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INFLUENCE OF CUTTING CONDITIONS ON MACHINING FORCES AND TOOL WEAR IN MILLING AISI304 STAINLESS STEEL

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Abstract Machining is one of the most popular manufacturing processes in the world. Despite this popularity, it is a complex task because of the difficulties in determining optimal cutting conditions capable of producing parts within shape, size and finish specifications at the lowest possible cost. Thus, the study of tool wear is of great relevance to the industry as it influences on operating costs. Tool wear is directly related to the machining parameters, such as cutting speed, feed and depth of cut, and other variables such as workpiece material. Therefore, optimizing these parameters enables a reduction in the machining cost by providing better performance of tool life. One way to predict tool life is by quantifying machining forces. This work aims to analyze different cutting parameters (cutting speed and feed per tooth rate) and the influence of lubrication upon tool wear and, consequently, machining forces on a top milling of a 304 austenitic stainless steel. Assessments of the rake face was performed by optical microscope (OM) to evaluate tool wear. The results showed that the higher the feed per tooth, the greater the magnitudes of the machining forces and that the tool wear were directly related to the machining forces values. In terms of lubrication, dry machining resulted in lower tool wear rates, compared to Minimum Quantity Lubrication (MQL). Machining with MQL aims to reduce machining forces and improve the surface integrity of machined parts. However, in the case of top milling, MQL resulted in increased tool wear, and led to deterioration of surface integrity.

Keywords: Milling, Tool Wear, 304 austenitic stainless steel, Roughness.

1. INTRODUCTION

Machining is widely applied in the final stages of manufacturing process. Hence, it is expected that at the end of these processes, dimensioning and surface quality desired is achieved according to project. However, tool wear may reduce machining accuracy, resulting in poor surface quality. Understanding the tool wear processes allows the operator to act consistently and effectively on cutting parameters while maximizing productivity. Thus, the study of tool wear is of great importance for the machining area. Although costs applied to inserts represent a small fraction of the manufacturing processes, tool wear can result in large losses in productivity during replacement, and directly impacts on production costs. Furthermore, understanding how the cutting parameters influence the cutting tool wear mechanisms may also lead to improvement of surface quality (COPPINI; DINIZ; MARCONDES, 2000; MACHADO et al., 2009).

Currently, there is an increasing usage of stainless steel in the aeronautical, aerospace, food and mechanical industries in general. For this reason, optimization of stainless steel manufacturing processes is becoming increasingly important. Among the manufacturing processes, machining is one of the most used processes due to the refined surface finishes, and sharp dimensional tolerances. The cutting parameters, tool geometry and cutting fluid application play a fundamental role in the optimization of the machining process, in the cost of production and, above all, in the quality of the final product (CARVALHO, 2018). Machining of AISI 304 stainless steel is widely used in various industrial applications, though it represents a major challenge in the production processes, as it has low thermal conductivity and a tendency to work hardening.

Machining results in large forces, and the generation of high temperatures in the tool's cutting zone, generally results in accelerated wear. These obstacles experienced during machining affect production cost, as well as the surface integrity. Therefore, the improvement of the application of cutting fluid in the cutting zone is an effective method to minimize the referred problems, increasing the cutting performance. The main functions of the cutting fluid are to reduce cutting forces and the temperature in the cutting zone, promoting better chip transport and increasing tool life. Conventional flood lubrication technique negatively affects the environment and operator health due to exposure to chemical composition. In addition, cutting fluid contamination can further damage the machined part. (TOUGGUI Y., UYSAL A., EMIROGLU U., 2021). In the last decade, there has been an increase in concern about pollution resulting from industrial processes,

demanding cleaner production, with less emission of pollutants. One of these standards that promote environmental guidelines environment the ISO-14000 standard. The emerging trend of sustainability is shifting the industry from non-biodegradable to biodegradable cutting fluid, thereby reducing tons of mineral-based fluid. The goal of achieving sustainable production processes is closely associated with energy consumption, carbon emissions and characteristics of the machining process, such as energy consumption and cutting fluid. Following the normative guidelines, it can be inferred that the application of MQL in machining is a trend, both from an environmental point of view and because of the result of better surface finish and reduced cutting forces and energy consumption (JAMIL et al., 2021)

