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SURFACE ROUGHNESS AND MACHINING FORCES WHEN APPLYING MINERAL AND VEGETAL BASED CUTTING FLUIDS IN END MILLING OF ABNT 1045 STEEL

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Abstract. *In end milling process the cutting edge is either in the tangential face as the front face, moreover, the relationship between the diameter and the length of the cutter is large, causing high overhanging of the tool. These factors characterize the low stiffness of these processes, making the chip removal rate small, and causing damages in the surface quality and the cutting forces. To obtain better tolerances and surface finish certain factors must be considered, including the stiffness of the tool, the cutting parameters, the machining forces and cutting fluid. For this reason, the cutting fluids are of fundamental importance in tool wear and quality of the machined surface. Due to high operational costs and legal requirements related to the environment and to human health, researchers have tried to minimize the use of cutting fluids or even eliminate them completely (dry machining). For this reason, among the conciliatory alternatives the use of a less aggressive fluid to the operator and environment and techniques for reducing the amount of fluid, especially the application MQL (Minimum Quantity of Lubricant) are included. This work studies the machining forces and the surface finishing when using different lubri-cooling systems of vegetable and mineral basis. The surface finish was quantified by Ra and Rz parameters and the machining force by the Fx component and torque. HSS-Co end milling cutters, with two sharp edges, coated with TiAlN and uncoated, with 10 mm diameter were used in machining of ABNT 1045 steel plates. In addition to the coating were varied the axial depth of cut, the feed rate, the cutting speed and the lubri-cooling system [dry machining, MQL, Low volume (dripping) and flood cooling]. Analysis of the results obtained through a Factorial Design of Experiments (DOE) with five factors at two levels suggests that the performances of the vegetal and mineral base cutting fluids were similar.*

Keywords: *End milling, Cutting fluids, ABNT 1045 steel, Surface roughness, Machining forces and torque*

1. INTRODUCTION

Currently environmental factors are of fundamental importance in the production process. In machining processes, cutting fluids are a chief polluting product that affects the environment and the worker. Environmental laws and work security are more rigid and require measures to reduce the environmental impact, and risks to the health of the operator. In this sense alternatives to ensure satisfactory ecological, technological and economic results are envisaged.

As a result, two lines of research are revealed quite strong: first, the development of new cutting fluids, environmentally friendly, they do not harm the health of the operator, which last longer in the machine and do not need to be exchanged as often; and second, the development of processes which do not require cutting fluid or the use of smaller amounts (Sales et al., 2001).

In this quest for sustainable machining, minimizing environmental impacts, leading to conservation of natural resources and energy and represent less risk to the operator and economically feasible (Jayal et al., 2010), dry machining emerges as the main alternative. Techniques such as machining with a minimum quantity of fluid and or use of vegetal-based cutting fluids also represent alternatives. The various features of sustainable machining are shown Fig. 1.

Dry machining has been possible because of new technologies, especially the great development of materials, coatings and geometries of the cutting tools that increase its resistance to wear and allow them to cut with elevated temperatures making up for the deficiency and even the lack the lubrication and cooling in the process (Kubel, 1998 and Teeter, 1999).

MQL system can be defined as the spraying of a minimum amount of lubricant in a stream of compressed air (Machado and Diniz, 2000). These small quantities of liquid is sufficient to substantially reduce friction on the tool and to prevent adhesion of the work material, since the tool-chip contact area is very small, which suggests that the flow needed to promote lubrication is also small (Costa et al., 2009).

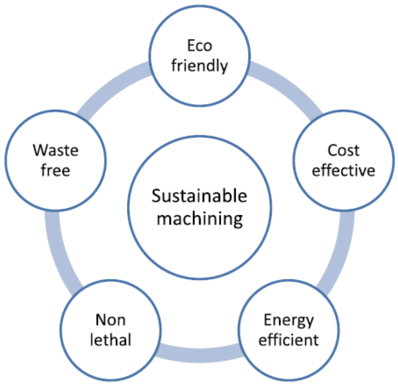

Figure 1. Characteristics of sustainable machining (Chetan et al., 2015)

The vegetable-based cutting fluids have been increasingly used in industry, because besides of polluting less the environment, they cause less harm to the operator and provide satisfactory tool lives. The vegetable-based cutting fluids have polar molecules that function as if they magnets that align at the metal surface, forming a lubricating film that can withstand high tensions, facilitating the machining, and improving the tool life. The molecules of mineral oils are nonpolar, and therefore its lubricating ability is lower than in vegetable oils (Woods, 2005). The main ecological advantage of vegetable oils, unlike mineral base oils, is because their raw material is degradable, which pollute less the environment. They may also be reusable, such as the mineral-based fluids (Kuroda, 2006).

