Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.7 n.31, p. 26-34. Sept/Oct, 2021
DOI: https://doi.org/10.5935/jetia.v7i31.772

RESEARCH ARTICLE OPEN ACCESS

EFFECTS OF LUBRICOOLING CONDITIONS ON MACHINING FORCES AND SURFACE ROUGHNESS IN RADIAL GROOVING

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ARTICLE INFO

Article History
Received: September 02th, 2021
Accepted: September 30th, 2021
Published: October 29th, 2021

Keywords:
Radial grooving,
Compressed air,
Minimum quantity lubrication,
Machining force,
Surface roughness.

ABSTRACT

Radial grooving is a machining process usually applied to generate grooves for thread relief, O-ring positioning, or even cutting-off operations. Due to the high machining forces and difficult chip removal, radial grooving is considered a critical process, and cutting fluids are usually applied for cooling, lubricating, and assistance on the chip removal. Compressed air (AIR) and minimum quantity lubrication (MQL) are lubri-cooling methods studied as environmentally-friendly alternatives to conventional flood (WET) applications of cutting fluids. Although already applied for years in several machining processes, the research associated with using alternative lubri-cooling techniques in radial grooving is incipient. This work presents a comparative analysis of these methods (WET, MQL, and AIR) and their radial grooving effects. In each case, a factorial design of experiments was used to evaluate the influence of lubri-cooling conditions, cutting speed, and feed rate over feed force, cutting force, and surface roughness. Results indicate that both AIR and MQL may be suitable substitutes for traditional WET lubrication when active force components and surface finish are considered. Besides, smaller cutting forces were obtained with AIR machining for radial grooving, followed by MQL and WET machining.

I. INTRODUCTION

Radial grooving is a variation of turning where the tool moves in the radial direction towards the rotation axis of the part. The main applications of this machining process are the production of radial grooves, e.g., to provide thread relief or to position O-rings [1], and parting-off. If this process is carried out until the rotation axis, the workpiece is separated into two parts, and the process is then called parting-off. The main process parameters in radial grooving are cutting speed (v_c), feed rate (f), and depth of cut (a_p). While f occurs in the radial direction, a_p is usually defined by the length of the main cutting edge (except in "partial grooving", where only a fraction of the cutting edge is used). Grooving and parting-off processes are subjected to several problems such as excessive forces, vibrations, and difficult chip removal.

In the radial grooving and parting-off process, the main cutting edge and both secondary flanks are in simultaneous contact with the workpiece. Thus, forces and heat generation concentrate on the weakest region of the cutting tool, making radial grooving a critical operation. Figure 1 presents a schematic representation of the orthogonal components of the machining force in the radial grooving and parting-off process. The vector sum of feed force (i.e., radial force F_x) and cutting force (i.e., tangential force F_y) denote the active force in the work plane. Both F_x and F_y are associated with relative tool/part movements. Passive force (i.e., axial force F_z) is related to possible deformations, strains, and vibrations experienced by the cutting tool in a direction orthogonal to the work plane.

Cutting fluids are commonly used to reduce the adverse effects of heat and friction on the tool and workpiece [2]. The primary functions of cutting fluid in radial grooving are heat removal and lubrication, thus reducing temperatures and friction in the tool-workpiece and tool-chip contact interfaces. However, cutting fluids can also represent a considerable threat to humans and the environment. Cutting fluid additives such as bactericides and fungicides, combined with reaction products originating from the cutting fluid and contaminants, may cause diseases. Also, the growth of microorganisms may degrade the quality of cutting fluids and pose health risks to workers [3]. The excessive increase in costs related to the use and disposal of cutting fluids, combined with new laws concerning environmental and health protection, led to in-depth scientific research on green machining [1]. Dahmus and Gutowski [4] report that, although environmental concerns related to material removal rate are focused on power consumption, the environmental problems related to cutting fluid preparations and cleaning are tied more closely to the liquid and hazardous waste that may cause issues in both local and global levels.

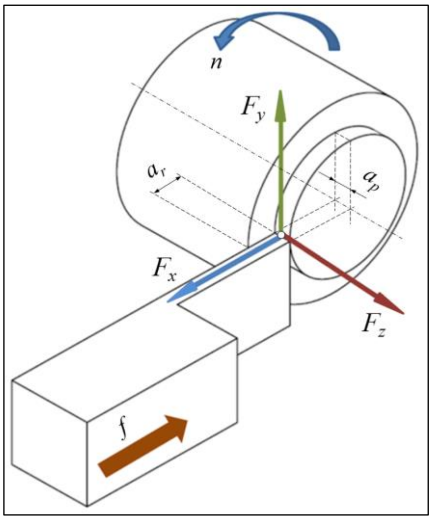

Figure 1: Schematic representation of the orthogonal components of machining force in single grooving (SG): cutting force (F_y), feed force (F_x), and passive force (F_z).
Source: Authors, (2021).

Considering the necessity of protecting humans and the environment, the focus on cutting fluids changed over the years, from biodegradation to renewability. Several techniques were developed to control the temperature in the cutting zone for enhancing machining performance, like solid lubricants, minimum quantity lubrication (MQL), near dry machining, high-pressure coolant, internal tool-cooling, compressed air/gas cooling, and cryogenic cooling [5]. Moreover, techniques aiming at reducing the use of cutting fluids, as MQL, or even eliminate their use as DRY cutting or compressed air-cooling (CAC) machining have received considerable attention. DRY and MQL techniques, classified as friendly to the environment, have been successfully applied in several machining processes [6, 7]. Otherwise, the use of vegetable oils as cutting fluids is also studied to reduce the environmental impact of the machining processes [8-11].