The optimization of cutting parameters is important when there is a demand for the improvement of surface integrity, machining efficiency and cutting forces (SU et al., 2020). This work aims to verify the types of tool wear on the top milling of austenitic steel 304, widely used in industry, and how tool wear influences the generation of cutting force during the production process, and the surface quality of the parts machined. A variation of two cutting parameters was analyzed in 8 different samples: cutting speed and feed per tooth rate in two lubrication-cooling conditions: dry and MQL. To evaluate tool wear, image analysis was performed using OM. Cutting force, obtained with a piezoelectric dynamometer, were analyzed together with tool wear and surface finish defined by the average surface roughness (R_a), which is the most important measurement of surface quality during machining. R_a can be optimized by many machining parameters, such as cutting speed, feed rate, depth of cut, nose radius, machining length with the intention to verify the optimum condition for machining with the studied parameters.

The results showed that the tests performed with MQL resulted in poor surface finish, accompanied by an increase in tool wear, when compared to dry machining. This result differs from the tests performed in different material removal methods, as turning 304 austenitic stainless steel found in the literature.

2. EXPERIMENTAL PROCEDURE

The workpiece analyzed is bar shaped made of AISI 304 stainless steel. The chemical composition was obtained through the chemical analysis performed at Centro Tecnológico do Exército - CTEEx, presented in Table 1.

Table 1 – Chemical composition on AISI 304 (weight %).

C	Mn	P	S	Si	Ni	Cr	N
0,04	1,56	0,025	0,025	0,55	8,45	18,00	0,022

The top milling used a indexable insert holder of 20mm in diameter, carrying two carbide inserts, model R390-11T3 08M-PM, grade 4240 from Sandvik Coromant. The MQL system used was Nebulizador IV Tapmatic from Quimatic and the synthetic soluble oil Quimatic Tapmatic M2-E, diluted in water in a proportion 1 to 19. The atomizing pump pressure was set to 4 bars and cutting fluid flow set to 40ml per hour. Figure 1 demonstrates how MQL system was positioned.



Figure 1: MQL system

In these top milling experiments, two cutting parameters were evaluated: cutting speed (v_c) and feed per tooth (f_z) under two lubrication modes: dry and with Minimum Quantity Lubrication (MQL), totaling 8 conditions, as shown in Table 2. Cutting speeds are set at the lower and upper limit of the cutting tool manufacturer's recommendations. Values for feed per tooth were at the minimum recommended by the tool manufacturer, and the maximum values available on the milling machine used. In addition, tool wear was evaluated according to the progress of the machined length. The design of experiments adopted had two levels for each cutoff parameter. Depth of cut remained constant at 0.2 mm.

Table 2 - Cutting Parameters Applied to the specimens.

Parameters setup	Lubrication	v_c [m/min]	f_z [mm/tooth]
1	Dry	210	0,080
2			0,135
3		225	0,080
4			0,135
5	MQL	210	0,080
6			0,135
7		225	0,080
8			0,135

Forces components were acquired with KISTLER 9257BA, a crystal piezoelectric dynamometer at the Laboratório de Pesquisa em Usinagem (LABUS), CEFET/RJ. The signals are amplified in the Kistler signal conditioner, model 5233A1 and transferred to an acquisition board, model USB6221 BNC, in order to convert the analogue into digital signal. A data acquisition board and a computer software, LabView Signal Express 2011, managed the system with an acquisition rate of 1kHz to collect orthogonal components of F_x , F_y and F_z , as illustrated in the label from Figure 2. To evaluate the machining forces, Eq.(1) was used to evaluate the resultant forces collected in the three orthogonal axes (F_x , F_y e F_z) of the dynamometer. The mean machining force was calculated based on the arithmetic mean of the 10 force peaks acquired in the dynamometer in the central region of the machined sample, which presented the most homogeneous region.

$$F = \sqrt{(F_x^2 + F_y^2 + F_z^2)}, \quad (1)$$



Figure 2. Dynamometer tag indicating Fx Fy and Fz axes orientation.