In milling operations, the use of cutting fluids can increase the shear strength of the material, hence the machining forces will increase. However, in general, the use of cutting fluids usually reduces tool wear and friction between tool and workpiece, contributing to improved finish (Machado et al., 2015).

The cutting forces not only influence the deformation of the workpiece, but also the tool deflection and thus the cutting accuracy. The surface finish is influenced by various machining parameters, including: the geometry of the cutting tool, workpiece geometry, machine tool rigidity, workpiece material, cutting conditions and material/coating of the tool. Knowledge of the variables affecting the machining forces and the surface finish is important for the correct design of the process.

This work is justified by its environmental appeal and its main objective is to evaluate the performance of the machining when the flow of cutting fluids are reduced and also the nature of the base fluid is modified (vegetable or mineral). The performance evaluators' parameters are: average roughness Ra and Rz and thrust force Fz and torque Mz. The variables under which was held the comparison were the lubrication and coolant system (dry machining, MQL, overhead flood cooling with mineral and vegetable based cutting fluids), the cutting speed, the feed rate, the axial depth of cut and the coating of the tool.

2. EXPERIMENTAL PROCEDURE

The tests consisted of machining channels in steel bars with HSS endmills with and without TiN coating. Besides the tool coating, the following input parameters were varied: lubri-cooling systems (dry machining, MQL, and flood cooling), cutting speeds (20 and 30 m/min), feed rates (100 and 150 mm/min) axial depth of cut (1 to 2 mm). Fractional Factorial Design was used in order to have statistical reliability on the results.

The machine tool used for testing was a CNC Vertical Machining Center - Discovery 760 Romi-Bridgeport with the main engine power of 15 kW and maximum speed of 10,000 rpm.

The work material was ABNT 1045 steel bars previously faced to the following dimensions 400 mm x 55 mm x 90 mm. For each test three channels were machined showed schematically in Fig 2. The width of the channels was 10 mm and the thickness of the wall between the channels was 4 mm.

The tools used were 90º end mills made of HSS M42 (8% Co) with 10 mm of diameter, length of 80 mm, two teeth, with corner radius of 0.5 mm each, coated with TiN and uncoated (Fig. 3), manufactured by OSG Sul American de Ferramentas Ltda. The tools were fixed in the mandril using the entire shank, living the 25 mm of length of cut overhanging.

For measurement of Ra and Rz roughness parameters a portable digital roughness tester, as shown in Fig.4, was used. This equipment was manufactured by Mitutoyo Sul Americana Ltda., SJ-201P model, with resolution of 0.01 μm and nose tip radius of 5 μm.

The cut-off value (Lc) used was 0.8 mm, resulting in a 4 mm measurement range (5x0.8). The roughness measurement was performed in two positions of each channel. Three channels were machined for each test, and the average values considered.

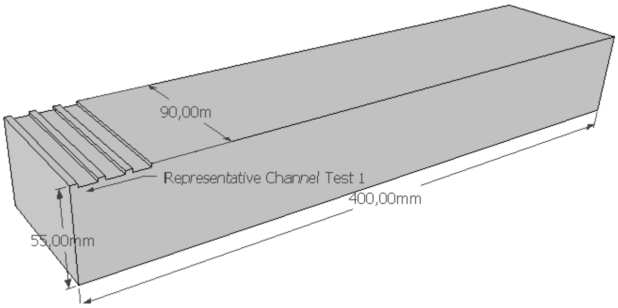

Figure 2. Dimensions of the workpiece of ABNT 1045 steel

Figure 3. The tools used in the tests

Figure 4. Measurement of the surface roughness at the bottom surface of the channels

For the measurement of the thrust force (Fz) and torque (Mz) a Kistler piezoelectric dynamometer, Model 9123C, with an amplifier and a signal conditioner (also manufactured by Kistler), a data acquisition board and Labview 7.6 software (both by National Instrument) were used. The acquisition of the thrust force and torque signals occurred in the initial stage of the cutting of the channels, with a rate of 1 kHz. Fig. 5 shows schematically this measuring system. The measurement occurred during the machining of three channels per test and the average values were considered.

