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INFLUENCE ON THE FEED-RATE AND MQL IN THE SURFACE ROUGHNESS AND CUTTING FORCE COMPONENTS DURING THE AISI 420C TURNING WITH STANDARD AND WIPER TOOLS

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Abstract. *The machining processes can be associated with the cutting forces and surface texture. The cutting forces can be represented by three orthogonal components (feed force F_f, passive force F_p and main cutting force F_c). The surface texture can be quantified by roughness parameters such as average (R_a) and total (R_t) roughness. A study of the orthogonal cutting forces and the analysis of R_a and R_t generated on the finish turning of AISI 420C stainless steel using minimum quantity of lubricant (MQL) were made. The influence of input parameters (feed rate, cutting tool geometry and MQL) on the surface texture and the cutting forces is assessed in a comparative way. A CNC lathe was used to machining two workpieces using two different cutting tool geometries (standard and wiper), four different feed-rates and three different MQL flow rates, totalizing 24 samples. A portable rugosimeter was used to measure the R_a and R_t, and a data acquisition system was used to acquire on-line the F_f, F_p and F_c generated during the turning. The experimental data showed that the surface roughness and the orthogonal cutting force components for wiper tool were much lower than the standard tool. Moreover, the variation of the MQL flow rate did not significantly affect the surface roughness with both tool geometries. However, the cutting forces decreased with higher MQL flow rates.*

Keywords: *stainless steel AISI 420C, finish turning, MQL, cutting force components, surface roughness.*

1. INTRODUCTION

There are several process used in the industry characterized by removal of material with chip generation. Between these, it includes the turning process. This process is characterized by the rotation of the raw material around an axis and the removal of the necessary amount of material by a tool in order to reach a defined geometry. As this process is widely used in the industries, it is fundamental its optimization, resulting in reduced costs and increased profits. There are several ways and studies about its improvement, covering a large field of possibilities. In particular, the control of the process output variables from the study of changes in input parameters has been target of several investments of new technologies (Thomas, 1982).

This paper aims to study the influence of the input parameters (feed-rate, minimum quantity of fluid and cutting tool geometries) in the surface roughness and the resulting force in the finish turning of AISI 420 stainless steel.

2. INPUT AND OUTPUT PARAMETERS

In the manufacturing processes with chip generation there are two kinds of variables in the process: dependent and independent. Independent variables are those in which can have direct intervention from the operator. Also known as input parameters, these can be chosen before the cutting. Among these parameters, it can be highlighted: workpiece material, cutting tool material, feed rate (f), depth of the cut (a_p), cutting speed (v_c), cutting fluid, among others. Meanwhile, the dependent variables are those in which the operator cannot intervene, because are influenced by input variables, as mentioned above. Also known as output variables, they can be seen as the result of the process input variables. In other words, these variables may have different results according the changes from the input parameters. As output parameters can be cited: chip type and geometry, force/power generated in the process, cutting temperature, vibrations of the process, surface texture and integrity (Black, 1997).

2.1 Martensitic Stainless Steel AISI 420C

The stainless steel AISI 420 is a chromium alloy steel, stainless, martensitic, temperable, magnetic, with high mechanical resistance to the temperature of 400 °C and good oxidation resistance up to the temperature of 610 °C. It is widely used for manufacture of parts with good mechanical resistance, ductility and wear resistance. In tempered it shows high corrosion resistance and may reach hardness up to 55 HRC. Its good machinability allows the manufacture of the high precision tools such as surgical tools. Through the tempering process it is given to the material a martensitic structure increasing its corrosion resistance and biocompatibility (Favorit, 2014). "Table 1" shows the chemical composition, in percentage of mass, of stainless steel AISI 420C used in the workpieces.

Table 1. The chemical composition of stainless steel AISI 420 C.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
Bulk [%]	0,37	0,34	0,36	0,04	0,01	12,3	0,48	0,07	0,09	0,03

2.2 Surface Roughness

In the industrial production processes, as projects demands increase, it becomes more necessary, among others, the improvement of the final surface texture. The presence of irregularities in the machined surface is inherent of the processes. The parameter that quantifies these irregularities at the microscopic level, known as roughness, takes into account the micrometric peaks and valleys present on the machined surface. These irregularities can be presented in disorderly manner, being necessary to evaluate them through specific parameters. It was used as a form of evaluation the texture the average and total roughness (respectively R_a and R_t) for being internationally recognized as roughness measures and in conformity with the ABNT NBR ISO 4287 (2002). According to Machado *et al.* (2009), the roughness average R_a is the arithmetic mean of the values from the clearances of a specified midline, while the roughness R_t evaluates the difference between the highest peak and the deepest valley of the surface, informing about the maximum deterioration of the piece. The roughness is used in many cases as an output parameter to control of the machining processes and can be measured by a rugosimeter, "Fig. 1".

