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ORIGINAL ARTICLE

Comparative study on lubricating and cooling conditions in the drilling process of electrolytic copper

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Abstract

The cutting fluids contributed for removing chips, cooling, and lubricating, on the other hand, are harmful to the environment. The minimum quantity lubrication technique (MQL) in machining operations proved to be suitable in addition to minimizing the environmental impact. The present work is focused on the drilling of electrolytic copper using biodegradable oil as cutting fluids applied by the MQL technique. The specific cutting pressure, burr height, and maximum diameter were measured varying the cutting parameters, cutting speed, feed, and lubrication condition (dry, flooded, and MQL). A statistical analysis was utilized to determine the influence of cutting parameters in the variables measured. The results indicated that the second-order interactions have a significant influence on the specific cutting pressure and in burr height. The lowest burr height was obtained using flood and MQL. The MQL system demonstrated the lowest specific cutting pressure, while the flood exhibited the best performance for diameter analysis. In addition to this, it can be confirmed that the MQL technique may replace the flooding drilling (abundant flow), minimizing the environmental impact.

Keywords Biodegradable cutting fluids · MQL · Drilling · Electrolytic copper · Environmentally friendly manufacturing

1 Introduction

During the last decade, many manufacturing/machining companies have gone with a green concept for a more sustainable pathway in order to minimize the environmental impact. They achieved this by using non-toxic, renewable, biodegradable cutting fluids with plant-based composition, free of chlorine/silicon and with the use of accurate application systems [1].

In recent years, the flooding technique has been suppressed by the minimum quantity of lubricant (MQL) technique, due to environmental issues [2]. In machining, the cutting fluid contributes to different functions, such as removing chips, cooling of the surface, lubricating of the interface between workpiece and the cutting tool, but, represents high costs to the manufacture of the piece. Therefore, the use of fluid must be economically justified and its selection must take into account the workpiece material and the tool, as well as the type of machining operation. Each operation has a severity.

In drilling, for example, the thermal conditions differ significantly from those in simpler processes such as orthogonal cutting and turning. The chip is formed at the bottom of the hole and remains in contact with the drill over a comparatively long distance, which increases tool temperatures. Drilling also differs from some other processes in that both transient and steady-state temperatures are of interest. In many cases, a steady state is never established; tool temperatures simply increase with hole depth. Increasing temperatures and the potential accumulation of hot chips at the bottom of the hole are serious problems in deep hole drilling and often require pressurized coolant to be

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pumped through the drill to ensure adequate cooling and chip evacuation [3]. The chip evacuation is more complicated in the ductile material machining, such as copper, because there is a strong tendency towards the formation of burrs and the adhesion of the material to the cutting tool.

The copper is a highly ductile metal and it has a higher melting point; these characteristics make this material complicated to be machined [4]. Electrolytic copper, the material of this study, has a high electrical conductivity that allows its use as electrical conductors, in the manufacture of electrical equipment, for highly conductive electrical products and for small high-performance heat exchangers [5]. The electrolytic copper consists of a commercially pure high-conductivity copper of any origin that has been refined by electrolytic deposition, then melted, oxidized, and brought to tough pitch or controlled low oxygen content, and finally cast into cakes, billets, wire bars, and so on, suitable for hot or cold working, or both [6]. Due to the large field of application of this material, which extends to virtually all industry segments, it is often necessary to make assemblies by means of mechanical gasket with screws and rivets, and for this purpose, drilling is required. In order to obtain a product with quality, it is sought to improve the machining operation, using cutting parameters and tools appropriate to the material to be machined. In copper drilling, tools of high-speed steel and cemented carbide can be employed [4].