In MQL machining, minimal quantities of cutting fluid, usually a straight oil, are applied to the cutting area. With MQL, the combination of DRY cutting advantages (i.e., low cost and clean production) with benefits of flood (WET) machining (i.e., lubrication, cooling, and chip removal) is very well achieved. Ranganath and Vipin [12] cite that when only surface roughness and cutting force are considered, MQL turning offers more advantages than WET turning.

According to Varghese et al. [13], the general use of cutting fluids offers inadequate temperature reduction in the machining of advanced engineering materials since they do not effectively reach the tool-chip interface. Dhar et al. [14] observed that the use of MQL allowed a substantial reduction of temperature in the cutting zone and resulted in better accuracy in turning of AISI 1040 steel. Lohar and Nanavaty [15] presented similar results, in whose smaller forces and temperatures and better surface finish were noticed in hard turning of AISI 4140 with MQL compared with DRY and WET turning using CBN tools. Kurgin et al. [16] evaluated the convective heat transfer coefficient for different lubri-cooling conditions and concluded that the mist oil volume does not significantly influence the convective heat transfer, therefore strongly dependent on the air pressure. However, the same study observed that convective cooling is not as significant for temperature reduction in machining as the presence of oil, concluding that the lubricating effect of MQL is more critical than convective cooling for temperature reduction. Islam [17] obtained lower average roughness (R_a) values for MQL than DRY and WET machining in turning AISI 1030 steel. Frăţilă and Caizar [18] found no relevant differences between the surface roughness of AISI 1045 after DRY, WET, and MQL turning. However, Tasdelen et al. [19] studied the contact length of chips in orthogonal cutting with different lubri-cooling methods. They concluded that MQL and CAC are potential candidates for grooving and parting-off due to the narrower chips noted after machining with these lubri-cooling methods, especially when compared with DRY cutting.

Better surface finishes were also associated with MQL in the hard turning of AISI 4340 steel [20, 21]. Okokpujie et al. [22] concluded that MQL is the best lubri-cooling technique, but there is still necessary to develop a single technique that can multi-deliver lubricant with efficient performance.

Several studies focused on the effect of the characteristics of the MQL over the machining results. Masoudi et al. [23] compared MQL turning with different nozzle positioning, finding better outcomes for the simultaneous cutting fluid application in the tool flank and rake face. When only one nozzle is used, better results were found when the rake face receives the MQL. Rahim and Dorairaju [24] studied the influences of the nozzle size and positioning for MQL turning and concluded that a wider nozzle provides better cooling and reduction of cutting forces. Another study also focuses on the characteristics of the MQL oil and its influence on the machining results. Sani et al. [25] evaluated the performance of some lubricant mixtures supplied via MQL in the orthogonal cutting of AISI 1045 steel and found a reduction of 4-5% in the cutting force, 7-10% in cutting temperature, and 8-11% in tool-chip contact length.

WET and MQL applications in machining have issues related to fluid disposal and mist generation, respectively. While the former is usually associated with environmental hazards and pollutions, the second might cause health problems to operators [26], which may, fortunately, be eliminated with mist extractors. Considering the limitations of both WET and MQL conditions, the challenge for researchers is to achieve environmentally-friendly machining without sacrificing process performance. Gas-cooled machining is a technique that may allow the industry to achieve these goals: it does not have any adverse effect on health and can be regarded as an alternative to WET machining [27].

Gas coolants are generally referred to as substances in the gaseous form at room temperature and are regarded as environmentally friendly. The CAC machining is a particular case of gas-cooled systems. In addition to being clean, this technique can be readily implemented since air is a natural resource and is available in the desired form in most floor-shop industries.

Stanford et al. [28] studied the use of gases, including compressed air (AIR) and nitrogen (gas N_2 and liquid LN_2) cooling in turning of EN32B (SAE 1016) steel. AIR machining resulted in a lower formation of crater wear compared to DRY cutting and N_2 cooling. Also, machining forces were lower in turning with AIR than with N_2 cooling and flood (WET) machining. Likewise, it was observed that oxygen generates a low lubricating effect in the cutting zone for continuous cutting operations. Sarma and Dixit [29] studied the DRY and AIR turning performance of grey cast iron with mixed ceramic insert. The authors noted that, compared with DRY cutting, AIR reduced both cutting force and feed force.

Additionally, AIR machining significantly reduced the flank wear rate and allowed higher tool life at high cutting speeds (at least 400 m·min^{-1}), thus being an economical and sustainable option.

Cryogenics express the utilization and study of materials at temperatures below –150 °C and have several industrial applications. The application of these extremely low temperatures in machining is called cryogenic (cryo) machining [30]. The most common cryogenic coolants are liquid nitrogen (LN_2), liquid carbon dioxide (LCO_2), and liquid helium (LHe). However, CO_2 is a greenhouse effect gas and is considered an air pollutant [31]. Due to the lower temperatures achieved, most studies involving cryo-machining concentrate on difficult-to-cut heat-resistant alloys [32, 33]. Nevertheless, some studies evaluated cryogenic cooling in machining AISI 1045 steel [34, 35].

Despite the increasing number of papers approaching DRY or near dry machining (NDM), research involving alternative lubri-cooling techniques in radial grooving is incipient. Obikawa et al. [36] compared MQL, DRY, and WET grooving of a 0.45% C steel and concluded that the lubrication at the tool-chip interface is strongly affected by the transportation mechanism of the oil into the interface. Machai et al. [37] compared the effect of various lubri-cooling techniques on the grooving of different tempers of β-titanium alloy, achieving higher tool lives with MQL and LCO_2.

Thus, this paper presents a comparative study of the effects of different lubri-cooling methods in radial grooving. The study focuses on the influence of minimum quantity lubricant (MQL), compressed air (AIR), and conventional flood (WET) machining on the active components of the machining force and surface roughness of the groove walls in single grooving (SG) and partial grooving (PG). Tests were performed with three different cutting speeds and feed rates to verify the feasibility of using sustainable cooling methods in different machining conditions.