Cutting fluids were applied externally to the tool. Vegetal and mineral-based fluids were used which resulted in 3 lubri-cooling systems, namely: dry machining, machining with minimum quantity of lubricant (MQL) and machining with conventional overhead flood cooling.

For the application of MQL a neat oil (Vascomill MMS SE 1®) was used at a flow rate of 240 ml/hr. This is a fluid based on natural esters, vegetable, with enhanced security due to its high flash point and low misting formation. The spray device used was the O2AO-STD model, manufactured by ITW Chemical Products Ltda, which works with a continuous flow of compressed air, set around 0.5 MPa (5 bar) of pressure.

Two flood cooling system were used. In the system Flood 1 (F1) a micro-emulsion of mineral base oil (specification BLASOCUT BC 40 NF®) at a concentration of 8%, with a flow rate of 940 l/h was used. In the system Flood 2 (F2) the cutting fluid used was a vegetal oil-based micro-emulsion (specification Vasco 7000®) at concentration of 8%, with an average flow of 930 l/h. In these cases the pumping system of the Machining Center was used.

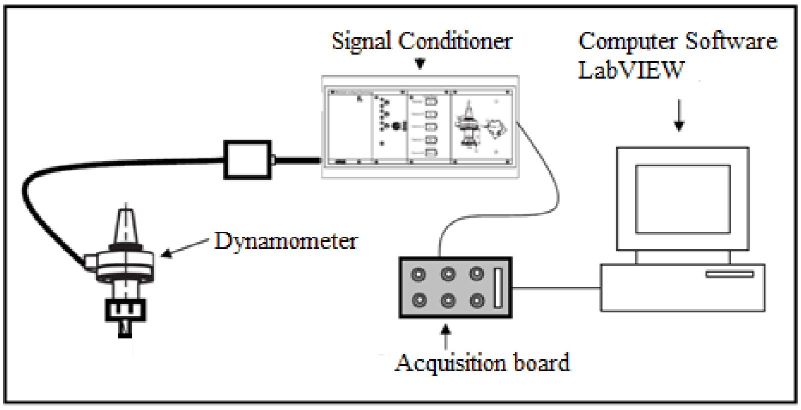

Figure 5. Schematic diagram of the force and torque measuring system

3. EXPERIMENTAL PLANINIG

The influence of the input variables (cutting fluid, cutting speed, feed rate, axial depth of cut and tool coating) were evaluated by means of a fractional factorial design 2^{5-1}, which resulted in 16 experiments. Since the variable "Cutting Fluid" had four levels (Dry, MQF, Flood 1 and Flood 2), the analysis was made by combining "Dry" (lower level) with the other lubri-cooling system (upper level), totalling 32 tests. Considering that each test consisted of three channels in sequence (test and two replicas) a total of 96 channels were machined. To avoid tool wear influences each tool was used only during the machining of two tests. Tab. 1 shows details of the tests.

Table 1. Experimental tests and their cutting conditions

TEST Nº	INPUT VARIABLES				
	Cutting Fluid	*v_c (m/min)*	*Feed velocity (mm/min)*	*Coating*	*Axial depth of cut (mm)*
01	Dry	20	100	Without	2
02-03-04	**MQF-F1-F2**	**20**	**100**	**Without**	**1**
05	Dry	30	100	Without	1
06-07-08	**MQF-F1-F2**	**30**	**100**	**Without**	**2**
09	Dry	20	150	Without	1
10-11-12	**MQF-F1-F2**	**20**	**150**	**Without**	**2**
13	Dry	30	150	Without	2
14-15-16	**MQF-F1-F2**	**30**	**150**	**Without**	**1**
17	Dry	20	100	TiN	1
18-19-20	**MQF-F1-F2**	**20**	**100**	**TiN**	**2**
21	Dry	30	100	TiN	2
22-23-24	**MQF-F1-F2**	**30**	**100**	**TiN**	**1**
25	Dry	20	150	TiN	2
26-27-28	**MQF-F1-F2**	**20**	**150**	**TiN**	**1**
29	Dry	30	150	TiN	1
30-31-32	**MQF-F1-F2**	**30**	**150**	**TiN**	**2**

4. RESULTS AND DISCUSSIONS

The average effects and the overall average, calculated using the fractional factorial design 2^{5-1}, provided by the change of level of the input variables in the thrust forces (Fz) and torque (Mz) and the surface roughness (Ra and Rz), are available in Tabs. 2 to 5, respectively. The following analysis and discussions are all related to the results presented in these tables.