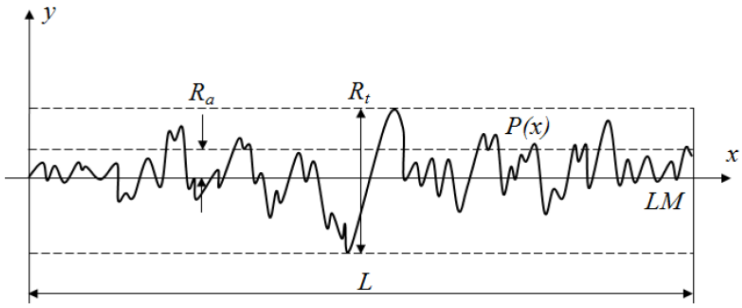


Figure 1. Schematic representation of the measurement made by a rugosimeter: roughness R_a and R_t in a surface profile *P(x)* in a sample of length *L* (Mello *et al.*, 2012).

To conventional tool geometry, it is possible to quantify the roughness R_a and R_t according to another two parameters: feed-rate (f [mm/rev]) and tool nose radius (r_ε [mm]), in accordance with Diniz *et al*. (2013). According to Machado *et al*. (2009), R_a follows a behavior that may be seen in "Eq. (1)", while the total roughness R_t, according to Kalpakjian and Schmid (2010), follows the behavior of the "Eq. (2)":

$$R_a\ [\mu\text{m}] = \frac{1000 \cdot f^2}{18\sqrt{3} \cdot r_\varepsilon} = 32,075 \cdot \left(\frac{f^2}{r_\varepsilon}\right) \tag{1}$$

$$R_t\ [\mu\text{m}] = \frac{1000 \cdot f^2}{8 \cdot r_\varepsilon} = 125 \cdot \left(\frac{f^2}{r_\varepsilon}\right) \tag{2}$$

To wiper tool geometry, according to Mello *et al*. (2012), the values of R_a and R_t follows the behavior described by "Eq. (3)" and "Eq. (4)", respectively.

$$R_a\ [\mu\text{m}] = 0,52 + 3,56 \cdot \left(\frac{f}{r_\varepsilon}\right)^{2,12} \tag{3}$$

$$R_t\ [\mu\text{m}] = \frac{0,667}{f} + 282 \cdot f^{\left(4,4 - \frac{0,664}{r_\varepsilon}\right)} \tag{4}$$

2.3 Machining Forces

The knowledge of the involved forces during the machining process is utterly important, because those forces affect a wide range of factor in the process, among them: temperature in the cutting zone, tool wear, and others. The forces generated in the machining can be viewed as the resulting force *F* acting in the cutting edge of the tool during the process (Diniz et al., 2013). According to Groover (2010), this force *F* is decomposed in three orthogonal components, as in "Fig. 2". This force *F* is decomposed in three orthogonal components:

- Main cutting force (F_c): component of the *F* along the cutting direction;
- Feed force (F_f): projection of the *F* along the feeding rate direction;
- Passive force (F_p): projection of the *F* along the perpendicular direction of the feed rate, in the work plan.

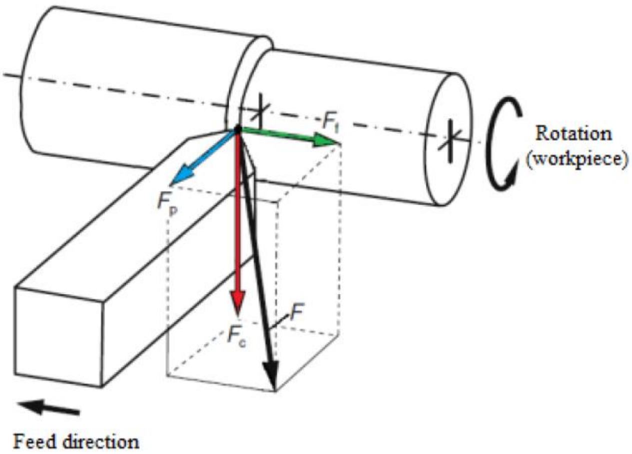


Figure 2. Scheme of the machining forces.

2.4 Wiper Cutting Tool Geometry

The cutting tools with wiper geometry are used in finishing and semi-finishing operations, in machining of high production. Create surfaces with low roughness even with cutting operations with high feed-rates and have a greater facility for chip breakage. Furthermore, the wiper tool, using twice the values of feed-rate and depth of cut of a standard cutting tool, can produce the same roughness surface values, "Fig. 3a". The nose radius in a wiper insert is constituted of 3 to 9 different nose radii, increasing the insert's contact length. The standard inserts, more commonly found, have a single nose radius, which may vary from 0,1 to 2,4 mm, "Fig. 3b" (Sandvik, 2012).

