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A STUDY ABOUT THE EFFECTS OF EMULSIFIABLE OIL CONCENTRATION OVER THE ROUGHNESS IN ALUMINUM AL-SI (10 ~ 12%) PARTS

Gustavo Henrique Nazareno Fernandes
Mariana Gomes
Pedro Rodrigues Lopes
Adelti Assis Silva
Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte, Minas Gerais. CEP 31270-901
ghnfernandes@gmail.com; mariana.ufmg@hotmail.com; pedrorodrigueslopes@gmail.com; adelti.silva@external.fcagroup.com.

Paulo Sérgio Martins
Luís Henrique Andrade Maia
Ítalo Bruno dos Santos
Pontifícia Universidade Católica de Minas Gerais. Av. Dom José Gaspar 500, campus Coração Eucarístico. Belo Horizonte, Minas Gerais. CEP 30.535-901
paulosergio.martins@fcagroup.com; luismaia@pucminas.br; italobsantos@gmail.com;

Breno Santos de Siqueira
Universidade Federal de São João del Rei, Praça Frei Orlando, 170, Centro, São João del-Rei, Minas Gerais, CEP: 36307-352
breno.siqueira@emuge-franken.com.br

Abstract. In order to make a critical study about the way to use a commercial cutting fluid in an industrial operation already established, it was evaluated how the level of emulsifiable semisynthetic oil concentration from mineral origin, varying between 4 and 8%, influences the final work piece roughness. It was analyzed a total of fifty gearboxes made of aluminum alloy, Ai-Si (10 ~ 12%). It was measured the surface roughness behavior in relation to Arithmetic Average Deviation parameters - Ra and Maximum Height Profile - RZ. The parts were machined in a milling operation using PCD (Polycrystalline Diamond) cutter, Ø = 80mm in a CNC machining - Computer Numeric Control. The results were shown in various Roughness X Concentration graphs, showing a different roughness behavior from that expected. Thus, new Roughness tests on well-established concentration levels (5,6,7 and 8%) in total of twenty-four pieces, were made again intending to confront this unexpected phenomenon.

Keywords: machining, cutting fluid, roughness, concentration, milling.

1. INTRODUCTION

Machining operations generally involve a wide range of variables. The usage of cutting fluids is one of them. They influence not only the produced parts quality, but also the machine and tools. The fluids help bearings lubrication and also avoid waste deposition between machine rolling parts, thus avoiding its premature wear. Other than that, it is also an important factor in relation to surface integrity of the produced piece.

Each machining operation, due to its specificity, need to be treated carefully and requires a technical-economic analysis that not only justifies the use of fluids, as well as the best way to use them, because they can entail costs to manufacturing process and can even be harmful to final products quality. The costs associated with the use of these materials typically range from 7 to 17% of the total production costs when compared, for example, with 4% of tool costs (KING et al., 2001). So, before proceeding to do operations, it is strong recommended to be made a study to assess the best way to use a cutting fluid and ensure that it is having a good performance. However, inside the industrial scenario, where it is difficult to have neither enough time and resources to do this study, technical managers often have to use cutting fluids in their conventional manner, usually that one specified by the supplier, but that is not always the most appropriated way for a particular operation.

Costs reduction for industry is of great importance because in a globalized scenario where there is a high level of competitiveness, processes production optimization is crucial for the company survival, especially for the automotive

industry, that is the case of this work. Other than that, there are still environmental and economic developments imposed by the government that have being led to changes in the way that cars are being designed. There are environmental laws increasingly stringent requiring from manufacturers the reducing in the emission of pollutant gases, such as those that cause greenhouse effects, it is also required an increasing energy efficiency of the vehicle. Improving the overall quality of the machining process can decisively contribute to these requirements.

In addition to the machining process, the materials chose can also contribute efficiency improvement. For instance, Aluminum alloys, such as those with silicon (Si), play an increasingly important role within the automotive industry as excellent substitutes for ferrous metals, due mainly to the low specific weight and its good mechanical properties. Out of these factors, addition of aluminum silicon decreases its melting point, improves the wear resistance (MARTINS *et. al., 2015*), and require less effort of the machine tool assembly mainly due to the good thermal conductivity of the Al-Si alloy (MARTINS *et. al., 2016*). Another factor favoring the aluminum usage is its machinability by the fact that it has lower shear strength compared to cast iron, for example.

The economic and environmental advantages of using engine blocks made of aluminum alloy in replace to cast iron can be achieved at 50,000 km of vehicle life. After this point, savings generated by weight reduction associated with lower fuel consumption offset the environmental impact and higher costs to extract aluminum (BONOLLO *et al.,* 2013).

Cutting fluids are generally used in aluminum machining operations. They must be applied at a way that makes possible for them to have a maximum performance in terms of lubrication and cooling. It implies that application direction must be given so that the fluid can get as closest as possible to the cutting edge (MACHADO *et. al.,* 2009*)*.