In order to evaluate the impact of tool wear on surface finish, workpieces were evaluated for each predefined machining length (l_f) (1000, 3000, 5000 and 9000mm). A Mitutoyo SJ-210 roughness meter acquired roughness Ra measurements, with a resolution of 0.002 μm . Cutoff was set to 0.8mm and the evaluation length (l_n) was 5mm. Experiments were carried out at Machining Laboratory (LABUS) at CEFET/RJ. Figure 3 displays the assembly and the measurement using a roughness meter during roughness analysis. For each cutting condition and machined length, the samples were submitted to three readings. Tool wear analysis was performed using an OM Olympus BX60M, with a magnification of 100X. Cutting tools were placed on the stage, providing view from the main cutting edge and the rake face.

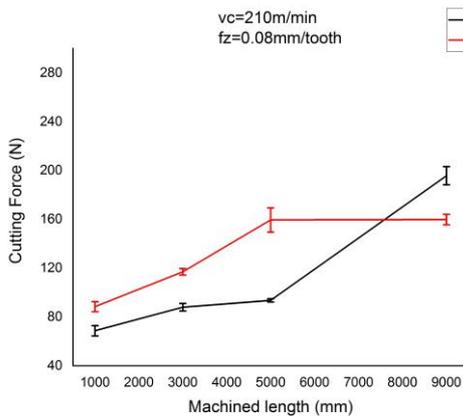


Figure 3: Measurement of Ra values on the workpiece

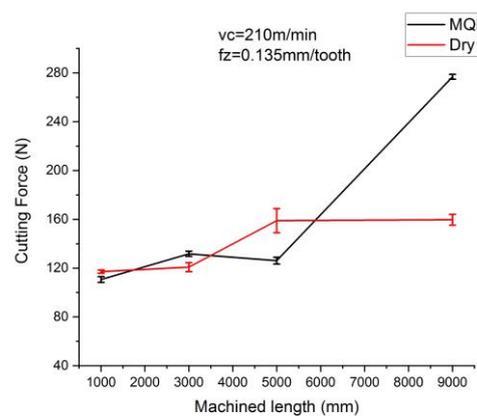
3. RESULTS AND DISCUSSION

3.1 Cutting forces

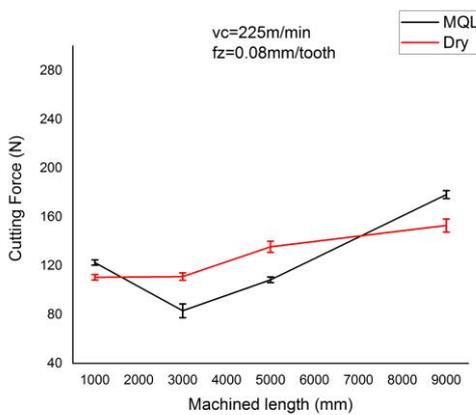
Figure 4 indicates that Machining Forces were significantly lower for MQL when machined length under 5000, which is expected since it improves chip flow on the surface of the inserts. However, from the machined length 5000 up to 9000mm, an expressive increase in cutting forces were acquired for all combinations of cutting parameters when MQL was used, as a consequence to the substantial increase of tool wear. An increase of cutting forces as consequence to tool wear was also observed in the micro-milling experiment (ZHENG et al., 2019). Regarding the magnitude of the machining forces, there is no significant variation under the conditions of greater feed per tooth (0.135 mm/tooth) and machined length up to length up to 5000 mm in the MQL condition. Nonetheless, there has been is increase of machining forces under dry cutting, which could have occurred as a consequence of flank wear. The lowest cutting forces were observed in the conditions of lower feed rate (0.008 mm/tooth), as lower feed values generate smaller chip area. However, cutting speed showed no relevance on cutting forces.