Table 2. Effect of the change of the level of the input variables in Fz

Input variable	Thrust force Fz (N)		
	Effect		
	Dry→MQL	Dry→Flood 1	Dry→Flood 2
General mean	217.19	240.50	219.00
Lubri-cooling system	-50.38(↓23.2%)	-3.75(↓1.6%)	-46.75(↓21.3%)
Vc: 20 → 30 (m/min)	-36.63(↓16.9%)	-29.00(↓12.1%)	-40.25(↓18.37%)
F: 100 → 150 (mm/min)	27.38(↑12.6%)	11.75(↑4.9%)	23.75(↑10.84%)
Coating: S/R → TiN	14.88(↑6.8%)	-7.75(↓3.2%)	11.25(↑5.1%)
Axial depth of cut: 1 → 2 (mm)	74.13(↑34.1%)	43.25(↑18.0%)	70.50(↑32.2%)

Table 3. Effect of the change of the level of the input variables in Mz

Input variable	Torque Mz (Nm)		
	Effect		
	Dry→MQL	Dry→Flood 1	Dry→Flood 2
General mean	0.83	1.07	0.93
Lubri-cooling system	-0.33(↓39.7%)	0.16(↑ 15.0%)	-0.13(↓14.0%)
Vc: 20 → 30 (m/min)	-0.27(↓32.5%)	-0.23(↓21.5%)	-0.28(↓30.4%)
F: 100 → 150 (mm/min)	0.29(↑34.93%)	0.49(↑45.8%)	0.36(↑38.7%)
Coating: S/R →TiN	-0.08(↓9.6%)	-0.25(↓23.3%)	-0.16(↓17.2%)
Axial depth of cut: 1 → 2 (mm)	0.56(↑67.4%)	0.54(↑50.4%)	0.56(↑60.2%)

Table 4. Effect of the change of the level of the input variables in Ra

Input variable	Surface roughness Ra (μm)		
	Effect		
	Dry→MQL	Dry→Flood 1	Dry→Flood 2
General mean	2.50	2.95	2.55
Lubri-cooling system	-0.91(↓36.4%)	-0.01(↓2.4%)	-0.82(↓32.2%)
Vc: 20 → 30 (m/min)	-0.25(↓10.0%)	-0.22(↓7.45%)	-0.25(↓9.8%)
F: 100 → 150 (mm/min)	0.30(↑12.0%)	0.16(↑5.4%)	0.14(↑5.5%)
Coating: S/R → TiN	-1.09(↓43.6%)	-0.62(↓21.0%)	-1.15(↓45.0%)
Axial depth of cut: 1→ 2 (mm)	-0.14(↓5.6%)	-0.20(↓6.7%)	-0.19(↓7.4%)

Table 5. Effect of the change of the level of the input variables in Rz

Input variable	Surface roughness Rz (µm)		
	Effect		
	Dry→MQL	Dry→Flood 1	Dry→Flood 2
General mean	14.68	17.97	15.01
Lubri-cooling system	-2.07(↓14.1%)	4.51(↑25.1%)	-1.42(↓9.4%)
Vc: 20 → 30 (m/min)	-0.75(↓5.1%)	-0.42(↓2.3%)	-1.15(↓7.7%)
F: 100→150 (mm/min)	1.22(↑ 8.3%)	1.13(↑ 6.3%)	0.37(↑ 2.4%)
Coating: S/R →TiN	-6.96(↓45.6%)	-4.27(↓23.7%)	-7.66(↓51.0%)
Axial depth of cut: 1→ 2 (mm)	-0.46(↓3.1%)	-1.06(↓5.9%)	-0.89(↓5.9%)

Tables 2 and 3 show that the most important influencing variables in the cutting force and torque for the confrontation between the different lubri-cooling systems are the axial depth of cut and feed rate. Changing the axial depth of cut from 1 mm to 2 mm resulted in average increases in torque (Mz) and thrust force (Fz) of around 44%, and the change in feed velocity from 100 mm/min to 150 mm/min resulted in a average increase of 25% in relation to the average value. This occurs by the areas of the primary and secondary shear planes increased with the increase of the axial depth of cut and the feed rate, resulting in increased machining forces and torque (Machado et al., 2015).