Emulsions used as cutting fluids are mixtures of water and oil. This oil can be synthetic or semisynthetic, originated from mineral, plant or even animal sources. Other important additives are also added in the oil to prevent bacteria and fungi propagation, foam, oxidation, among others. Cutting fluids are extremely important because they can provide not only quality gains as well as economic gains in many kinds of cutting conditions such as in the external cylindrical turning of the stainless steel 304L (De MAGALHÃES, 2013).

There is a direct relationship between cutting fluid and roughness of the finished part. Abram et. Al. (2001) made a study about the effects of cutting fluids when machining hardened steel 4340. One of the conclusions were as follows: *"In the finishing operation at high speeds, the use of cutting fluids is responsible for reducing the variation of surface roughness values. "* (ABRAO, AVILA, 2011).

Oil concentration in the mixture is an important factor since oil plays a major lubricity function without which the machining parameters are greatly changed since it affects the sliding interface between chip tool, responsible for a considerable part of the energy losses during the process due to the friction between surfaces, as well as the operations near the cutting edge, which mainly changes the work piece surface finish.

Then, the main objective of this work is to study the roughness behavior, R_a and R_z, of two gearbox surface plans, using a PCD tool, in relation to the variation of emulsifiable oil concentration in a mixture with fresh water.

2. METHODOLOGY

2.1 Matherials and Equipaments

It was used a CNC - Computerized Numerical Control machining, Grob brand, BZ500T-105A model, $\emptyset=80mm$ PCD soldier tool. It was also used: one rugosimeter, brand Hommewerke, Waveliit 400 model, 235531 ID, a digital refractometer Atago brand, Pocket PAL-1 model, 1-425-637-2107 ID and a benchtop refractometer brand Atago, ID 80017 (see Fig. 1).
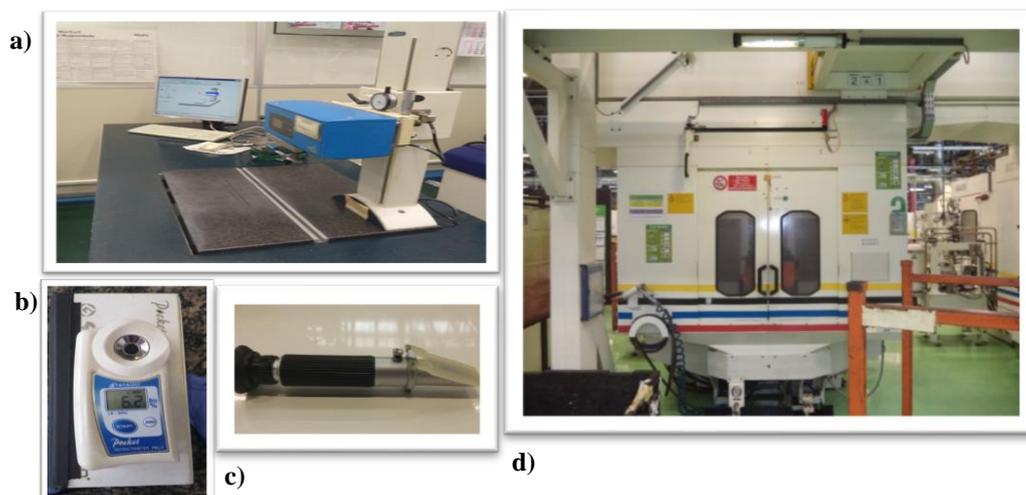

Figure 1. **a)** Rugosimeter Hommewerke, Waveliit 400 model; **b)** Digital refractometer Atago Pocket PAL-1;
c) Benchtop refractometer brand Atago; **d)** CNC, Grob brand, BZ500T-105A Model

2.2   Operational procedures

2.2.1 Tests methodology

Intending to study surface roughness variations due to changes in the amount of emulsifiable oil concentration, two steps were adopted, as follows:

Step I: The oil level concentration in the emulsion was not adjusted, that is, as the machine was operating the measurement was performed using first a benchtop refractometer (Atago), and then the digital refractometer (Atago Pocket PAL-1) (see Fig. 1), thereby, **concentration continuously varied** ranged from 4 to 8%. **50 pieces** were used for measurement in **step I**;

Step II: in order to compare the results obtained in the previous step I and verify the obtained results validity, before taking the surface roughness measurement, a discrete concentration level of 5, 6, 7, and 8% was established and only after the emulsion stabilization in these conditions, the R_a and R_z were performed, six roughness measures were made for each concentration in six different pieces. **24 pieces** were used for measurement in **step II**.