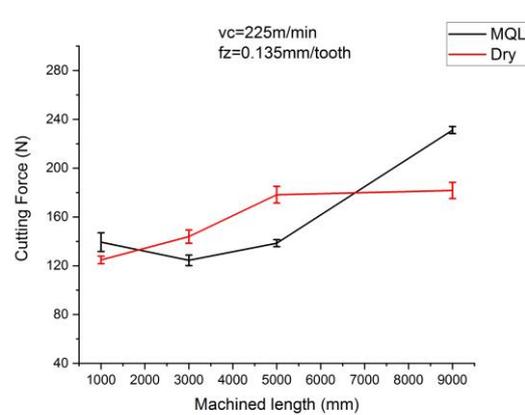
(a) $v_c = 210$ m/min $f_z = 0,08$ mm/tooth



(b) $v_c = 210$ m/min $f_z = 0,135$ mm/tooth



(c) $v_c = 225$ m/min $f_z = 0,08$ mm/tooth



(d) $v_c = 225$ m/min $f_z = 0,135$ mm/tooth

Figure 4: Cutting forces evaluated for dry and MQL (Units: v_c in m/min and f_z in mm/tooth)

3.2 Tool Wear

During machining process, different kinds of tool wear may occur simultaneously. This is especially prominent when milling, due to active and inactive phases endured by the inserts during rotation. When dry machining was performed, flank wear was mostly relevant. However, during MQL, not only development of flank wear, represented in (number 1 on Fig 5(a)), but also a large plastic deformation (number 2 on Fig 5(a)) accelerated abrasion (number 3 on Fig 5(a)) and chipping (number 4 on Fig 5(a)) has also taken place. Figure 5b shows a view from the flank face, both photos for $v_c = 225$; $f_z = 0,135$ with MQL, which showed most tool wear.

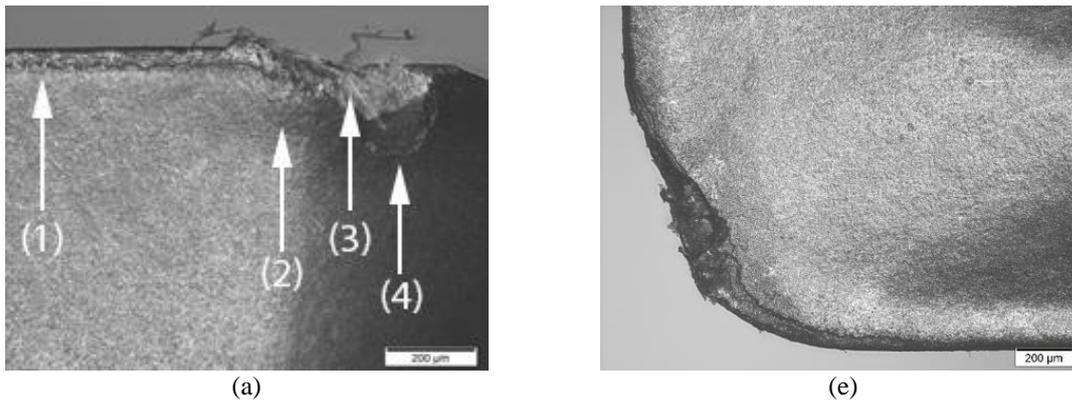


Figure 5. (a) Flank face (b) Rake face for $v_c = 225$; $f_z = 0,135$ with MQL, OM.