II. MATERIALS AND METHODS

The experimental procedure consisted of the machining of radial grooves in cylindrical workpieces. Due to the low quantity of research papers concerning radial grooving, it was decided to use a material whose machining behavior was well documented, especially in turning. For this reason, the runs were performed in cylindrical parts of 170 HV AISI 1045 steel. Grooving runs were carried out on a CNC lathe Mazak QTN 100-II, with 3.0 mm wide PVD-TiAlN/TiN coated carbide inserts (Sandvik N123F2-0250-0002-CM 4125) and a LF123F20 2020B tool holder.

In order to enable the assessment of surface roughness in inner faces, 8 mm wide grooves were machined in 50.8 mm diameter workpieces, resulting in three plunges. The first plunge consisted of a single grooving (SG), where the depth of cut was defined by tool width (3.0 mm). The second and third plunges were done with a_p = 2.5 mm. In this case, only one secondary cutting edge contacted the workpiece; this variation of the cutting process is named in this paper as "partial grooving" (PG). Surface finish for a_p = 3.0 mm was measured in Face#1 of each groove, while Face#2 was generated with a_p = 2.5 mm. Each workpiece (Fig. 2) allowed the machining of three grooves.

Three lubri-cooling conditions were tested: flood (WET), with BD-Fluid B90 water-miscible bio-lubricant at 20% wt. and 720 l·h^{-1} flowrate; MQL, with Quimatic Jet water-based synthetic fluid applied at 400 kPa with 0.24 l·h^{-1} flowrate; and compressed air (AIR), provided at 600 kPa and 2500 l·h^{-1} flowrate. BD-Fluid B90 is a biodegradable 100% oil-free bio-lubricant developed by the Bondmann Chemical Co. This cutting fluid allies high lubricity, similar to straight oils, with high cooling capacity without toxic steams. Since it was developed especially for MQL application with the Nebulizer IV sprinkler, Quimatic Jet was used for the MQL tests. It is a synthetic, water-based cutting fluid developed by the Tapmatic Co. This oil was selected due to its lubricating and cooling capabilities, noticed in recent publications [38, 39], and, according to the manufacturer, it is not hazardous to the machine operator or the environment. Nebulizer IV was fixed in the lathe turret during the experiments, and the spray nozzle was positioned 25 mm from the tool cutting edge. AIR was also delivered through the Nebulizer IV system, in the same position used for MQL. Figure 3a presents the cutting fluid supply placed for the WET machining tests, and Figure 3b shows the positioning of the nebulizer nozzle for MQL and AIR machining tests.

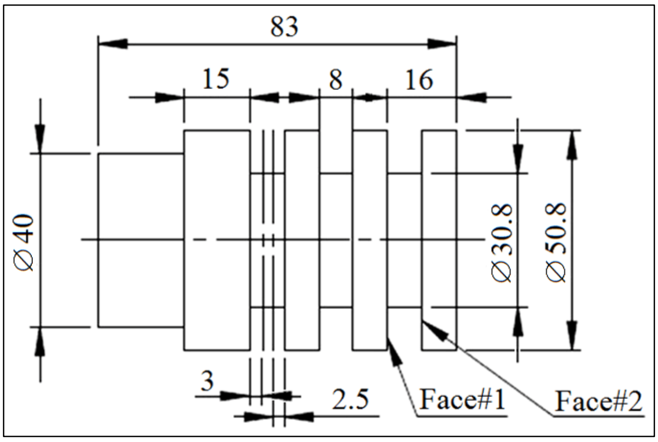

Figure 2: Workpiece geometry and dimensions (mm).
Source: Authors, (2021).

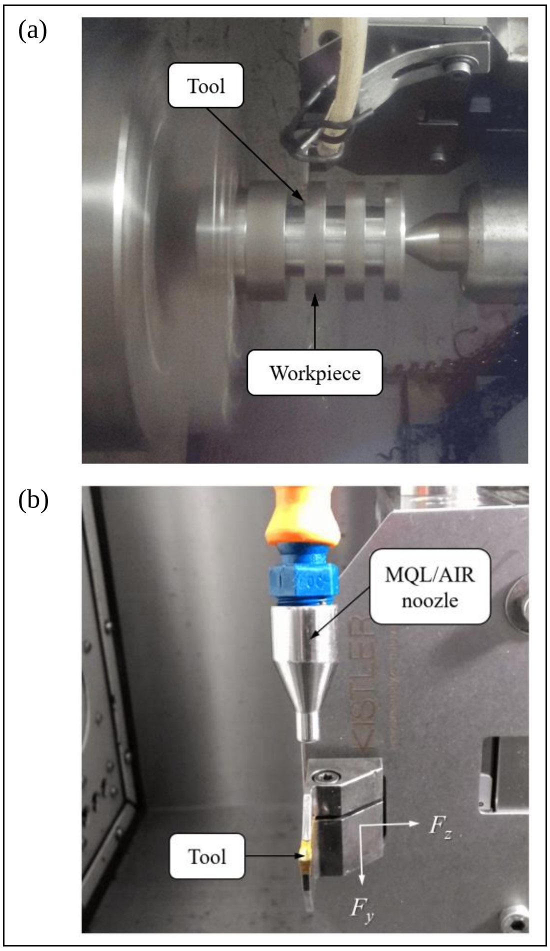

Figure 3: Experimental setup: (a) positioning of cutting fluid hose for WET machining; (b) MQL/AIR nozzle positioning.
Source: Authors, (2021).

A factorial DOE (design of experiments) was used where three machining parameters (cutting speed, feed rate, and lubri-cooling condition) were tested at three levels, resulting in 27 treatments for each grooving type (single or partial grooving). Three replications were used, each in the same workpiece. The influence of tool wear was controlled using a new cutting edge for each tested condition. Table 1 presents the machining parameters used in the experiments.