Oil concentration varies continuously during manufacturing process. Thus, to relate the R_a and R_z roughness with the concentration of cutting fluid, the following criteria were adopted:

1. **Emulsion oil level concentration (benchtop refractometer);** initially it was measured the emulsion oil level concentration using a benchtop refractometer (see Fig. 1). In this case, the emulsion was always taken from the fluid reservoir surface;
2. **Machining operation (GROB BZ500T-105A)**; following programming source code, milling operation was performed in the two pieces plans (see Fig. 6 and 7);
3. **Roughness measurement;** Both roughness parameters, R_a (Arithmetic Mean Deviation) and R_z (Maximum Profile Height), were measured in order to see the surface roughness variation in relation to oil level concentration. Measures were made at a specific metrology laboratory (see Fig. 1);

2.2.2 Emulsion preparation procedures

Emulsion is composed by fresh water with commercial oil. This oil is composed by naphthenic mineral oil based product severely hydro treated, boric amide, fatty acids, tertiary alkanolamine, bactericide, fungicide, synthetic sulfonate and antifoam (organ modified siloxanes) (FUCHS, 2007). The total CNC machine tank capacity for cutting fluid, counting with pumps and pipelines was estimated to be approximately to 1200l, 800l being related to the storage capacity of the tank.

The oil concentrations controlled was performed in two ways. In s**tep I**, oil concentration varies continuously between 4 and 8%. Water or oil was added inside tank when concentration was out of parameters. Three times per day oil concentration was measured. In **step II,** oil level concentration was measured and adjusted for specified values, 5, 6, 7 and 8%. The collected sample was forwarded to specific laboratory and the following procedures were adopted to adjust concentration:

1. Refractometer was calibrated with distilled water, concentration 0% [v / v];
2. A small amount of the emulsified fluid was poured into the refractometer prism avoiding the formation of bubbles;
3. The reading was performed 3 times to increase measurements reliability.

The emulsified fluid concentration can be calculated by the following equation (1):

$$Concetration\ [\%] = C_m\ xF_c \tag{1}$$

Where: $Concentration[\%]$: Oil level concentration;
C_m: refractometer oil level concentration measured;
F_c: Specific oil correction level.

So, the amount of oil/water added in the tank was calculated by the following equation (2):

$$Q_{ad} = \frac{(C_d - C_a)xQ_R}{100} \tag{2}$$

Where: Q_{ad}: оil/water amount to be added into the emulsion;
$\qquad C_d$: oil concentration desired for the emulsion;
$\qquad C_a$: in fact oil concentration present in emulsion;
$\qquad Q_R$: Emulsion tank machine capacity;

2.2.3 Milling operation

After performing initial stages, such as the measuring of oil level concentration, it was proceeded to the gearbox machining procedure. Pieces (see Fig. 2 to 5) correspond to these gearboxes produced in aluminum, *Ai-Si (10 ~ 12%)*. These parts have flat surfaces called faces. In this study, Fig. 2 and 4 correspond to without machining work pieces, and show faces *F2* and *F3*, respectively. Figures 7 and 9 correspond to machined pieces just after milling procedure and also show the faces *F2* and *F3*. Table 1 contents all the parameters used for milling operation.

Figure 2. *C513* gearbox. Face *F2* (before milling)

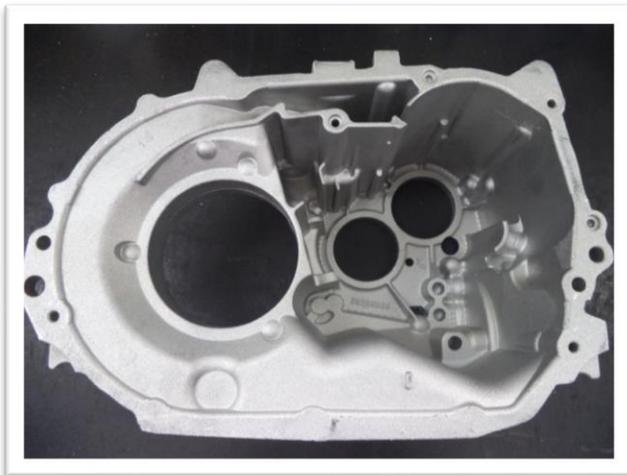Figure 3. *C513* gearbox. Face *F2* (after milling)

Figure 4. *C513* gearbox. Face *F3* (before milling)

Figure 5. *C513* gearbox. Face *F3* (after milling)

Table 1. Milling operation main parameters

Cutting Speed Vc [m/min]	Feed rate f [mm/min]	Rotation [rpm]	Tool diameter Ø [mm]	Machine	Tool	Cuttind fluid
2,512	9,000	10,000	80	CNC, Grob brand, BZ500T-105A Model	PCD, 16 soldier inserts	Fuchs, semi-synthetic, MH-2030, 60 bar, overflood

2.2.4 Roughness measurement procedures

After **steps I** and **step II** being conducted, it could be passed to the next step relating to the roughness measurements. Procedure were performed inside an instrumented laboratory, controlled temperature in ~25°C, always in the same piece point in order to keep the logic of the measurements. Figures 10 and 11 shows a worked piece schematic of plans *F2* and *F3*. Table 2 contents roughness parameters adopted for measurements.
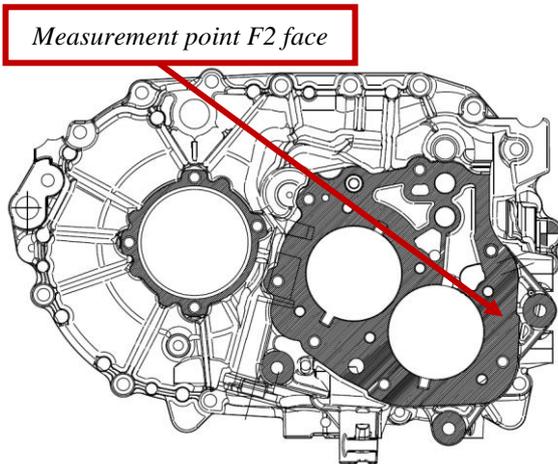