The selection of cutting parameters as well as other attributes of the operation is defined so that problems, defects, and costs can be minimized. Among the main problems in drilling are the burrs (at the entrance and/or at the exit of the hole), circularity errors, and geometric damages. The burrs at the exit hole need more attention because they are bigger and more difficult to remove [7]. Various burr types occur in drilling; they can be classified as uniform, transient, and crown [8]. Another problem in drilling is circularity deviation that quantifies the variation of the hole geometry from a perfect circle and its bidimensional tolerance [9]. Several authors have studied these problems in machining; in this work, [10] the authors evaluated burrs. The feed was the most significant factor in burr size and the second most significant factor was the chisel edge to drill diameter ratio. In copper micromachining [11], it was concluded that the crystallographic orientation too has an important influence on the cutting force and the burr formation. The authors [12] evaluated the performance of coated tools by analyzing thrust force and burr height, and also evaluated the drilling of a sandwich composite material consisting of aluminum and polyethylene core. The drilling tests were carried out using a TiO_2-coated high-speed steel drills deposited by the sol–gel process. The results underline that the TiO_2-coated tool exhibits the best performance and improves the hole quality. The use of the coated drill indicates the formation of smaller burrs. This fact is due to a lower friction of the TiO2 film with the drilled composite. The maximum diameter is significantly affected by the cutting speed, feed, and the interaction between tool and cutting speed. The rise of the cutting speed leads to the rise of maximum diameter due to the increase of the temperature favoring the plastic deformation of the hole during the drilling process. The coating seems to decrease the maximum diameter of the hole avoiding the formation of build-up-edge of aluminum due to a higher thermal stability of the coated drill surface. Rezende et al. [13] studied the drilling of the same aluminum-PE sandwich material. In order to minimize thrust force and burr height, the influence of drill geometry and the pilot hole was assessed. The results indicated that drilling with a pilot hole of Ø4 mm exhibited the best performance with regard to thrust force but facilitated plastic deformation, thus leading to the elevation of burr height, while the lowest burr height was obtained using a particular geometry drill (brad and spur).

In the work cited previously, the authors measured thrust force, and in this work measured thrust force, and by Eq. 1 the specific cutting pressure.. In lubrication and cooling study, it is important to evaluate the specific cutting pressure. There is a modification of the friction conditions between chip and tool and cutting temperature, and consequently, there is variation in the value of Ks [14]. The specific cutting pressure is also

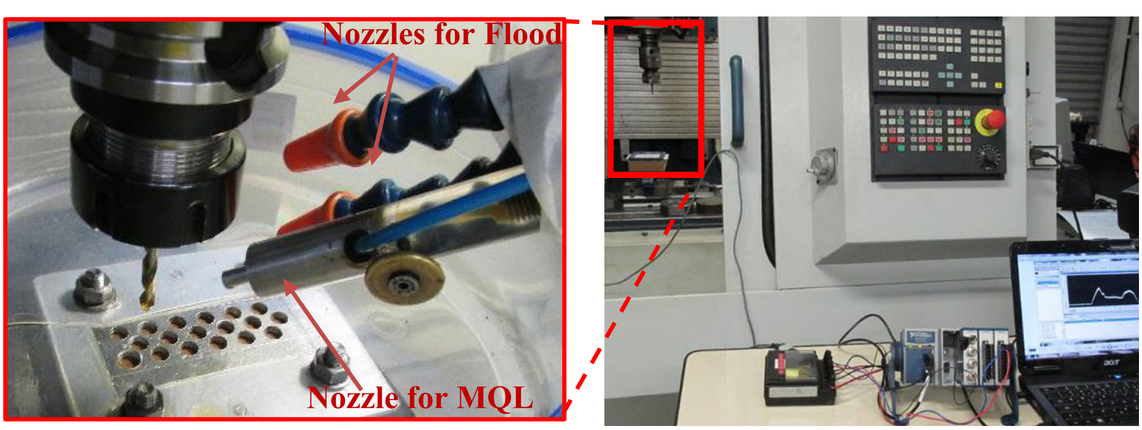


Fig. 1 Experimental setup for the drilling tests

Table 1 Results for specific cutting pressure (SCP), burr height, and maximum diameter