Table 1: Machining parameters and conditions.

Input variables	Levels
Cutting speed (v_c)	150, 175, 200 m·min^{-1}
Feed rate (f)	0.05, 0.075, 0.1 mm·rev^{-1}
Depth of cut (a_p)	3.0 mm (SG), 2.5 mm (PG)
Groove depth (a_r)	10 mm
Lubri-cooling method	WET, MQL, AIR

Source: Authors, (2021).

The assessment of the orthogonal components of machining force (F_x, F_y, F_z) in radial grooving was carried out with a Monitor System composed of a Kistler® 9129A piezoelectric dynamometer, a Kistler 5070A charge amplifier, a Measurement Computing PCIM-DAS 1602/16 DAQ board, and a dedicated PC with LabVIEW 9.0. The data acquisition rate was set at 1 kHz, allowing for at least 30 samples per revolution.

The surface finishing of the machined grooves was evaluated through average (R_a) and total (R_t) roughness with a Mitutoyo SJ 201P roughness tester, using a 4 mm evaluating length with 0.8 mm sampling length according to DIN EN ISO 4288. The roughness of the machined surfaces was measured in three equidistant points around the workpiece circumference.

The influence of controllable input parameters over the response variables was investigated through the Analysis of Variance (ANOVA).

III. RESULTS AND DISCUSSIONS

III.1 ANALYSIS OF MACHINING FORCE

In this study, the active components of machining force were measured under different cutting conditions, defined through a factorial DOE. Figure 4a presents two-factor graphs of average feed forces (F_x) considering a_p = 3.0 mm (single grooving). F_x results for a_p = 2.5 mm (partial grooving) are presented in Figure 4b. In Figure 4c, F_x values are presented against cutting speed (v_c) for the lubri-cooling methods tested (WET, MQL, AIR) for single grooving (SG), while Figure 4d presents F_x against v_c for partial grooving (PG). Compared with the same cutting condition in WET machining, MQL presented feed forces 5.3% smaller on average, against 10.1% for AIR machining in PG. The worst result for feed forces in MQL machining for PG was observed for the tests performed with the lowest feed rate and cutting speed (+6.6%), and the best result (–17.8%) occurred with the most aggressive cutting condition, which indicates better penetration of lubricant in MQL than in conventional WET machining at high cutting speeds and feed rates. For the AIR condition, the best result in PG (–24.9%) was registered with a cutting speed of 150 m·min^{-1} and a feed rate of 0.1 mm·rev^{-1}, and the highest value of feed force (+3.7%) at the same v_c with f = 0.075 m·min^{-1}. Both AIR and MQL turning presented similar average differences from WET machining (–5.0% for AIR and –4.0% for MQL) in SG. As noted for PG, the worst result for MQL occurred with the mildest machining conditions (+14.1%) and the best result with the most aggressive condition (–17.1%), confirming the high performance of this lubri-cooling condition in higher cutting speeds. As for MQL tests, both best (–20.7%) and worst (+8.8%) relative results for AIR machining in SG occurred in the same conditions noticed for PG.

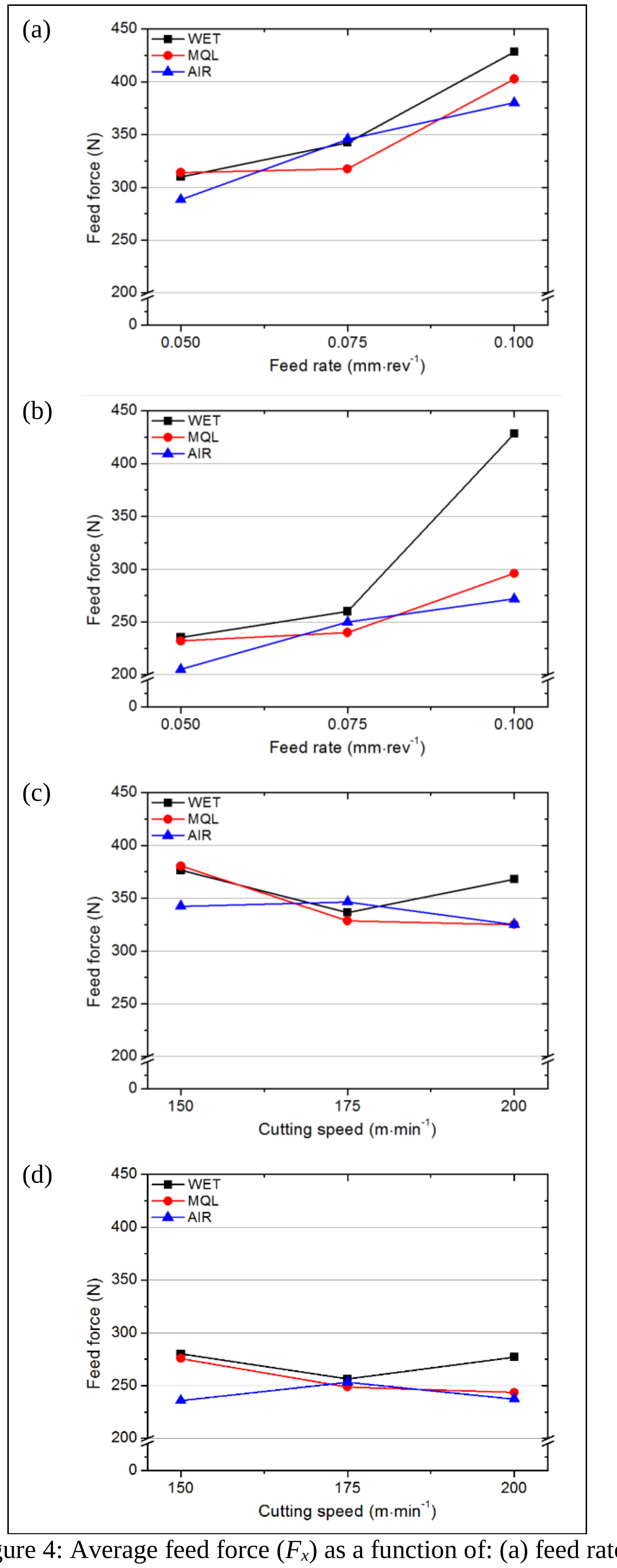

Figure 4: Average feed force (F_x) as a function of: (a) feed rate for SG; (b) feed rate for PG; (c) cutting speed for SG; (d) cutting speed for PG.