Figure 6. *C513* Schematic drawing Face *F2*
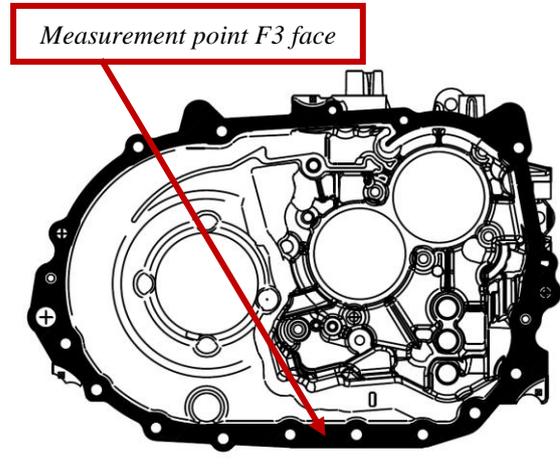
Figure 7. *C513* Schematic drawing Face *F3*

In order to isolate the effects of normal tools wear above the roughness measurement results were separated by tool cycles, i.e., for every tool change in the machine, the results were shown in different graphics intending to avoid interferences. So, there are Tool *Cycle 1*(middle lifetime) and also Tool *Cycle 2* (initial lifetime).

3. RESULTS AND DISCUSSION

3.1 Step I

Following the methodology applied for this job, it has been done the measurement of R_a and R_z of a total of **50 gearboxes** for the **step I**. Data were worked to leave the concentration [v/v] in an increasing order to make possible to visualize the roughness effects. Figures XX to XX shows graphs of Concentration X Roughness.
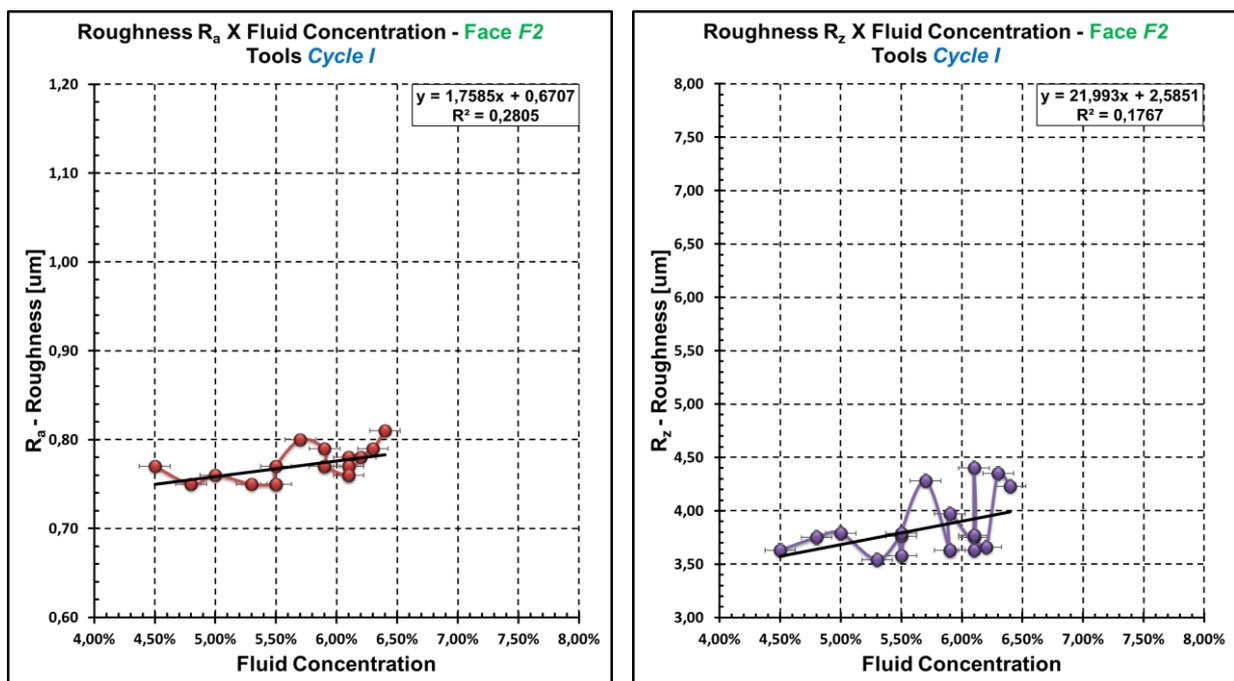