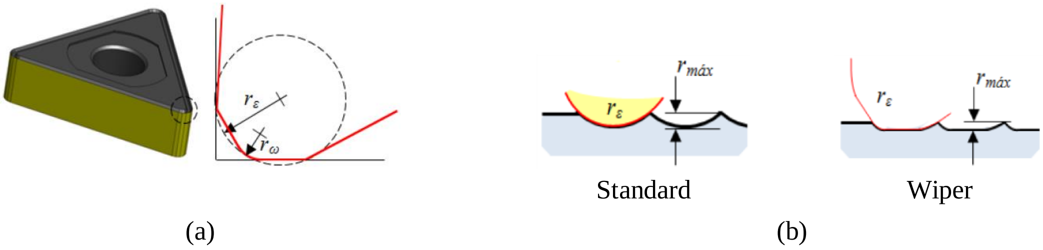


Figure 3. Tool geometry (a) nose radii (r_ε e r_ω) in wiper tool tip; (b) comparison between standard and wiper tool geometries in a profile surface roughness (Mello *et al.*, 2012)

Furthermore, Azambuja *et al.* (2013) show that the wiper tool has a greater life expectancy when compared with the standard tool in SAE 4140 dry finish turning operations.

2.5 Cutting Fluid

Many of the machining processes use a cutting fluid, which must refrigerate the tool and the workpiece while cutting, in order to maintain its physics properties (without losing its cutting efficiency), to reduce its wear (improving tool life) and to reduce thermal effects (enabling to achieve the precise dimensions desired for the workpiece). It also may lubricate the cutting zone in order to reduce the coefficient of friction between chips and tool (favoring the removal of chips and metal fines and reducing the cutting force and power) when low speeds of cutting does not generate high amounts of heat (Aronson, 1994; Diniz *et al*., 2013; Silliman and Perich, 1992; Sluhan, 1994).

In despite of the improvement at machining, the conventional system of applying the coolant, the Flood Coolant System, also has its drawbacks, such as the product's cost, cost and difficulty of recycling fluid and chip, damage to the environment, health and safety risks to the machine operator (skin and lung), and more. Then, at the last years, studies of new techniques have been made to minimize or eliminate the use of fluids in machining: Dry Machining and Minimum Quantity of Lubricant (MQL) (Diniz *et al*., 2013; Dixit *et al*., 2012; Villena-Denton, 1994).

While the flood coolant system requires a large quantity of the cutting fluid, the MQL technique uses a small quantity of cutting fluid mixed with compressed air as the cutting fluid. As it uses very small amount of fluid, it causes less damage to the environment and reduces the operation's cost, it may also maintain or even improve the machining result. Nevertheless, it has some problems, for example the atmospheric pollution due to its very thin particulate that stands in the air, demanding a ventilation system and a closed work cabin. Another disadvantage is the noise made by the use of compressed air, which reaches high levels, over 80 dB.

3. METHODOLOGY

The machining tests performed are characterized by the external axial cut of 12 samples of 7 mm long, in two cylindrical workpieces (CP) of a martensitic stainless steel AISI 420C, using two different cutting tools (standard and wiper, each in one workpiece). Keeping the cutting speed and the depth of cut fixed (respectively v_c = 290 m/min and a_p = 1 mm), each sample was composed of the combination of four feed-rates (f = 0.15, 0.20, 0.25 and 0.30 mm/rev) and tree MQF outputs (Q = 1.4, 2.0 e 3.0 ml/s), as shown in "Tab. 2" and "Fig. 4".

Table 2. Input parameters and generated samples.

Tool geometry	**MQL flow rate *Q*** [ml/s]	**Feed-rate *f*** [mm/rev.]			
		f_1 = 0.15	f_2 = 0.20	f_3 = 0.25	f_4 = 0.30
Standard (S) CP1	Q_1 = 3.0	S01	S02	S03	S04
	Q_2 = 2.0	S05	S06	S07	S08
	Q_3 =1.4	S09	S10	S11	S12
Wiper (W) CP2	Q_1 = 3.0	W01	W02	W03	W04
	Q_2 = 2.0	W05	W06	W07	W08
	Q_3 =1.4	W09	W10	W11	W12

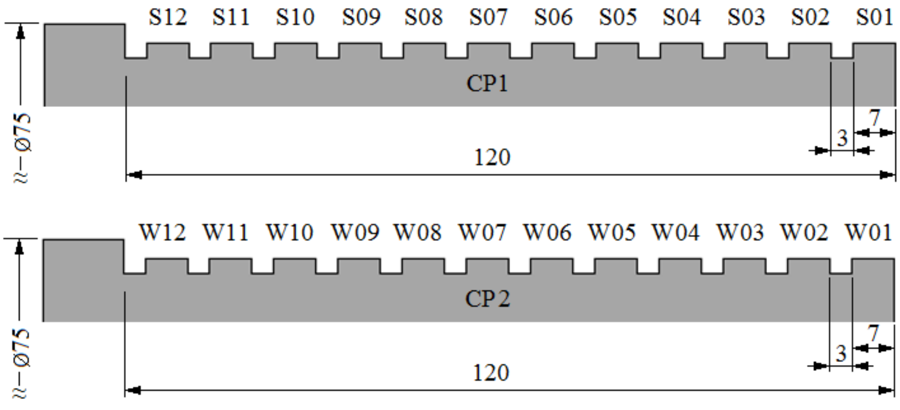
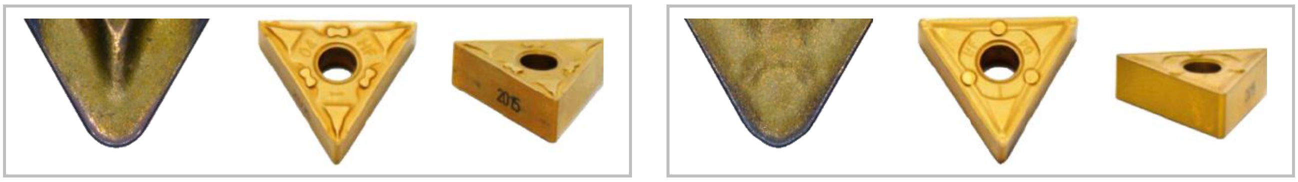