Source: Authors, (2021).

The ANOVA of the results indicated a significant influence of all evaluated parameters and interactions over feed force (F_x) for both single grooving (SG) and partial grooving (PG). For the three lubri-cooling conditions, it was observed that F_x values rise with the increase of feed rate (f). Three different behaviors were identified for the three tested lubri-cooling conditions when the cutting speed (v_c) is considered: as v_c is increased from 150 to 175 m·min^{-1}, a decrease is noticed for F_x under MQL and WET machining. However, while a new increase to 200 m·min^{-1} shows low influence when MQL is used, it increases the F_x under WET machining. For SG, AIR machining results showed a slight increase from 150 to 175 m·min^{-1}, followed by a decrease of F_x when grooving with 200 m·min^{-1}. PG presented an initial growth of F_x, followed by a stable behavior between 175-200 m·min^{-1}.

Figure 5a presents two-factor graphs of average cutting force (F_y) against feed rate (f) for single grooving (SG). The equivalent plot for PG is presented in Figure 5b. As shown in Figure 4 for feed force (F_x), F_y values also increase with feed rate (f), but, in this case, the relationship appears to be linear for all the lubri-cooling methods evaluated. Since higher f implies the increase of the cutting section, the behavior observed for F_x and F_y is expected. Figure 5c presents the average F_y versus cutting speed (v_c) for SG, while Figure 5d presents the equivalent plot for PG. As noticed for F_x in Figure 4, each lubricant condition presented a distinct behavior, replicated on a different scale for SG and PG. The average differences between the cutting forces measured for the MQL condition, compared to AIR and WET, were –3.1% and –8.2% for PG, against –2.5% and –6.0% for SG. When comparing each value with the reference (WET machining in the same cutting condition), the worst average F_y for MQL was noted with the mildest machining condition (f = 0.05 mm·rev^{-1} and v_c = 150 m·min^{-1}) for both PG (+1.6%) and SG (+2.6%). The best results for MQL were also associated with the same condition (highest cutting force and feed rate) and were –5.6% for both PG and SG. These results indicate better performance of MQL at the higher levels of v_c and f tested, reinforcing the better access of lubricants in the cutting zone for this condition while evidencing that WET machining can perform better in low cutting speeds.

Compressed air (AIR) condition resulted in the lowest cutting forces (F_y) for all cutting speeds and feed rates, followed by MQL. This effect is explained by the thermal softening of workpiece material due to the higher temperatures related to compressed-AIR machining than the other lubri-cooling techniques tested [40, 41]. This effect can also be observed for feed force (F_x), especially for high cutting speeds. During machining with the highest v_c (200 m·min^{-1}), both AIR and MQL systems allowed significantly lower F_x values than WET machining. According to Hadad and Sadeghi [42], the more effortless penetration of oil droplets in the cutting zone that reduces the friction in tool-workpiece and tool-chip contact interfaces explains the high performance of the MQL system. Thus, there is a high probability that both AIR and MQL allow smaller cutting forces than WET machining due to different mechanisms.

The relation between cutting force and feed rate followed similar patterns for single grooving (SG) and partial grooving (PG), with minor scale differences observed for the results related to the different lubri-cooling techniques. As expected, the increase of feed rate (f) results in a proportional increase in the cutting section, with a proportional increase in the cutting force. On the other hand, no significant influence was noted between the cutting force and the cutting speed other than a slight reduction tendency with MQL. This result agrees with Amorim and Kunrath [43], which studied the relationship between cutting force and maximum flank wear in turning AISI 1045 steel with a carbide tool and found no significant influence of cutting speed (v_c).