Lubrication condition	V_c (m/min)	*f* (mm/rev)	SCP K_f (N/mm^2)		Burr height h (mm)		Max. diameter D_{max} (mm)	
Dry	25	0.08	251.92	269.97	1.00	0.50	5.029	5.008
Dry	25	0.16	132.41	132.41	2.10	2.13	5.007	5.020
Dry	25	0.24	107.18	105.47	2.71	2.74	5.100	5.018
Dry	50	0.08	277.71	264.82	0.36	0.22	4.997	5.009
Dry	50	0.16	140.14	145.30	1.79	2.09	5.011	5.049
Dry	50	0.24	92.57	92.57	2.62	2.82	5.004	5.012
Dry	70	0.08	277.71	269.97	0.70	0.62	4.995	4.998
Dry	70	0.16	145.30	138.86	2.69	2.43	5.009	5.018
Dry	70	0.24	107.18	92.57	2.85	3.02	5.017	5.035
Flood	25	0.08	251.92	290.61	0.22	0.26	4.997	5.001
Flood	25	0.16	136.28	137.57	0.32	0.36	4.993	4.994
Flood	25	0.24	105.47	90.85	2.62	2.65	4.994	5.000
Flood	50	0.08	269.97	277.71	0.22	0.25	5.001	4.999
Flood	50	0.16	138.86	145.30	0.43	0.46	5.000	5.000
Flood	50	0.24	86.55	88.27	2.61	2.60	4.996	5.014
Flood	70	0.08	280.29	285.45	0.20	0.24	4.992	5.000
Flood	70	0.16	134.99	137.57	0.34	0.28	4.998	5.003
Flood	70	0.24	91.71	97.73	2.26	2.55	5.004	5.005
MQL	25	0.08	251.92	244.18	0.64	0.40	5.055	4.997
MQL	25	0.16	132.41	134.99	1.42	0.43	5.003	5.000
MQL	25	0.24	92.57	88.27	2.60	2.52	5.002	4.991
MQL	50	0.08	254.50	246.76	0.42	0.60	4.998	5.000
MQL	50	0.16	141.43	138.86	0.70	0.93	5.033	4.995
MQL	50	0.24	88.27	101.17	2.00	2.26	5.013	5.039
MQL	70	0.08	244.18	239.03	0.40	0.35	5.072	5.045
MQL	70	0.16	134.99	138.86	0.60	0.71	5.040	4.997
MQL	70	0.24	88.27	93.43	1.19	1.71	5.011	4.995

related to feed and hole diameter. Equation 1 [15] summarizes this relation.

$$k_{\mathrm{f}} = \frac{2F_{\mathrm{f}}}{fd} \tag{1}$$

where F_f is the thrust force (N), f the feed rate (mm/rev), d the drill diameter (mm).

Various authors studied the use of MQL and reported that dry and MQL machining have been calling the attention of researchers in the machining area as an alternative to traditional methods. Dry machining operations are now of great interest and currently meet with success in the field of environment-friendly manufacturing. The MQL system is based on the residue-free cutting oil usage principle, with a low flow of cutting fluid, which one is mixed with compressed air and utilized

Table 2 Analysis of variance (ANOVA) for specific cutting pressure (SCP), burr height, and maximum diameter

Parameters	SCP (N/mm^2)			Burr height (mm)			Maximum diameter (mm)		
	Adj SS	*F* value	*p* value	Adj SS	*F* value	*p* value	Adj SS	*F* value	*p* value
Lubrication Condition	1358	11.80	*0.000*	7.3032	94.73	*0.000*	0.003862	5.69	*0.009*
V_c	55	0.48	0.625	0.2079	2.70	0.086	0.000116	0.17	0.844
f	276900	2405.23	*0.000*	38.7015	501.99	*0.000*	0.000188	0.28	0.760
Lubrication × V_c	170	0.74	0.573	1.1178	7.25	*0.000*	0.002325	1.71	0.176
Lubrication × f	1628	7.07	*0.000*	5.8952	38.23	*0.000*	0.003060	2.25	0.090
$V_c \times f$	369	1.60	0.202	0.3329	2.16	0.101	0.001378	1.02	0.417
Lubrication × $V_c \times f$	375	0.81	0.597	0.4841	1.57	0.181	0.004712	1.74	0.135
R^2	99.45			98.11			63.06%		