In general the lubri-cooling systems have reduced Fz and Mz, with best results being given by MQL (approximately 23% and 39% less than the dry machining, for Fz and Mz, respectively, comparing the average values of the tests), followed by Flood 2 (approximately 21% and 14% less than the dry machining). Flood 1 system showed only a discreet influence on the machining force and torque.

When the cutting speed was increased from 20 m/min to 30 m/min, the thrust force and the torque decreased at all confrontations between the lubri-cooling systems in an overall average of 22%, probably due to the higher heat generation, thereby causing an increase in temperature, which contributes to reduction in cutting forces.

The coating, with respect to input variables, was the less influential. Analysing Tabs. 2 and 3, a slight tendency to decrease Mz values is observed, though the Fz values have not followed the same trend (increased when changing from Dry → MQL and Dry → Flood 2 and decreased when changing from Dry → Flood 1). It was expected that the coating, being considered a lubricant, would reduce the cutting forces, since the friction generated between chip and tool is expected to be less, thus with lower cutting forces. The fact that the coating had different influences on the thrust force and torque might be related to the optimization of the geometry of the drill by the manufacturer, which ensures good results for both drills coated and uncoated, as shown in the present work.

Regarding the quality of the machined surfaces, Tabs. 4 and 5, the coating was the most influential variable. Using coated tools, the average roughness parameters Ra and Rz, decreased for all confrontation between the dry condition and the lubri-cooling systems, a general average of 38%. This is explained by the fact that the coating acts as lubricant and/or decreases the chemical affinity between the workpiece material and tool, thus contributing to better improve the surface finishing (Machado et al., 2015).

The surface quality also improved with increasing cutting speed, with a reduction in Ra and Rz parameters, generally around 7%. This can be explained by the fact that both the temperature increased in the chip-tool interface that facilitates shearing of the material, and thus a higher surface quality was produced. Another important fact is the possible reduction in size of the built-up edge (BUE) under higher cutting speeds (Machado al., 2015).

The increase in the feed rate produced surfaces with poor surface finish and this was expected since the height of peaks and depth of valleys of the feed marks tend to increase.

The increase in the axial depth of cut also generated better surface finishing, in a general average of 6%. This reduction in the average roughness may be linked to decreased vibration of the machine.

In general, the lubri-cooling systems reduced the values of average roughness except for the confrontation of Dry → Flood 1. The possible reason could be linked the characteristics of the cutting fluid used and the chemical affinities resulting from the use of this fluid. For the other comparisons, Dry → Flood 2 and Dry → MQL, the use of a fluid improved the surface finishing.

The average values of thrust force, torque and surface roughness for the different lubri-cooling systems investigated can be seen in Fig.6. Albeit with high dispersion, which puts the differences without statistic significance, analysis of the trends of the average values in this figure, allows to conclude that it is clear that the use of vegetable-based cutting fluids (MQL and Flood 2), always reduced the average values of Mz, Fz, Ra and Rz when compared to the dry cutting condition. It is also possible to note that the "MQL" system that used vegetable-based oil, presented the best performance.