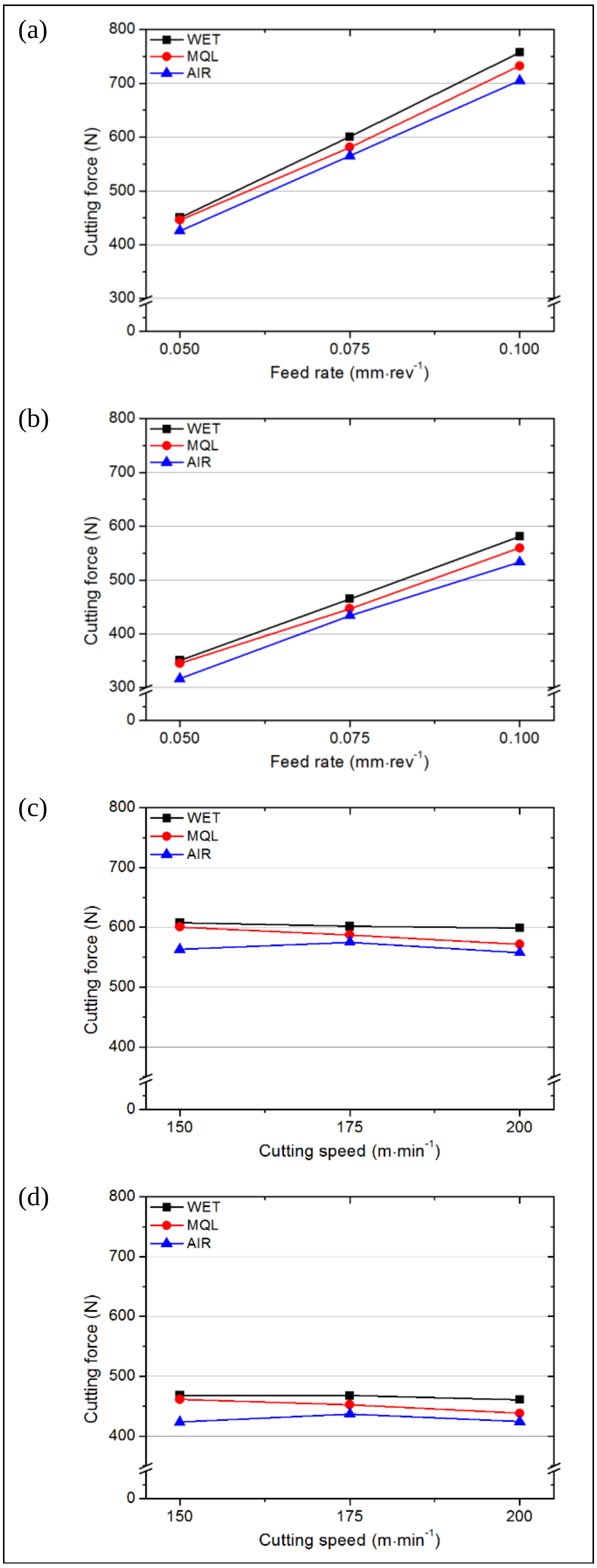

Figure 5: Average cutting force (F_y) as a function of: (a) feed rate for SG; (b) feed rate for PG; (c) cutting speed for SG; (d) cutting speed for PG.
Source: Authors, (2021).

The analysis of the results measured in SG and PG indicates similar feed force (F_x) and cutting force (F_y) behavior in both cutting operations. However, the differences were noticed when SG grooving was performed with a_p = 3.0 mm, while PG was executed with a_p = 2.5 mm. Despite the 16.7% reduction in the cutting section, an average reduction of 23.4% was observed in F_y. Probable causes for this difference are associated with higher friction in SG due to the contact between the workpiece and the two secondary cutting edges and the easier chip removal in PG.

As mentioned, passive forces (F_z) represent possible vibrations, strains, and deformations experienced by the grooving tool. The main difference between single grooving (SG) and partial grooving (PG) is that, while the former has opposing F_z due to two tool corners in simultaneous cut, F_z in PG is not balanced, thus being susceptible to more significant fluctuation and generating vibrations that affect surface finish regardless of cutting parameters or lubricant condition.

Tests performed with WET grooving presented a decrease of average F_z as cutting speed (v_c) increases from 150 to 175 m·min^{-1}, followed by a rise from 175 to 200 m·min^{-1}. Testes carried out with AIR showed a slight increase of F_z from 150 to 175 m·min^{-1}, followed by decreasing these values at higher v_c. On the other hand, tests executed with MQL presented a slight decrease of F_z throughout the tests, with an apparent tendency to stabilize at higher v_c.

III.2 ANALYSIS OF MACHINED SURFACE ROUGHNESS

Surface roughness is a widely used quality parameter, usually a technical requirement for mechanical products [44]. Considering its importance as a project requirement, knowing the relationship between surface roughness and cutting conditions is extremely important to allow the machining parameters correctly. Thereby, this study measured the average (R_a) and total (R_t) roughness parameters under different cutting conditions, defined through a factorial DOE.

Figure 6a presents two-factor graphs of average roughness (R_a) versus feed rate (f) for the surface generated by single grooving (a_p = 3.0 mm) and Figure 6b for partial grooving (a_p = 2.5 mm). Despite the good agreement observed between the active force components' behavior, surface finish results for SG showed poor agreement with results obtained for PG. Similar results are presented for total roughness (R_t) against feed rate in Figure 6c and Figure 6d. The results presented in Figure 6a and Figure 6c indicate that higher roughness was obtained in SG using AIR machining, with WET and MQL machining resulting in statistically equivalent surface roughness (R_a and R_t) for all tested feed rates. For PG, similar behavior was observed for average roughness (R_a) after AIR and WET machining, while MQL resulted in a smaller R_a with f = 0.05 mm·rev^{-1} and higher R_a for the other feed rates. The behavior presented for total roughness (R_t) in Figure 6d agreed with the shown in Figure 6b for R_a with AIR and MQL. However, R_t for WET machining was significantly higher than those noted for tests performed with AIR.

The measured roughness values are plotted against cutting speed (v_c) for SG (a_p = 3.0 mm) and PG (a_p = 2.5 mm) in Figure 7. Both WET and MQL machining allowed smaller values of R_a than AIR for SG (in Fig. 7a) at all cutting speeds. Similar behavior was observed for R_t in Figure 7c. For PG, R_a varies between 2.9 µm and 3.6 µm for all conditions except for MQL at the highest cutting speed, reaching 4.2 µm (Fig. 7b). A decrease of R_t with the increase of v_c was noted for all lubricant conditions (Fig. 7d). Smaller values of R_t were noticed in all v_c for tests with AIR, followed by MQL.

ANOVA indicates a significant influence of all evaluated parameters over R_a for single grooving (SG) tests. Both the lubricant condition and feed rate (f) presented significant influences over R_t for SG. No significant interaction effect was identified for SG for the roughness parameters evaluated. However, only the interaction between the lubricant condition and cutting speed (v_c) for R_t was not significant in PG.