Figure 4. Schematic drawing of the samples (regions) machined in each workpiece.

Carbide inserts of triangular shape, negative basic (T-Max P), with nose radius r_ε = 0,4 mm, chip breakers for finish machining (MF and WF) and coating of MT-CVD of $TiCN/Al_2O_3/TiN$ (GC2015) was used in the experiments (Fig. 5). The tool holder MTJNL 2020K used has an position angle χ_r = 93°.

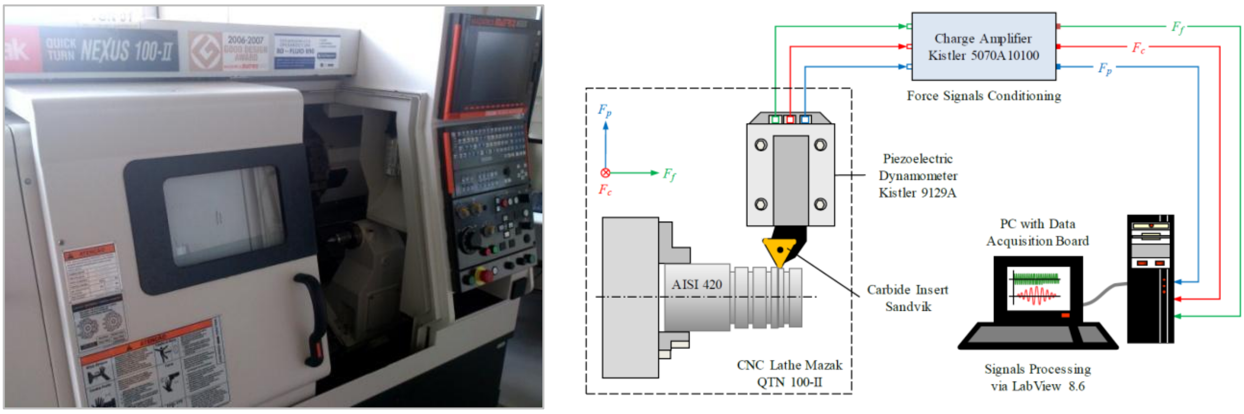


(a) TNMG 160404-MF 2015 (b) TNMX 160404-WF 2015

Figure 5. Carbide tools: (a) standard; (b) wiper.

The CNC Lathe Mazak model Quick Turn Nexus 100-II available in the Laboratory of Machining Automation (LAUS-UFRGS) was used for the turning tests (Fig 6a).

The piezoelectric dynamometer Kistler Type 9129A was used in the experiment to acquire the data of the tree orthogonal components of the machining force (F_f, F_c and F_p). The machining force produced by the turning process is resolved directly into three significant components by the multi-component dynamometer on the Cartesian direction (respectively F_x, F_y and F_z). With the assistance of the signal amplifier Kistler 5070A10100 and the software LabVIEW 8.6 it was possible to process the acquired data. "Figure 6b" shows the experimental system used.



(a) (b)

Figure 6. (a) CNC Lathe Mazak QTN 100-II; (b) Force acquisition data system used during the experiment.

Three values of each surface roughness parameter (R_a e R_t) were taken and registered for each section machined. For measuring, it was used a portable rugosimeter Mitutoyo model Surftest SJ-201P, "Fig. 7". The instrument has resolution of 0.01 μm. It was utilized a sampling length λ = 0.8 mm and an evaluation length L = 5·λ = 4 mm.

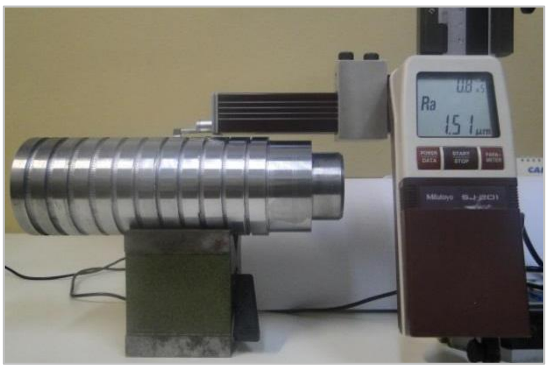


Figure 7. Surftest SJ-201P used in the roughness surface measurement.