The material removal process influences on tool wear. Despite being the same material, (PEREIRA et al., 2016), machined AISI 304 stainless steel through turning process and found higher tool wear levels for the dry turning. The increase of tool wear in milling process also differed from the turning experiments described to perform better with MQL (ALI, S.M., DHAR, N.R., DEY, 2011; J; N, 2020). Nevertheless, more accelerated wear in MQL can be explained in accordance with (COPPINI; DINIZ; MARCONDES, 2000) who found an increase of tool wear when the tool is subjected to thermal variations between the active and inactive phases in milling. In these experiments, tool wear remained below the maximum indicated by Standard 3685/1993, and the experiments were limited by the decrease in the thickness of the workpieces and the impossibility of assembling them to the dynamometer. Figure 6 is used to compare the rake faces of the inserts, and they demonstrate abrasion on the tip of the inserts, especially in cases of those submitted to MQL. The view from the rake faces enables characterization of crater wear, which is in consonance to (COPPINI; DINIZ; MARCONDES, 2000), which may impact on surface roughness.

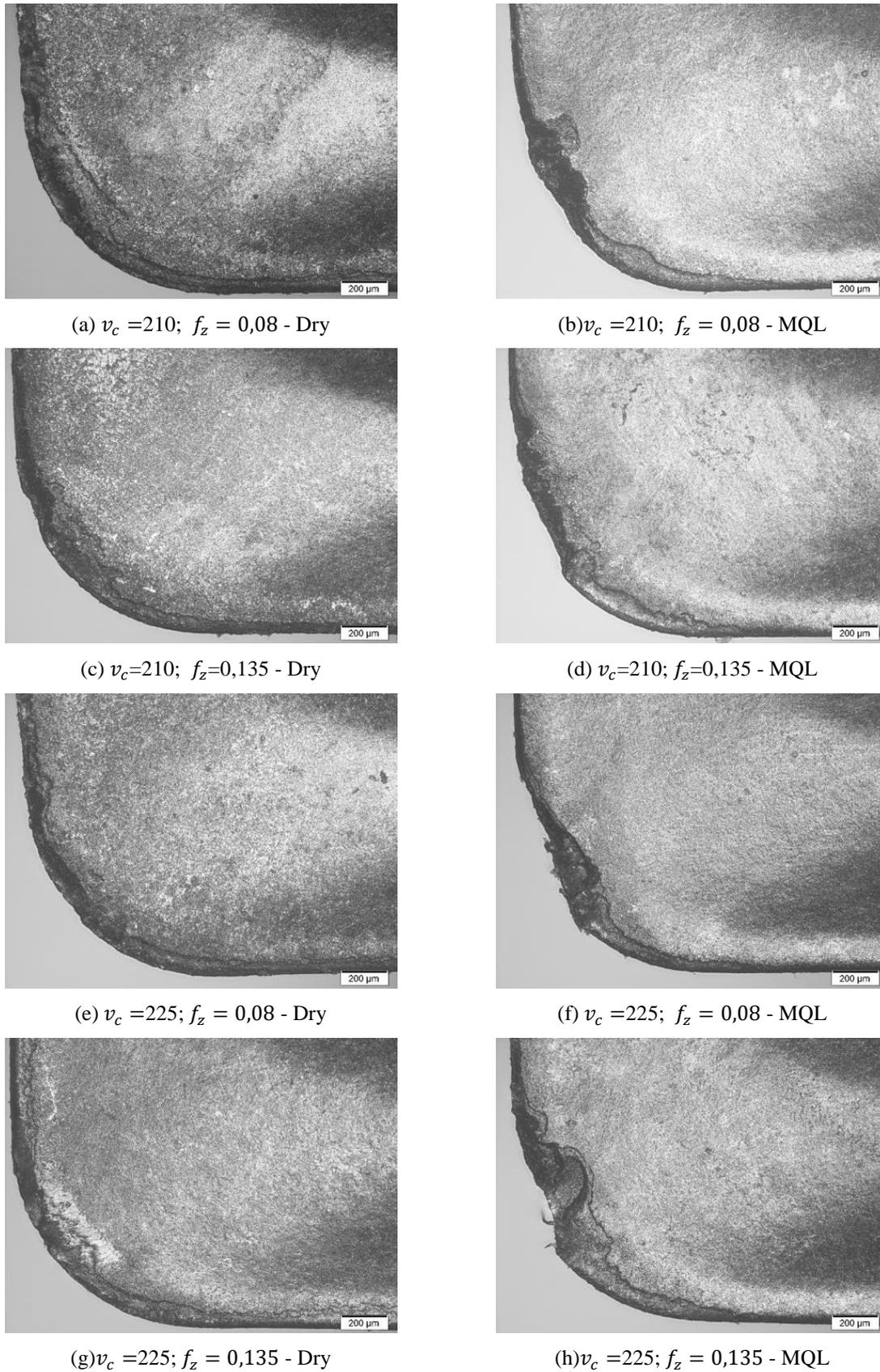


Figure 6. Tool wear investigated at different parameters (units: v_c : m/min e f_z : mm/tooth), OM.

3.3 Surface Intefrity

The search for the best surface integrity is of great importance for machining. According to (SIVAIAH; BODICHERLA, 2020), because MQL is supplied with high pressure on a rake face, coolant can effectively reach to the cutting zone, providing effective cooling and lubrication, leading to better tool life and formation of less tool marks on the machined surface. Although the literature shows the benefits of applying MQL, tool wear results demonstrated that dry machining performs better than when MQL was used for top milling. Figure 7 confronts the grooves generated for different parameters, and cooling conditions using a stethoscope image acquisition. The evaluation of machined surfaces shows feed marks are uniform. The surface of machined parts also display periodical imperfection, or waving occurred for MQL at $v_c = 225$ m/min, for both Fig 6(f) and Fig 6(h).

