameter (2b) = 1.695 mm Wear area = 3.510 mm ^{2} Detergency = Good

During visual analysis performed to compare the detergency ability of oils A and B, it can be noted that cutting fluid A did not show good detergency ability when compared to cutting fluid B. Vegetable-based cutting fluid B presented a worn area 36% smaller than the vegetable-based cutting fluid A, indicating a higher efficiency in lubricating power.

3.5 Tool Life

For the roughing test results, three different feed rates (f_n) were performed for constant cutting speed (v_c) and depth of cut (a_p). The sessions of wear measurement were based on the end of life criterion of VB = 0.2 mm for all cutting parameters. Figures 12, 13 and 14 present the results in cutting conditions 1, 2 and 3.

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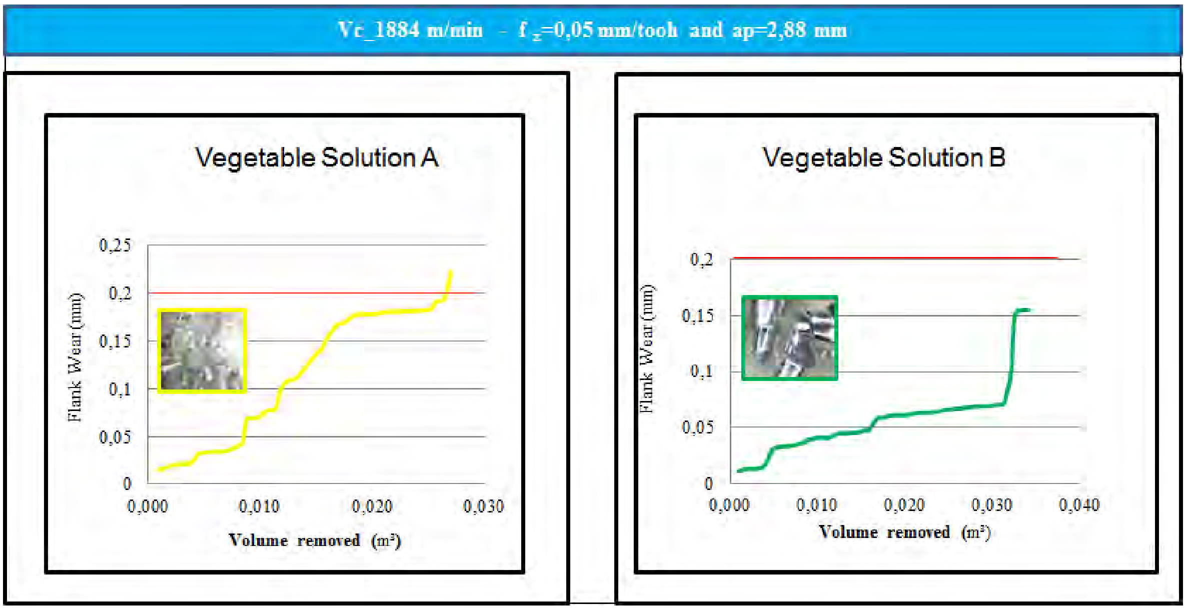

Figure 12. Graphs of flank wear on condition 1.

It was observed in the graphs of the condition 1 (Figure 12) that the volume removed of aerospace aluminum for vegetable base cutting fluid B was superior compared to vegetable base cutting fluid A, with higher refrigeration and lubrication capacity, when applied to lower feed rates in milling process.

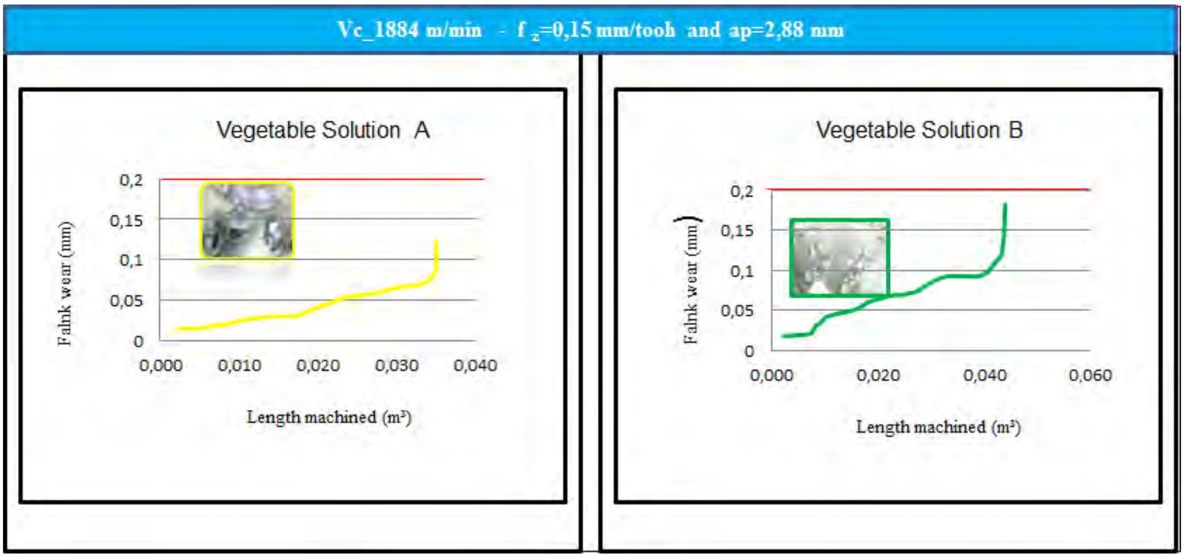

Figure 13. Graphs of flank wear on condition 2.