4. RESULTS E DISCUSSION

First the force signals as function of *f* [mm/rev.] and *Q* [ml/s] for each of the 24 samples (12 for each tool) will be analyzed. Afterwards the results obtained for roughness (R_a e R_t) for the same samples will be evaluated.

4.1 Force Signals

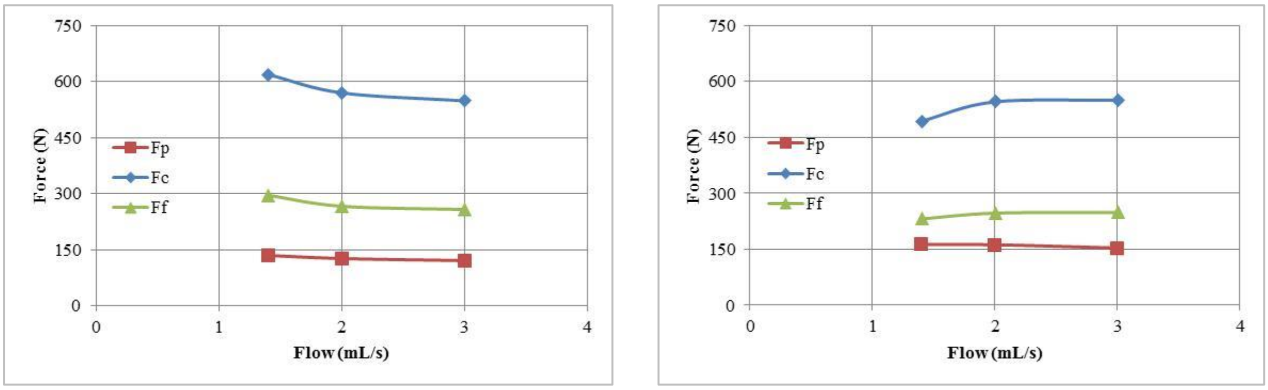
4.1.1 Static forces

“Table 3” shows the average values of the orthogonal components for the machining force (feed force F_f, passive force F_p and main cutting force F_c) obtained when performing the tests.

Table 3. Average values of the measured forces for the combinations of feed-rate/tool/MQL flow rate.

		Passive Static Force [N]				Cutting Static Force [N]				Feed Static Force [N]			
Tool	Flow [mL/s]	Feed rate [mm/rev.]				Feed rate [mm/rev.]				Feed rate [mm/rev.]			
		f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30	f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30	f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30
Standard (S)	Q1 = 3.0	85	108	133	161	384	502	584	725	205	244	268	317
	Q2 = 2.0	88	112	141	170	388	509	633	751	207	246	289	327
	Q3 =1.4	91	117	148	186	405	532	672	869	221	259	310	397
Wiper (W)	Q1 = 3.0	119	142	161	192	408	494	592	707	220	235	255	285
	Q2 = 2.0	129	150	173	197	392	495	599	696	213	235	257	283
	Q3 =1.4	136	152	174	189	361	450	548	616	203	221	243	260

“Figure 8” shows the graphics of average values of the force in four feed-rates (S01-S04, S05-S08, S09-S12) for both tools as function of fluid output for the data of “Tab. 3”.



(a) Standard (b) Wiper

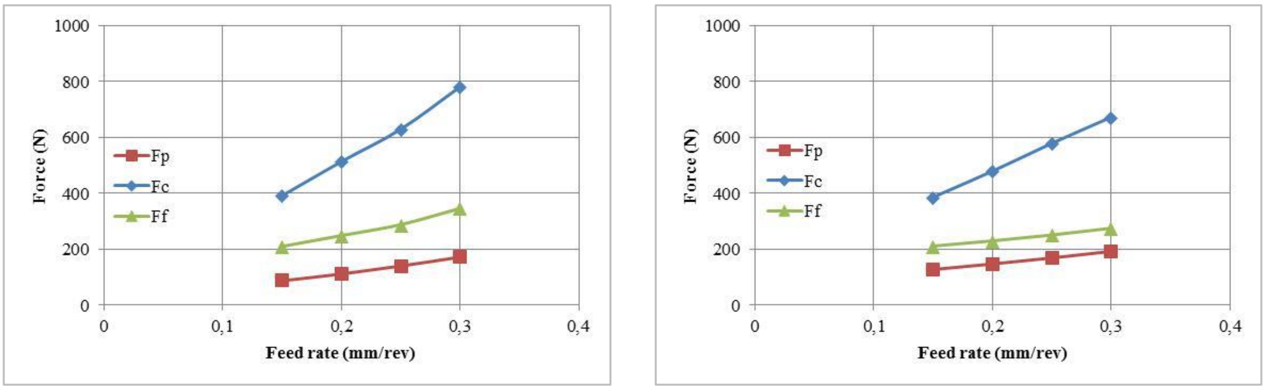
Figure 8. Comparison between the forces averages values generated by the tool for different feed-rates as function of MQL flow rates.