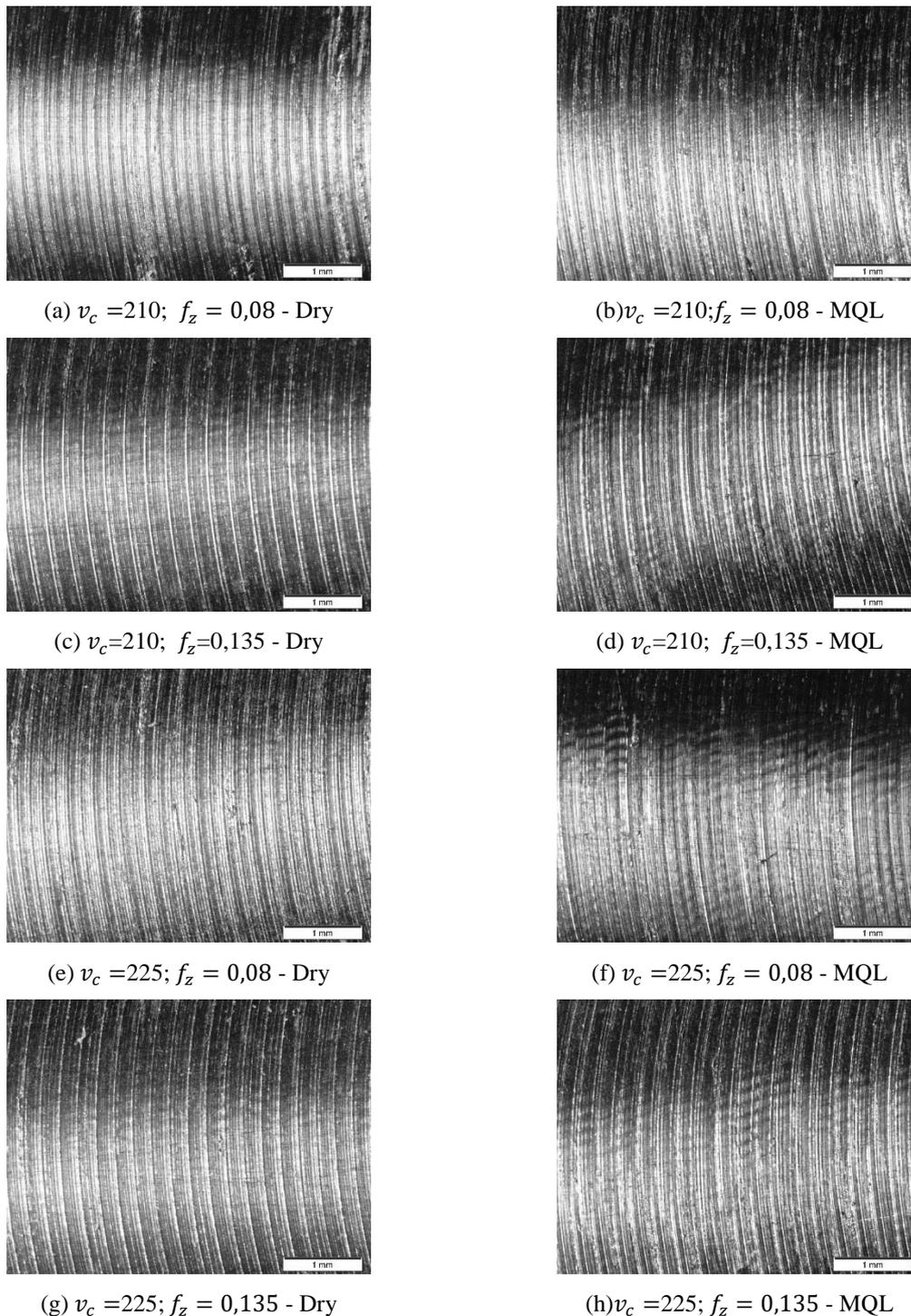


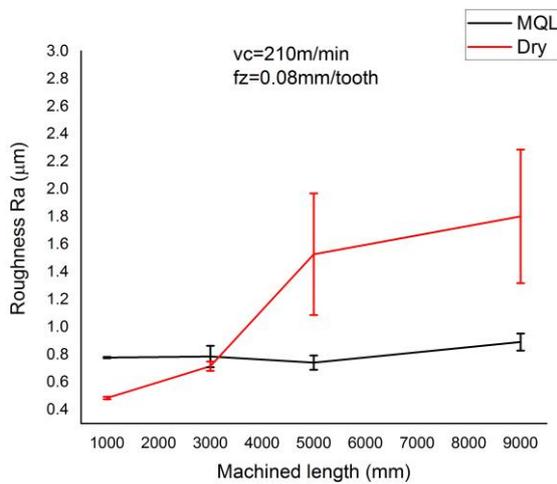
Figure 7: Grooves generated for milling at different parameters and cooling conditions (units: v_c in m/min and f_z in mm / tooth).

Figure 8 indicates Ra measured on the surface of the samples machined under different machining parameters, for dry cutting or for those with MQL application. The roughness evaluation Ra can also be calculated using theoretical solutions. In the case of top milling, the Ra can be calculated using Eq. 2, and for these experiments, two theoretical values can be assumed, since there are two f_z being analyzed. For f_z equal to 0.08mm, theoretical solution gives $R_a = 5 \times 10^{-4} \text{ mm} = 0.5 \mu\text{m}$. For f_z equal to 0,135, theoretical solutions gives $R_a = 1.42 \mu\text{m}$