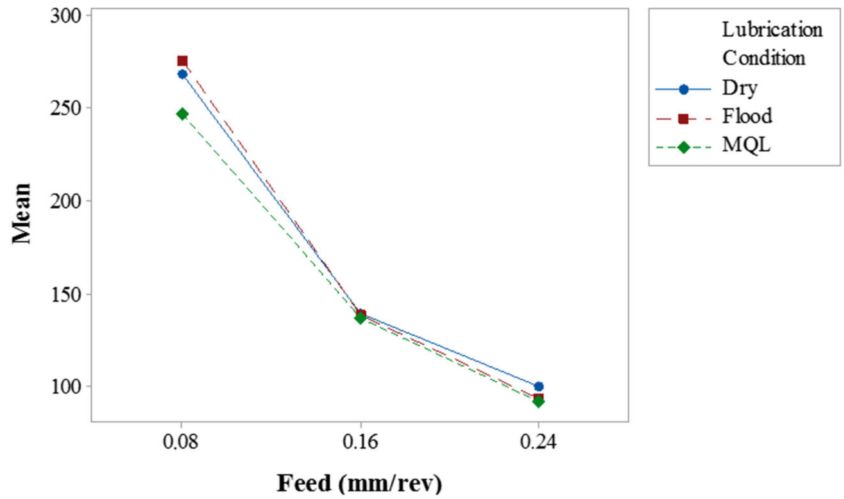


Fig. 2 Lubrication condition × cutting speed interaction plot for specific cutting pressure

in high pressures. The lubricating function is conditioned by the oil and the cooling function by the compressed air. This small quantity of oil (usually < 100 mL/h) is sufficient to reduce the friction in the cutting, as in conventional fluid (mixture of oil and water). Considering the high cost associated with the use of cutting fluids and the increasing costs when the stricter environmental laws are enforced, the choice seems obvious.

Bhowmick and Alpas [16] studied the effect of the lubrication condition in the drilling of the magnesium alloys using diamond-like carbon-coated drills. The results showed that the application of 30 mL/h H_2O-MQL with NH-DLC-coated drills improved the tool life and reduced drilling torque due to the lower coefficient of friction of NH-DLC under H_2O-MQL conditions. Sheng Qin et al. [17] studied the use of MQL technique for different coating tools during turning of titanium alloy. These factors are used when machining difficult-to-cut materials. The authors concluded that the use of MQL contributed to the reduction in cutting force and the reduction in temperature and tool wear. The workpiece material deposited on the tool faces can be significantly reduced and the occurrences of chip breaking and coating peeling off too.

Liu et al. [18] analyzed environmental impacts of direct energy deposition and traditional machining processes for a typical metal part; the results show that the gear laser fabrication process consumes more energy and releases more negative emissions compared with the traditional gear-manufacturing processes.

The authors [19] studied the performance of the MQL system compared to the dry machining in the drilling process of GLARE fiber metal under different cutting parameters. The rise in cutting temperatures during the machining process can influence the final quality of the machined part and the use of the lubrication has contributed to reducing this. The main results in this study showed that the application of MQL cooling can considerably reduce the machining temperatures in GLARE, and the MQL lubricant reduces the friction between the workpiece and cutting tool, while the air pressure assists in transporting the chips and waste material away from the cutting zone. This contributes to the quality of the hole.