Figure 8. Roughness X Fluid Concentration for Face *F2, Cycle I,* parameters: R_a (left) and R_z (right)
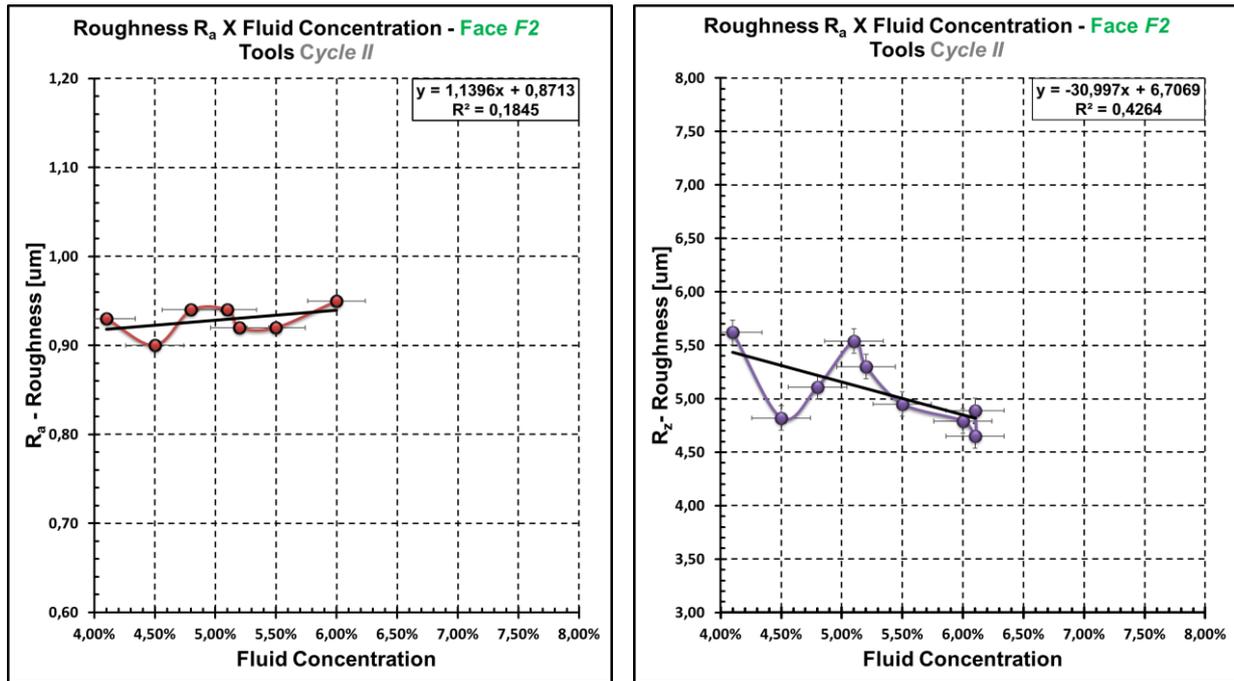
Figure 9. Roughness X Fluid Concentration for Face *F2, Cycle II,* parameters: R_a (left) and R_z (right)

In relation to Face *F2* results had an unexpected behavior, also for the other results as it will be described forward. It was expected that with emulsion oil level concentration rising, the lubricity would also increase, leading to an improvement over surface finish. Figures 8 and 9, exception for R_z in *Cycle II,* roughness behaved inversely, i.e., decreased with emulsifiable oil level decreases. Even data having a considerable dispersion results, the tendency linear line demonstrates the same increasing roughness behavior. An increasement in roughness for Tool *Cycle II* could be observed and this behavior was expected, since that the tool used was new, and had an accommodation period, where roughness have higher values, as explained in tool lifetime curve. Same observations for Face *F2* are valid for Face *F3*. R_a roughness values measured for Faces *F2* and *F3*, Fig. 8 to 11, naturally showed less dispersion in relation to R_z values. This is because R_a is characterized by the arithmetic mean of the roughness measurements, then there will be more measurements and greater reliability.
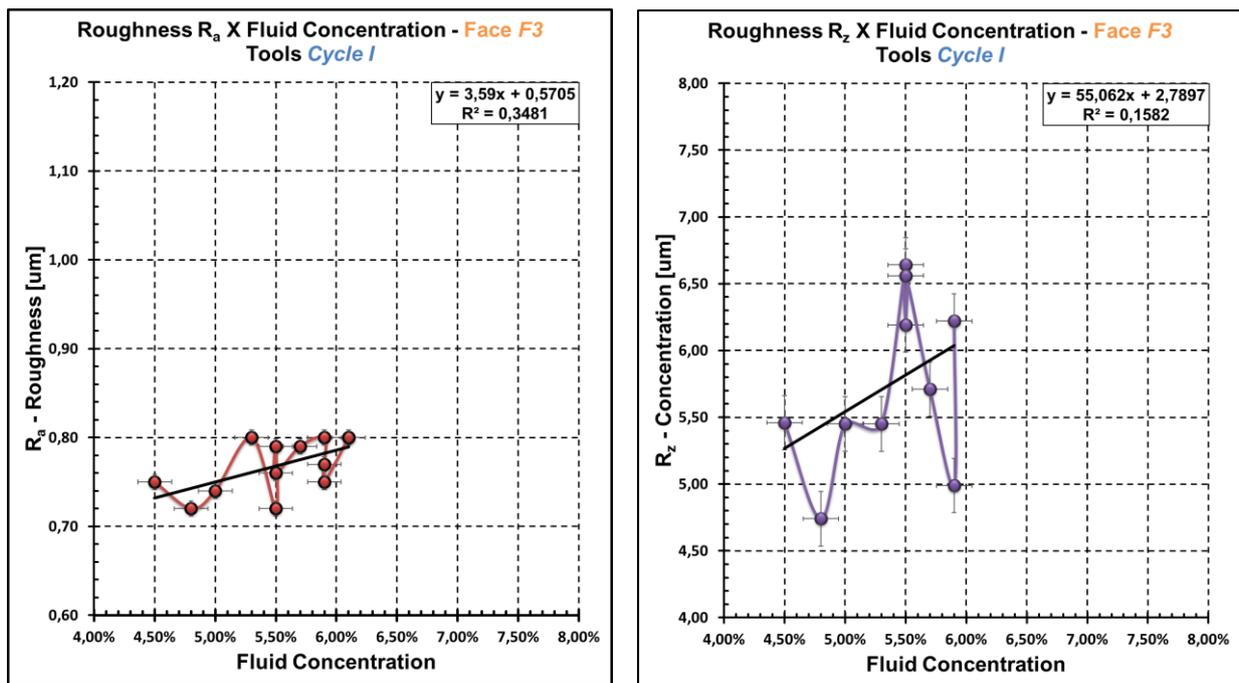