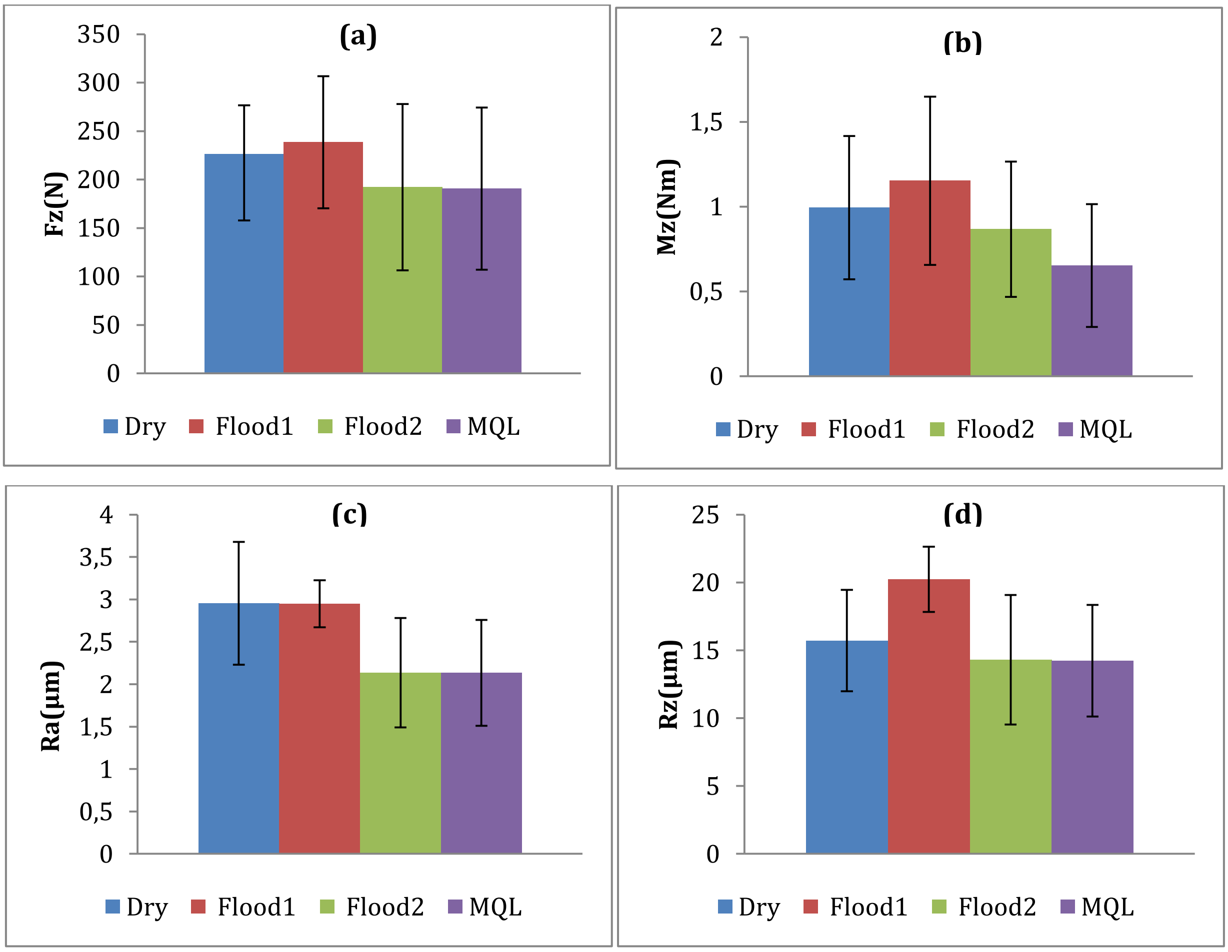

Figure 6. Average of output variables for the different lubri-cooling systems applied: (a) Thrust force Fz [N]; (b) Torque Mz [Nm]; (c) Surface roughness Ra [µm]; (d) Surface roughness Rz [µm]

5. CONCLUSIONS

The results of the end milling tests under the conditions imposed by the methodology of the present study allowed the following conclusions to be drawn:

- The axial depth of cut was the most influencing variable on the thrust force and torque, with an average increase of 43%, followed by the feed rate, cutting speed, lubri-cooling system and tool coating.
- The variation of feed rate from 100 mm/min to 150 mm/min increased the thrust force and torque, on an average of 24.6%. However, increasing the cutting speed from 20 m/min to 25 m/min reduced the thrust force and torque on an average of 21%. In relation to the lubri-cooling systems, when using MQL and Flood 2 instead of dry condition, the thrust force and torque reduced by 31% and 17%, respectively. When the Flood 1 condition was used there was a reduction in Fz and an increased in Mz.
- Regarding to surface roughness, the coating was the most influential variable. The lubri-cooling system decreased Ra and Rz values on averages of 25% and 20% for the used of MQL and Flood 2, respectively, instead of the dry condition. When applying the Flood 1 system, there was no reduction in the surface roughness. Increases in he cutting speed and axial depth of cut promote reduction of the surface roughness around 5% and 7%, respectively. The augment of the feed rate caused increases in the surface roughness of an average of 6%.
- All cutting fluids applied, regardless of the system used, reduced the thrust force and torque and improved the surface finish. However, the machining with the "Flood 1" system, did not showed the same results. The MQL system with vegetal-based oil tended to perform better than its competitors. Thus showing that the technique that reduces the amount of fluid (MQL) proves to be a good alternative for the process studied, considering both technical and environmental issues.
- The Flood 2 system also presented good results, which demonstrate that vegetal fluids, also used in the MQL, has great potential for use in end milling process.

6. AKNOWLEDGEMENTS

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