Looking at the graph in “Fig. 8a”, it can be seen that the standard tool presents a decrease in all three components of force during the turning with higher values of MQL. This happens because the specific cutting force (k_s) lowers due to the lubricant effect, which lowers the friction between cutting tool and workpiece. It is noticeable too that the cutting force has a tendency of becoming less sensitive for higher values of MQL.

Now with the use of the wiper cutting tool (Fig, 8b), F_c and F_f have a tendency of growth, while the passive force has of diminish, with the increase of MQL values. A hypothesis for that is that the wiper geometry, by being composed of several radii, has a bigger contact area with the workpiece, thus generating higher temperatures. Those high temperatures reached, associated with higher rates of heat removal, due to more MQL, can cause a local hardening of the material, by quenching the material. This effect raises the specific cutting pressure, opposing the lubricant effect.

“Figure 9” shows the graphics of average values of the force in three MQL flow rates (S01-S05-S09, S02-S06-S10, S03-S07-S11, S04-S08-S12) for the same tools as function of advancing for the data of “Tab. 3”.

The expected behavior of the forces during the process is a gradual increase with greater values of feed-rate (*f*), “Fig. 9”. It can be noticed the major influence that the *f* has over forces. While for an increase of 100% in the MQF values, there was a different of about 12% in the F_c. For increase of 100% in the *f*, there was an increase of 99% in the same F_c. That shows the strong influence of the *f*.



(a) Standard (b) Wiper

Figure 9. Comparison between the forces averages values generated by the tool for different MQL flow rates as function of feed-rates.

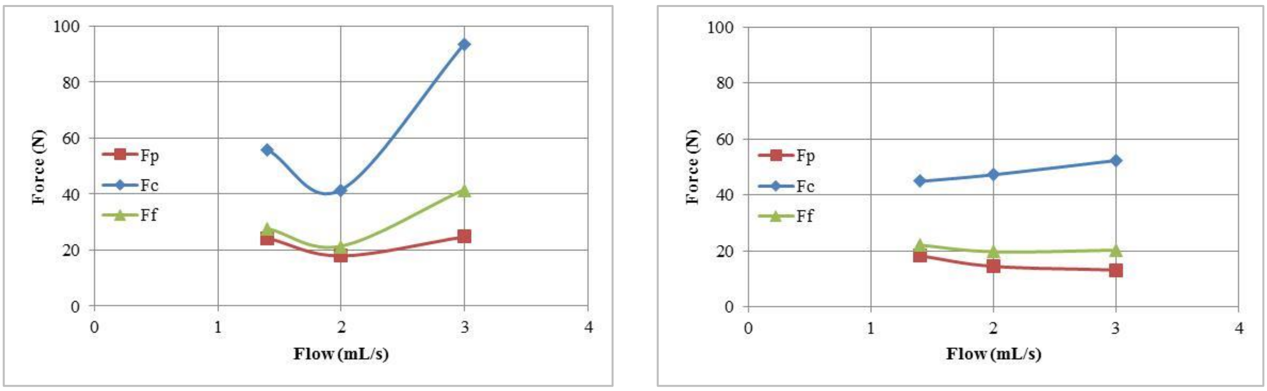
4.1.2 Dynamic forces

"Table 4" shows the variations of the orthogonal components of the machining forces (feed force ΔF_f, passive force ΔF_p and main cutting force ΔF_c) obtained during the tests.

Table 4. Average values of the measured force variations for the combinations of feed-rate/tool/MQL flow rate.

Tool	Flow [mL/s]	Passive Dynamic Force [N] Feed rate [mm/rev.]				Cutting Dynamic Force [N] Feed rate [mm/rev.]				Feed Dynamic Force [N] Feed rate [mm/rev.]			
		f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30	f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30	f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30
Standard (S)	Q1 = 3.0	11	18	35	36	39	65	154	117	18	28	66	56
	Q2 = 2.0	8	14	22	28	34	37	51	45	15	19	25	26
	Q3 =1.4	11	18	27	41	41	57	47	79	21	25	24	41
Wiper (W)	Q1 = 3.0	5	10	17	21	13	44	74	80	8	18	28	28
	Q2 = 2.0	9	10	14	26	16	31	49	93	11	15	21	33
	Q3 =1.4	9	13	13	39	13	33	30	104	11	18	17	44

"Figure 10" shows the graphs of the average recorded values of the force in the four feed rates (S01-S04, S05-S08, S09-S12) to the two tools, depending of the flow.