Figure 10. Roughness X Fluid Concentration for Face *F3, Cycle I,* parameters: R_a (left) and R_z (right)
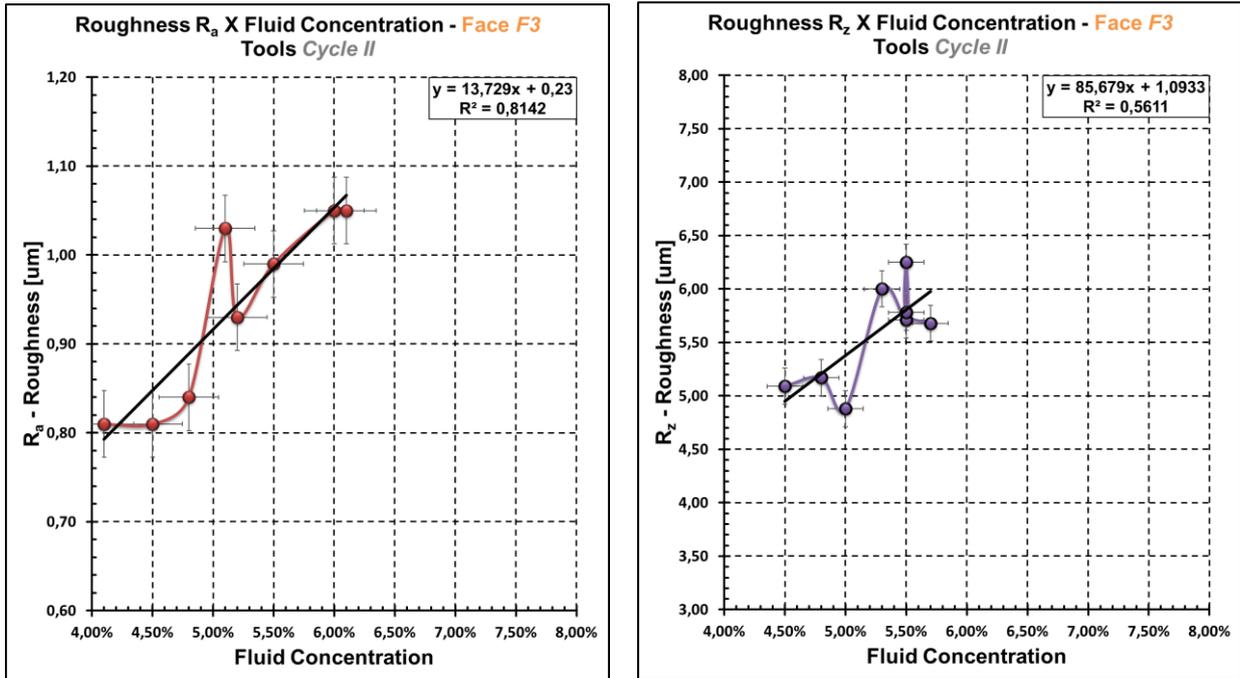
Figure 11. Roughness X Fluid Concentration for Face *F3, Cycle II,* parameters: R_a (left) and R_z (right)