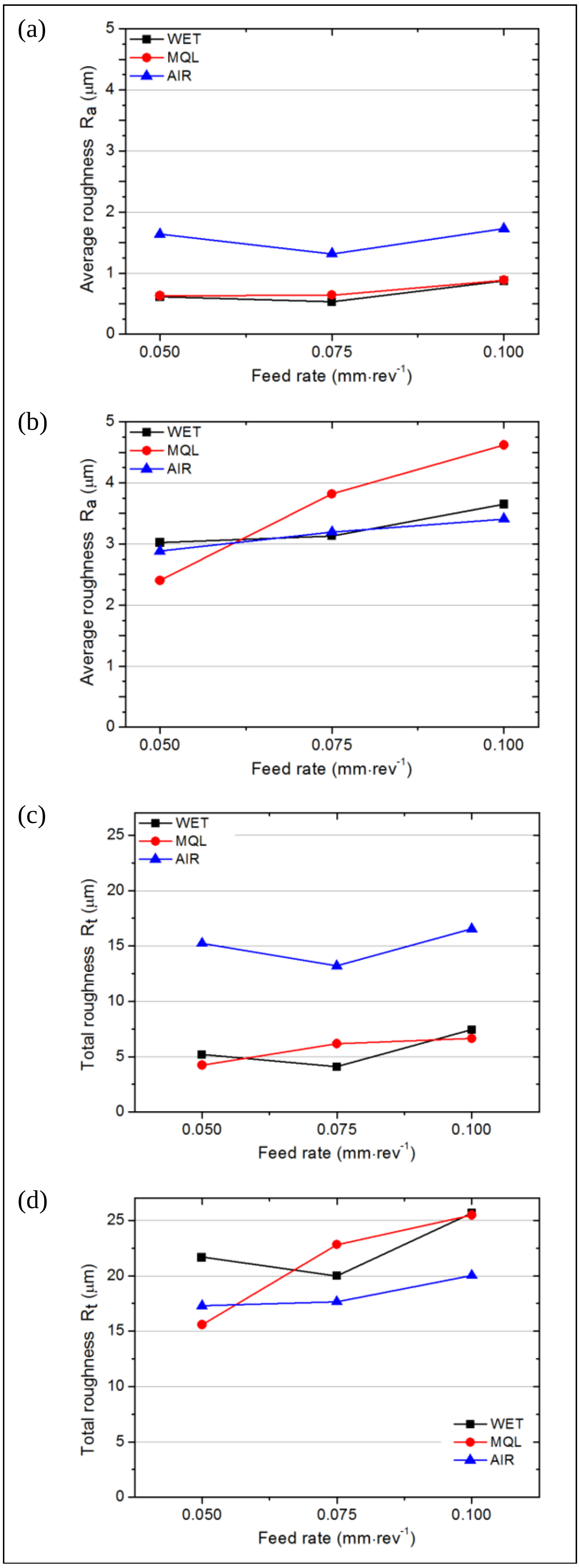

Figure 6: Effect of feed rate on: (a) average roughness (R_a) for SG; (b) average roughness (R_a) for PG; (c) total roughness (R_t) for SG; (d) total roughness (R_t) for PG.
Source: Authors, (2021).

A slight tendency in decreasing R_a and R_t values as cutting speed (v_c) is increased was observed for single grooving (SG). This effect is even more pronounced for R_t after PG and may be related to the temperature increase in the cutting zone in higher v_c, reducing the material hardness and decreasing the friction in the tool-workpiece and tool-chip interfaces.

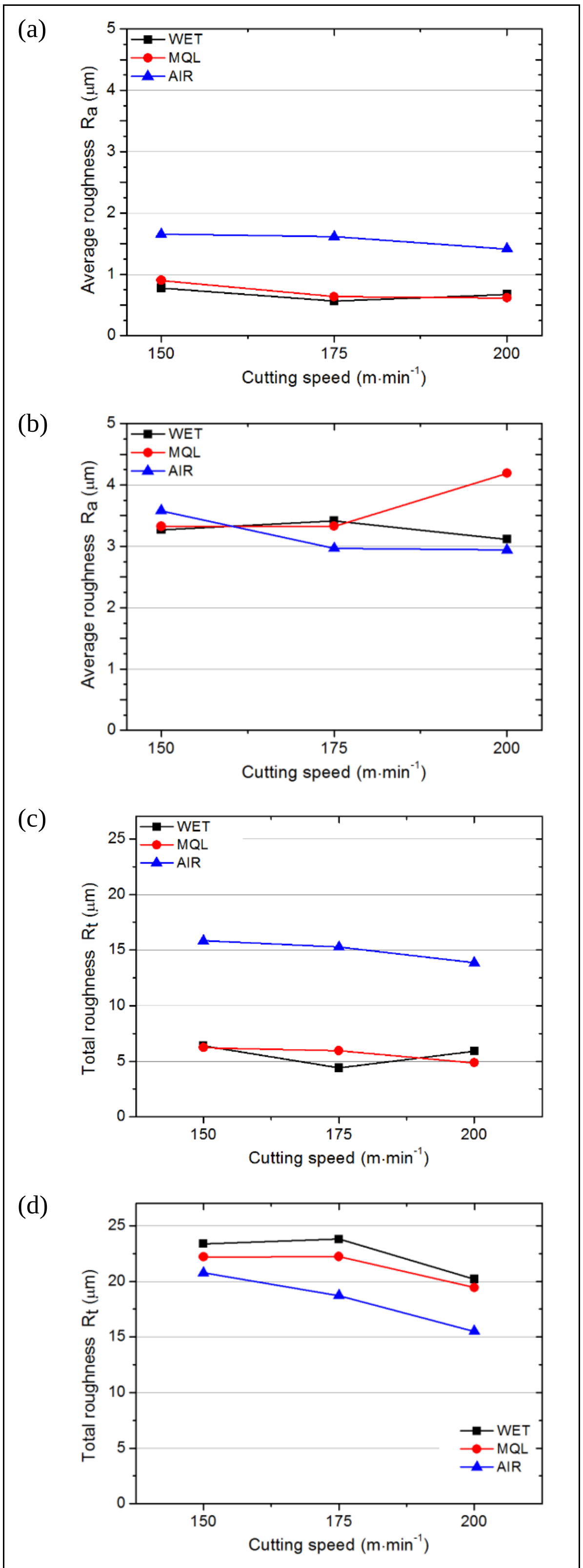

Figure 7: Effect of cutting speed on: (a) average roughness (R_a) for SG; (b) average roughness (R_a) for PG; (c) total roughness (R_t) for SG; (d) total roughness (R_t) for PG.
Source: Authors, (2021).