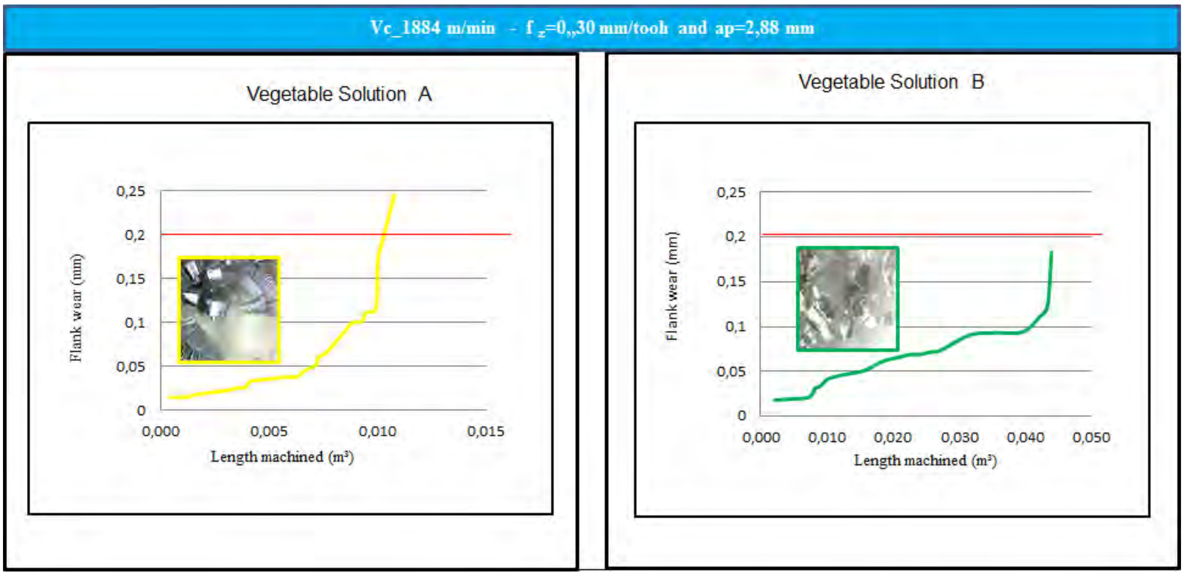

Figure 14. Graphs of flank wear on condition 3.

On conditions 2 and 3, with feed rates (fn) of 0.15 mm/rot e 0.30 mm/rot, respectively, greater lubricating power was demanded due to the facility of material adhesion on the cutting edge of the cutting tool. On condition 2, vegetable-based cutting fluid B showed larger volume of aluminum removed (m³) when compared the flank wear. It was also noted that on condition 3, the vegetable-based cutting fluid B performed better in terms of aluminum removed (m³). This may be due to the low lubricity of vegetable-based cutting fluid A, resulting in premature wear of the cutting tool.

It was observed in the milling tests of aluminum alloy that vegetable base cutting fluid B obtained better results of volume of aluminum removed (m³) when analyzed flank wear of the cutting tool.

In accordance with ISO 3658, it may be noted that the chips were short conical helical shape. According to Schroeter *et al*. (2002), this type of chip is considered "good".

4. CONCLUSION

With the results obtained in the comparison of vegetable-based cutting fluids, it was possible to show with this experiment the efficiency of the results of tribological pre-tests (Pin-on-Disk and Reichert test) applied to milling tests of aluminum alloy, reaching the following conclusions.

4.1 Pre-Test

- Pin-on-Disk

  - Coefficient of friction and Suspended Solids: The results obtained indicated that the cutting fluid B showed a lower coefficient of friction compared to cutting fluid A, this fact can be explained by the smaller amount of suspended solids found in the sample during testing and by presenting good lubricity;

  - Track Width: The results found showed that the vegetable-based cutting fluid B led to a wear track with smaller width, demonstrating its greater lubricant capacity compared to cutting fluid A. It was also noted that the cutting fluid with better performance presented less amount of suspended solids.

- Reichert Test

  - Wear area: Vegetable base cutting fluid B had higher lubricant capacity. This can be shown in its smaller wear area size compared to cutting fluid A.

  - Detergency: Following visual analysis, it can be concluded that vegetable base cutting fluid B showed better detergency result compared with vegetable base cutting fluid A.

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It was noted in the evaluation of the Reichert Test that the Jatropha oil B had better results compared with Canola oil A.

- Machine Tool

Tool life:

- Condition 1: For presenting a low feed rate to the process of aerospace aluminum (fz = 0.05 mm/tooth), the cutting tool keeps contact longer with the piece generating more heat, and this heat causes the need for greater cooling power of the emulsion. Between vegetable base fluids A and B, the one which presented the best efficacy in cooling power was vegetable-based cutting fluid B (Jatropha), which obtained better efficiency reducing the wear of the cutting tool. The chips from lubricants A and B showed no abnormality.

- Condition 2: The results achieved on condition 2 show that vegetable base fluid B performed larger volume removed totaling 0.042 m^3 compared to vegetable base fluid A that achieved a total of 0.033 m^3, leading to the conclusion that the greatest cooling and lubrication power is presented by cutting fluid B.

- Condition 3: The tool life test result shows that cutting fluid B had smaller flank wear compared to cutting fluid A, demonstrating its good lubricity when subject to greater feed rates. As for cutting fluid A, the results of condition 3 indicate that more lubrication is required when subject to greater feed rates.

With this study, it can be remarked the feasibility of using tribological experiments as alternative tests before the application of cutting fluids for testing on machine tools, observing that Jatropha-based cutting fluid B achieved better results both in tribological and machining tests.

5. ACKNOWLEDGEMENTS

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