3.2 Step II

In order to compare the phenomena observed in **step I**, wherein the surface roughness increases with the oil concentration, it was performed other Roughness X Concentration tests following **step II** provided by the methodology of this study. For each concentration level six roughness measurements were done and the results were computed in the following graphics (see Fig. 12 and 13).
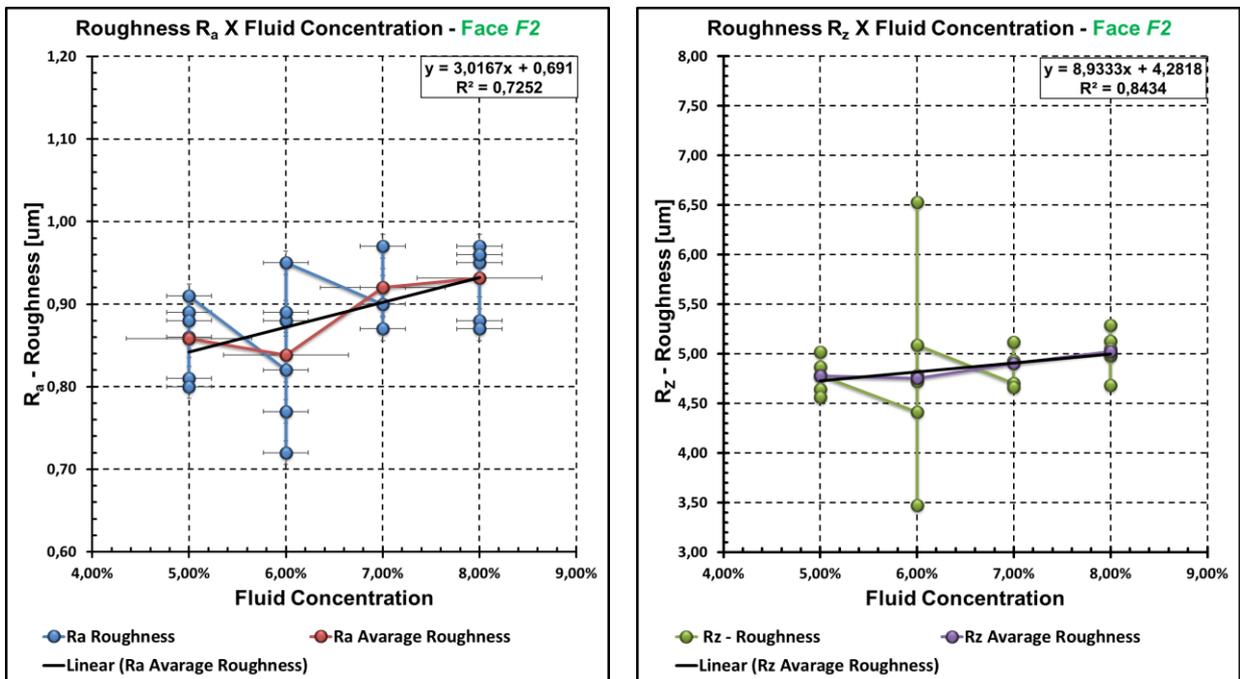

Figure 12. Roughness X Fluid Concentration for Face *F2, Step II,* parameters: R_a (left) and R_z (right)
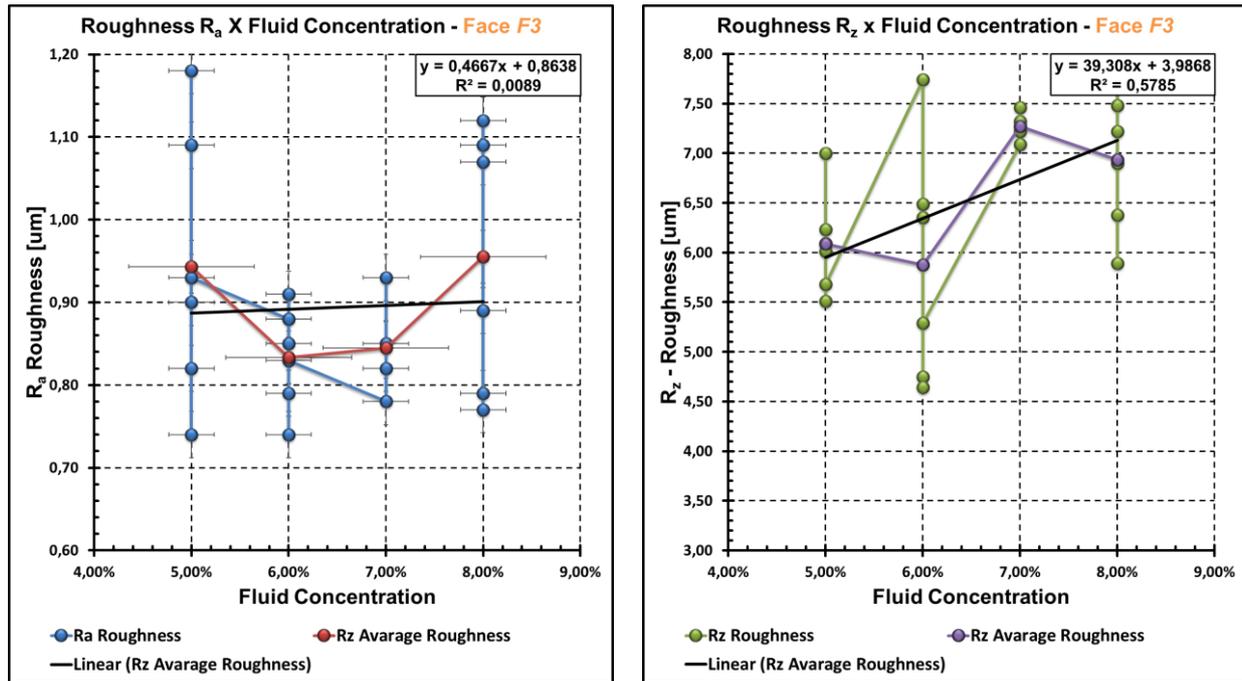
Figure 13. Roughness X Fluid Concentration for Face *F3, Step II,* parameters: R_a (left) and R_z (right)