For SG ($a_p = 3.0$ mm), both WET and MQL systems allowed the best results for surface roughness. The smaller surface roughness values resulted from the application of both systems using $v_c = 175$ m·min^{-1} and $f = 0.05$ mm·rev^{-1} with corresponding $R_a = (0.45 \pm 0.08)$ µm and $R_t = (4.01 \pm 1.54)$ µm for WET machining, and $R_a = (0.47 \pm 0.06)$ µm and $R_t = (3.28 \pm 0.39)$ µm for MQL machining. The smaller values expanded the uncertainty of the results indicates a more stable grooving with MQL. AIR system, on the other hand, delivered the worst surface finishing for SG. Possible reasons for this poor behavior are the lack of lubrication in the tool-workpiece and tool-chip interfaces and the weak chip removal assistance.

Surface finishing results for PG ($a_p = 2.5$ mm) are not as well-conditioned as noticed for SG ($a_p = 3.0$ mm), with surface roughness results, both R_a and R_t, significantly higher. Also, while SG showed no significant interactions over roughness parameters, all interactions were statistically significant for R_a in PG, and only one was not significant for R_t. The high quantity of significant parameters and interactions may indicate the influence of parameters not evaluated in this study.

AIR machining resulted in better surface finishing for PG ($a_p = 2.5$ mm) in several cases, such as at higher v_c (175 and 200 m·min^{-1}) and higher f (0.075 and 0.1 mm·rev^{-1}), which can be partially explained by the workpiece softening, which facilitates chip formation [45]. However, the best results were found with AIR and MQL machining using $v_c = 200$ m·min^{-1} and $f = 0.05$ mm·rev^{-1}. The roughness values found with AIR condition were $R_a = (2.42 \pm 0.15)$ µm and $R_t = (11.35 \pm 1.36)$ µm; with the MQL, the values were $R_a = (2.08 \pm 0.20)$ µm and $R_t = (11.59 \pm 1.27)$ µm.

IV. CONCLUSIONS

This study conducted a comparative evaluation of lubri-cooling methods in radial grooving of AISI 1045 steel. The initial hypothesis adopted was that the application of minimum quantity lubricant (MQL) and compressed air (AIR) could lead to results equivalent to those obtained with conventional flood (WET) machining regarding active force components and surface roughness. The following conclusions can be drawn from the analysis of the results:

- AIR machining resulted in lower cutting forces (F_y) in most tested conditions, implying lower energy consumption. It means that this condition is more economical and sustainable from an energetic point of view. The highest F_y observed in this study occurred in tests performed with WET machining.
- The lubri-cooling condition significantly influenced the feed force (F_x), with higher forces related to the WET condition in most tested conditions. AIR machining resulted in smaller F_x values for the lowest and highest levels of cutting speed (v_c) and feed rate (f) tested.
- The difference between F_x generated under WET, MQL, and AIR machining grows when v_c and f increase. This outcome is possibly related to higher heat removal in WET than AIR and the lower lubrication of this condition than MQL.
- Cutting forces in MQL, when compared with WET machining, were constantly higher at the lowest cutting speed tested, with the best results (highest percent reduction) at all times noticed for the highest v_c. These data support the hypothesis that the cutting fluid in WET machining does not penetrate the cutting interface at high cutting speeds, while MQL droplets do.
- MQL and WET machining generated lower surface roughness for single grooving (SG) tests, while AIR machining resulted in higher roughness for both evaluated roughness parameters (R_a and R_t) evaluated in all tested conditions. The poor surface finishing with AIR indicates that the access of the compressed air in the groove is not sufficient to assist the chip removal.
- AIR machining led to lower total roughness R_t values in partial grooving (PG) for all cutting speeds tested and decreased

average roughness R_a values as cutting speed increases. This effect is probably related to the easier chip removal associated with this condition.

- PG led to poorer surface finishing compared to SG for both roughness parameters considered. The main reason for this is the higher stability of SG due to the opposed components of passive force (F_z). Considering that F_z occurs in the direction where the grooving tool presents its lowest rigidity (and, thus, most prominent tool deflection), the absence of an opposite force in PG leads to vibrations, increasing surface roughness.

The conclusions indicate that MQL is a suitable substitute for WET machining when lower machining forces (and thus energy consumption) and high-quality surface finishing are required. MQL is also better than WET machining when the green machining process is considered. Finally, applying AIR machining allowed smaller F_x and F_y values in the most tested conditions and seemed a suitable substitute for WET machining in certain conditions.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Elias S. C. Espindola and André J. Souza.
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Investigation: Elias S. C. Espindola and Heraldo J. Amorim.
Discussion of results: Elias S. C. Espindola, Heraldo J. Amorim and André J. Souza.
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Writing – Review and Editing: Heraldo J. Amorim and André J. Souza.
Resources: (not applicable).
Supervision: Heraldo J. Amorim and André J. Souza.
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VI. ACKNOWLEDGMENTS

The authors thank Arsenal de Guerra General Câmara (AGGC) for donating material and cutting tools, Bondmann Chemical Industry for BD-Fluid B90, and Quimatic-Tapmatic Co. for Quimatic Jet and Nebulizer IV.

VII. DATA AVAILABILITY

All experimental data that support this study are available online in Mendeley Data entitled "Radial grooving of AISI 1045 steel under different lubri-cooling methods" with the identifier https://doi.org/10.17632/rjxgw8d4fz.1.

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