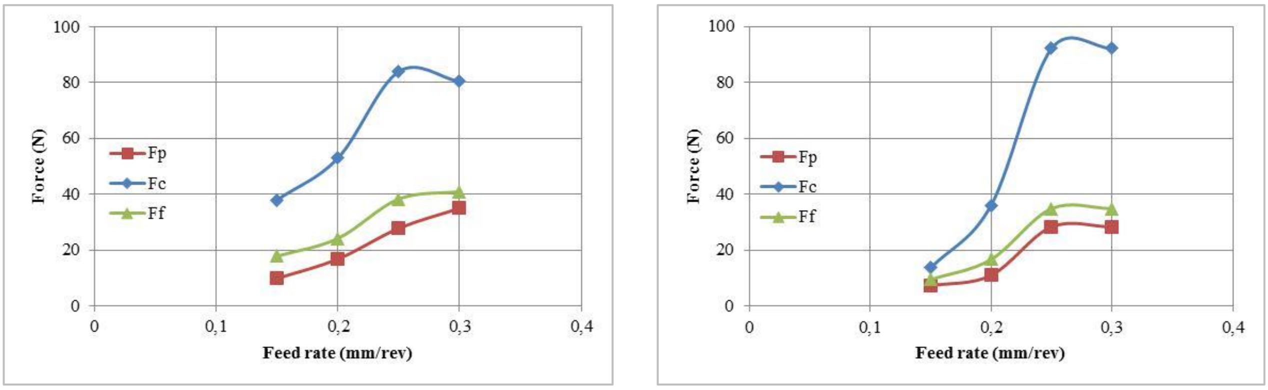


(a) Standard (b) Wiper

Figure 10. Comparison between the averages values of force variations generated by the tool for different feed-rates as function of MQL flow rates.

The variations of the forces indicate an increase of vibration in the different directions. It can be seen the highest variations with the MQL flow rate are associated with the F_c of the standard geometry (Fig. 10a). It is possible to note that the situation more stable to this tool occurred for Q = 2 ml/s. In the case of the wiper geometry (Fig. 10b), the variations of the forces are nearly linear. There was a decrease in vibration in the axial direction (F_f) and radial (F_p) and an increase in the tangential direction (F_c) with the increase of Q.

"Figure 11" shows the graphs of the average recorded values of the forces in the three flow rates (S01-S05-S09, S02-S06-S10, S03-S07-S11, S04-S08-S12) for the two tools, depending of the feed rate, both for the data of "Tab. 4".



(a) Standard (b) Wiper

Figure 11. Comparison between the averages values of force variations generated by the tool for different MQL flow rates as function of feed-rates.

The graphs in "Fig. 11" clearly show increase in vibration with the increase of feed-rate (f) in all three directions. A raise in the f promotes an increase of the chip thickness (h). As the chips of AISI 420C deforms continuously in narrow bands between segments as it is formed (lamellar chips), as higher the variation of h, higher is the variation amplitude of the resulting forces.

4.2 Surface Roughness

"Table 5" shows all measured values of surface roughness as well the calculated values by the theory.

Table 5.Values of surface roughness generated by AISI 420C turning

Average Roughness (Ra)

Tool	Flow [ml/s]	Feed rate [mm/rev.]			
		f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30
Standard (S)	Q1 = 3.0	1,73	3,04	4,61	7,00
	Q2 = 2.0	1,76	3,01	4,87	6,93
	Q3 =1.4	1,78	3,05	4,90	7,26
Wiper (W)	Q1 = 3.0	0,99	0,97	1,46	2,06
	Q2 = 2.0	1,19	0,64	1,04	1,83
	Q3 =1.4	1,50	0,71	0,84	1,70
Standard theorical	-	1,80	3,21	5,01	7,22
Wiper theorical	-	0,97	1,34	1,83	2,45

Total Roughness (Rt)

Tool	Flow [ml/s]	Feed rate [mm/rev.]			
		f_1=0,15	f_2=0,20	f_3=0,25	f_4=0,30
Standard (S)	3,00	8,24	13,98	20,88	30,93
	2,00	8,30	13,73	22,58	30,92
	1,40	8,31	13,54	23,28	33,08
Wiper (W)	3,00	8,14	7,70	7,71	11,49
	2,00	11,49	5,15	7,29	11,22
	1,40	9,13	7,10	6,03	10,79
Standard theorical	-	7,03	12,50	19,53	28,13
Wiper theorical	-	6,01	6,76	8,99	12,64