In general, the results obtained in **step II**, where concentration values were set discretely at 5, 6, 7, and 8% had an upward tendency, as well as those obtained in the **step I**. It was observed that with concentration increasing roughness was increased too for most tests. Some results, as presented to R_a and R_z of face *F2*, showed dispersion values (R^2) fairly priced, of 0.7252 and 0.8434, respectively. However, to face *F3* concise results were not obtained due to low values of R^2.

These results could be interpreted considering that the lubricity oil effect in the emulsion causes several changes over tool-chip interface. Actually, it is responsible for reducing the friction between tool and chip, especially in the sliding zone. Then it was expected that, with oil level decreasing, lubrication would be affected making it more difficult to remove the chips and thereby increasing the roughness of the piece. However, the opposite occurred, which led to a direction to other theories that could explain this behavior.

The cutting fluid access to the chip tool interface is essential for ensure that the use of it is given in the most efficient way possible. Thus, it is desirable to seek fluid acts as close as possible to the cutting edge. This region is characterized by high stresses, strains and temperatures, reaching melting points between tool and material in some cases, so it must have appropriated cooling and lubrication to ensure that the set machining conditions are being attended.

The lubricity effect, that constitutes the fluid ability to form a liquid film able to withstanding the active of shearing forces on the cutting edge of the workpiece, is highly important to reduce the *cut-off* specific pressure (k_s) and improve the surface finish, acting on the roughness of the material.

On the other hand, cooling effects is very important to increase dissipation of heat generated in the process and avoid a large increase in the temperature and a consequent coalescence of the tool and workpiece materials, that could induce to low finish effects. In this case, the emulsion with less oil has higher cooling capacity because of the greater heat conductive coefficient of water relative to the oil, which favors the reduction of the roughness with lower operating temperature.

One specific and essential fluid characteristic is its viscosity. This property means the resistance, that comes from the intermolecular interaction forces, that any fluid has into flowing. Fluids having a high viscosity value tends to flow more slowly, because, being the chemical bonds stronger, they restrict the movement of the fluid. This is the case of hydrocarbon that compounds the cutting fluid mineral oil based used in this work. These compounds have a long molecular chain that forms strong, diffuse and non-linear chemical interactions hindered from sliding one molecule above others, and as a result, it forms a high viscous fluid. When the emulsion has a large amount of oil, it becomes more viscous and increases the difficulty of the fluid to interact with the tool-chip interface and the cutting-edge region. Especially for this work that was based on a milling operation, that is characterized by a high material removal rate due to the high cutting speed (v_c) and feed rate (f), as well as the various tools of cutting edges ($n = 16$).

It is reasonable to infer from the results that the viscosity and thermal conductivity, and not directly the concentration of the oil in the emulsion, are mainly responsible for the variation of the roughness in the fluid. The fact that the fluid with lower concentration has greater flow capacity, makes it has an action of increased capillarity, able to penetrate more efficiently into the tool-chip interface and modify processes involving the formation of chips, passing through adhesion

zones and slipping area of the tool rake surface. Also, a less viscous emulsion, i.e., that a higher amount of water, has a higher thermal conductivity, being able to dissipate heat more efficiently.

4. CONCLUSIONS

For milling operation with parameters and methods used in this work, it is believed that the increased roughness is associated with the concentration increasing due to the intrinsic viscosity. The fact is that, being the fluid less viscous, there is an easier access into the tool-chip interface so that there is a greater lubricity and cooling efficiency. Also the higher coolant capacity of lower concentration cutting-fluid can probably be associated with this phenomena.

Based on the results obtained and considering that cutting fluids represent a significant part of the costs relating to the machining operation, it was observed that the use of this input should be performed on strict criteria, preferably studied in loco in order to have an optimization for costs and/or quality of the process.

Information passed by suppliers takes into account internal studies of these manufacturers, there is a high safety margin for the product to meet a wide range of operations and also work with a security clearance. In this case, a working range of concentrations given should not be the optimum concentration for a particular operation and, where feasible, it is quite advisable to develop internal studies to improve the process avoiding wastes.

5. ACKNOWLEDGEMENTS

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