Different statistical techniques can be used for validation and description of the experimental results obtained. One is the ANOVA, which is used to verify how much a variable response depends on parameters that have been modified. Several authors use ANOVA for a better explanation of the results; in [20], the authors studied cyclic fatigue strength (CFS) with different parameters and used ANOVA to confirm that the differences have a significant effect on CFS. In [21], the authors

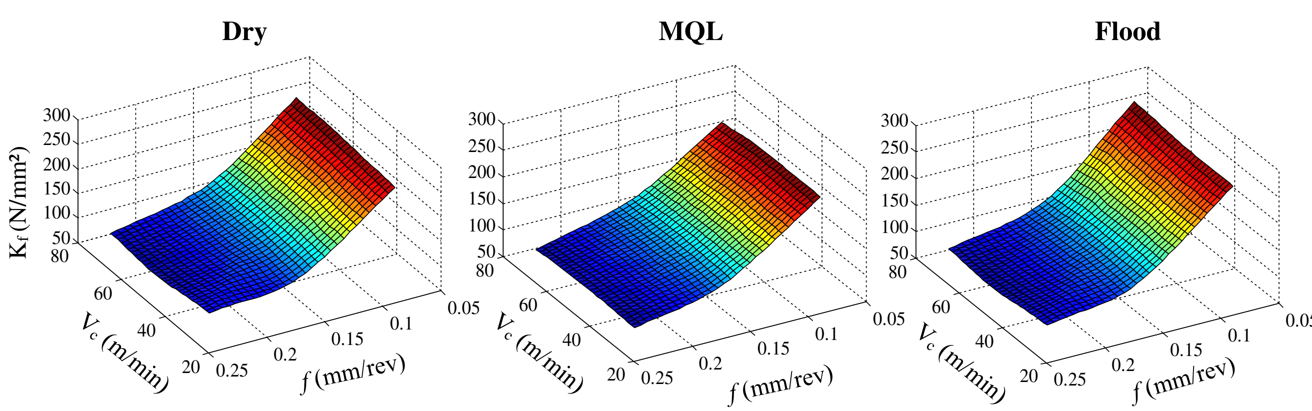
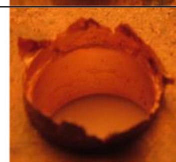
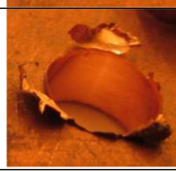
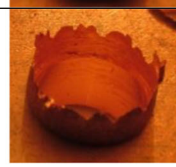
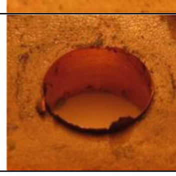
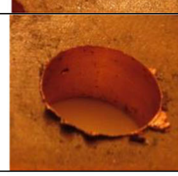
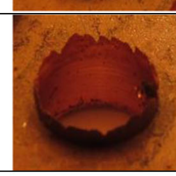


Fig. 3 3D graphics of the specific cutting pressure as a function of the feed and cutting speed for dry, MQL, and flooding drilling

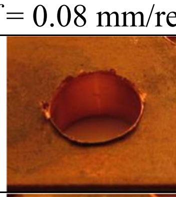
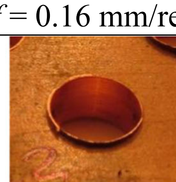
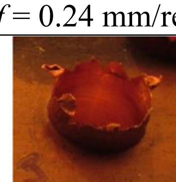
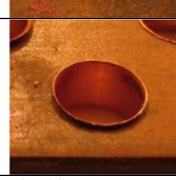
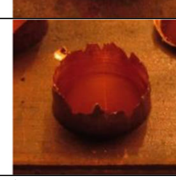
Table 3 Burrs obtained for each drilling condition

	f = 0.08 mm/rev	f = 0.16 mm/rev	f = 0.24 mm/rev
V_c = 25 m/min			
V_c = 50 m/min			
V_c = 70 m/min			

Burrs obtained for MQL drilling.

	f = 0.08 mm/rev	f = 0.16 mm/rev	f = 0.24 mm/rev
V_c = 25 m/min			
V_c = 50 m/min			
V_c = 70 m/min			

Burrs obtained for flooding drilling.

	f = 0.08 mm/rev	f = 0.16 mm/rev	f = 0.24 mm/rev
V_c = 25 m/min			
V_c = 50 m/min			
V_c = 70 m/min			

The values in italic are p-values smaller than 0.05, that is, they present the significant parameters and/or interactions