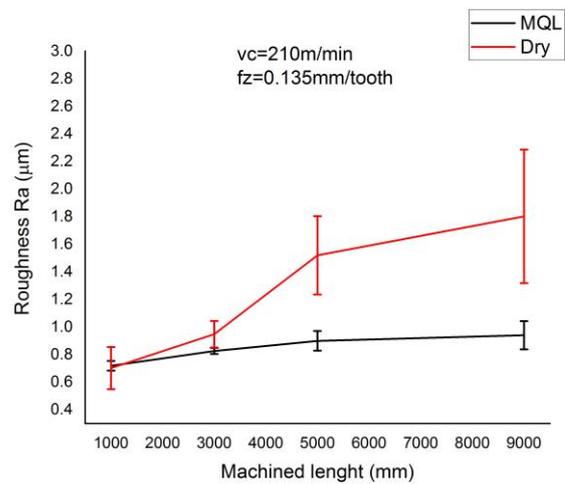
$$R_a = \frac{r\epsilon - \sqrt{r\epsilon^2 - \left(\frac{f_z}{z}\right)^2}}{2} \quad (2)$$

Where $r\epsilon$ and f_z are the tool tip radius and feed per tooth rate, respectively.

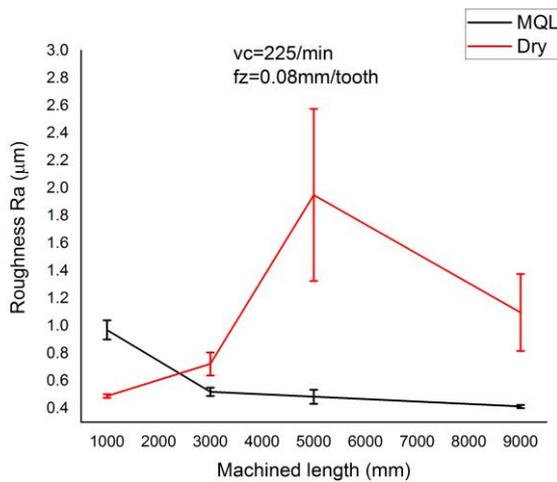
The graphics show a clear advantage of using MQL when the machining objective is to obtain the optimized surface finish. This result is in agreement with (FERRARESI, 1970), since the usage of MQL promotes cleaning and lubrication of tools during the inactive phase of milling, contributing to better chip flow during the active phase. The error bars demonstrate the heterogeneity on dry cutting and also an uneven finish.



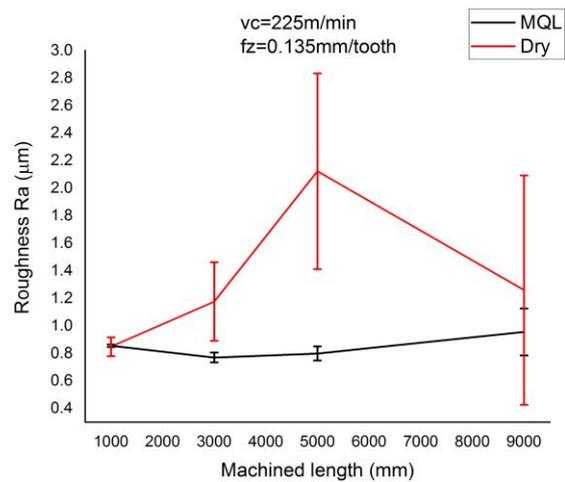
(a) $v_c = 210$; $f_z = 0,08$



(b) $v_c = 210$; $f_z = 0,135$



(c) $v_c = 225$; $f_z = 0,08$



(d) $v_c = 225$; $f_z = 0,135$

Figure 8: Roughness Ra values (units: v_c in m/min; f_z in mm/tooth).

4. CONCLUSIONS

The following conclusions can be drawn from the present experimental work

- 4.1 Feed per tooth was the most relevant parameter that influenced cutting force.
- 4.2 Up to the machined length of 5000 mm, the MQL machining condition presented, in general, lower cutting force values.
- 4.3 In the MQL condition, after machining 5000 mm there was an increase of tool wear, and the advantages of MQL started to be suppressed.
- 4.4 Ra values for MQL were better than dry machining. However, an increase of tool wear led the texture of samples with periodical imperfection, larger than roughness profiles, and could not be evaluated with the roughness meter.
- 4.5 The present work reveals that MQL accelerates tool wear for top milling of AISI 304.

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