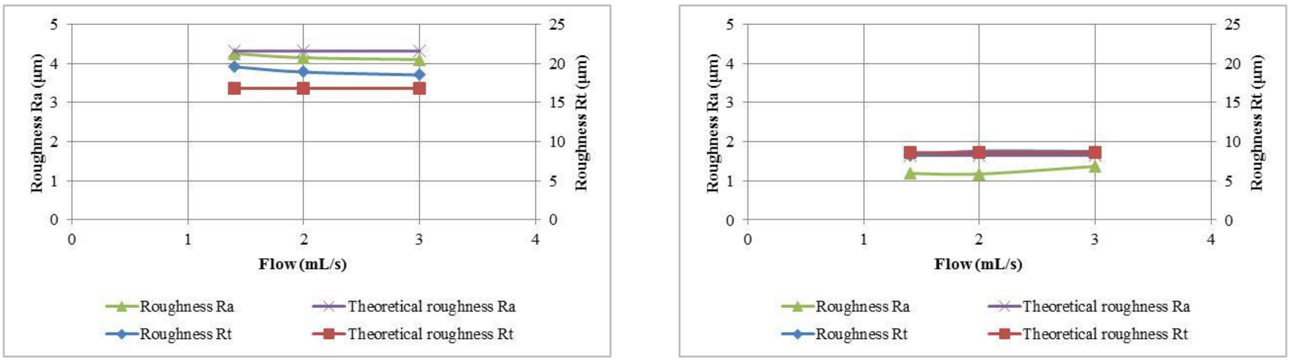
The graphs of surface roughness obtained by standard and wiper tools in AISI 420C turning with different MQL flow rates (Fig. 12) and feed-rates (Fig. 13) were made.

It can be noticed that for the wiper tool there is a minimum point in the values of R_a and R_t, unlike in the standard tool, that has a growth in the average values of roughness the higher the feed-rate (f). It's possible to notice that the standard tool has shown itself insensitive to the MQL (cooling/lubricant effects), not showing any substantial improvement of roughness.

It is possible to appreciate that the values of surface roughness generated by standard tool are very close of expected theoretical behavior. To the values of average and total roughness (R_a and R_t) it is possible to draw a trend line by the average values of roughness to every feed-rate. Based on that, it can be realized that this trend line shows lower errors at 10% with respect to the values of theoretical roughness R_a and lower errors at 15% to the values of total roughness R_t.

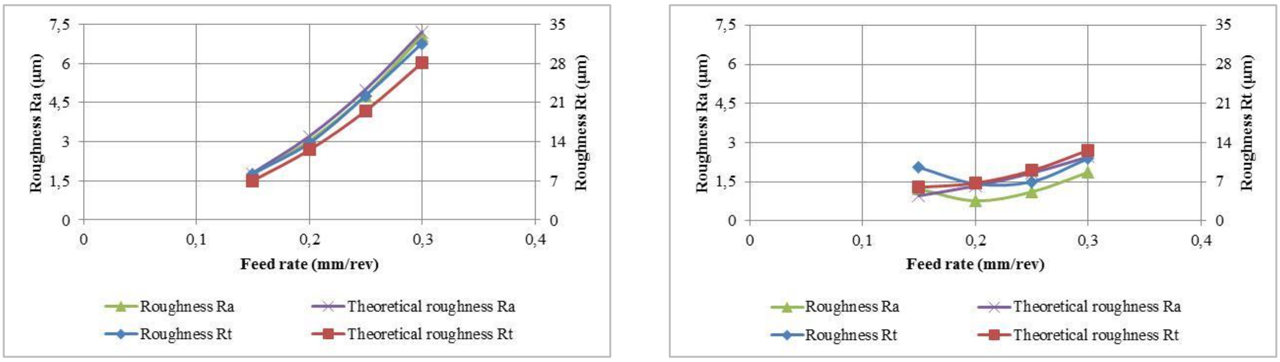
The building of a trend line for comparison with the theoretical values for the wiper tool shows that the values of surface roughness found experimentally do not follows the behavior described by formulation exposed above. To the average roughness R_a occurs errors around 40% in comparison with the theoretical values, while to the total roughness

R_t this errors reach at 59%. However, for the values of feed-rates $f > 0.2$ mm/rev. the theoretical behavior of the total roughness agrees with the measured. A possible explanation about this variance it is that the formulation described for Mello *et al*., (2012) to the wiper tool are empirical formulas developed from parameters of the better tool performance. In the tests made in this work, the workpieces were machined out of these optimization parameters, causing high errors when compared at the values generated by these empirical equations.



(a) Standard (b) Wiper

Figure 12. Values of roughness (R_a e R_t) generated by the tool for different feed-rates as function of MQL flow rates



(a) Standard (b) Wiper

Figure 13. Values of roughness (R_a e R_t) generated by the tool for different MQL flow rates as function of feed-rates.

5. CONCLUSIONS

The forces involved in the process of turning have shown the expected increase with rises of feed-rate (*f*). For higher MQL flow rate (*Q*), the standard cutting tool geometry generated a reduction for both the static and dynamic forces, while the wiper tool geometry produced an elevation in the cutting force (F_c). The “Fig. 10” indicates as well, an increase in the dynamic forces for both cutting tools.

The graphs in “Fig. 11 and 12” make it evident the quality surface finishing by the wiper tool, wherein, even operation in the condition of maximum *f* and minimum *Q*, it has presented a surface roughness lower than that obtained by any combination of *f* and *Q* tested with the standard tool. It is to be noticed as well that the wiper tool has a minimum point for the variation of feed-rate.

Still regarding surface roughness, both tools were little sensible for MQL flow rate variation in the range tested, confirming the studies done thus far, that suggest a strong connection between surface roughness and feed-rate.

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