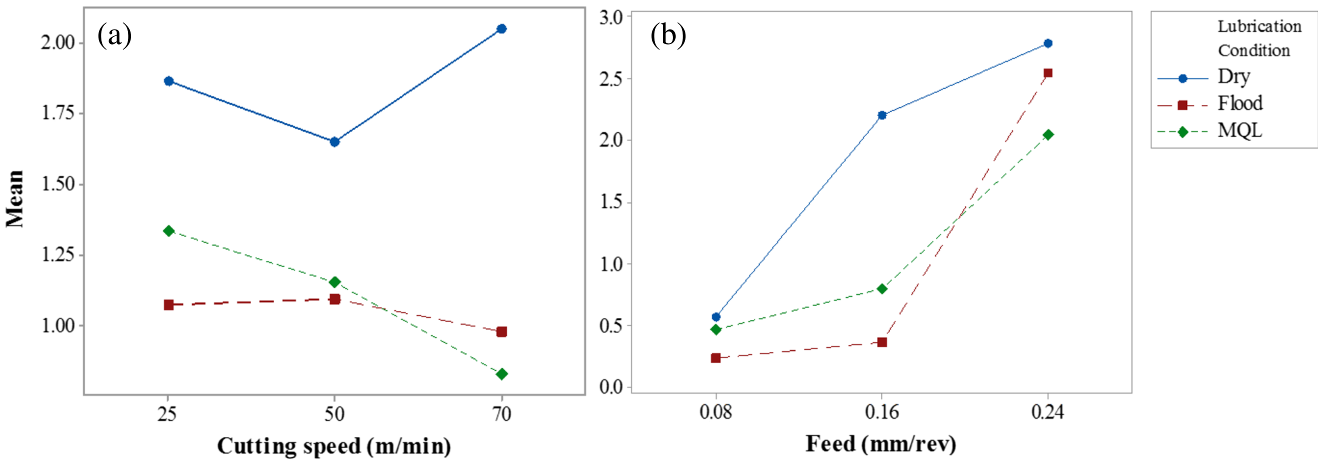


Fig. 4 Interaction plot for burr height (**a**) lubrication condition × cutting speed and (**b**) lubrication condition × feed

studied ANOVA to ensure the validity of experimental results in a novel method for improving fatigue behavior.

In this study, drills with titanium nitride coating were used. This coating is commonly used in cutting tools because of its excellent tribological properties such as high hardness, good adhesion, and chemical stability [22]. Therefore, the aims in this work are the investigation of drilling of electrolytic copper and the comparison with distinct lubrication conditions (dry, flood, and MQL). And then, the thrust force, burr height, and maximum diameter have been measured. The ANOVA technique has been used to check the influence of this conditions and cutting parameters in drilling.

2 Materials and methods

2.1 Workpiece and cutting tool

The investigated work material is an electrolytic copper. The dimensions of the specimens are 25 mm × 80 mm × 3 mm. High-speed steel drills (length of 62 mm and diameter of 5 mm) with a coating of the titanium nitride (TiN) were used in this work. The point angle used was 135°.

2.2 Experimental setup

Copper drilling process has been realized. The machining center used has 9 kW maximum spindle power and maximum spindle speed of 7500 rpm. Thrust force was measured by means of extensometric dynamometer with a resolution of 0.01 N. And then, the specific cutting pressure was calculated, by means of Eq. 1. Burr height was assessed with an optical microscope Askania (model GSZ 2T, Germany) at the exit of the hole. The maximum diameter was measured at the middle of the copper hole depth using a coordinate measuring machine, Tesa Micro-hite 3D, and seven points were measured.

The cutting conditions employed in the experimental work were dry, flood (concentration of 5%, flow rate of 500 l/h), and MQL (vegetable oil, flow rate of 15 ml/h, and pressure of 4 bar) for lubrication condition; 25, 50, and 70 m/min for cutting speed; and ultimately 0.08, 0.16, and 0.24 mm/rev for feed. A full factorial experimental design was employed. Each drilling condition was replicated once, thus resulting in 54 tests. Figure 1 shows the experimental setup.

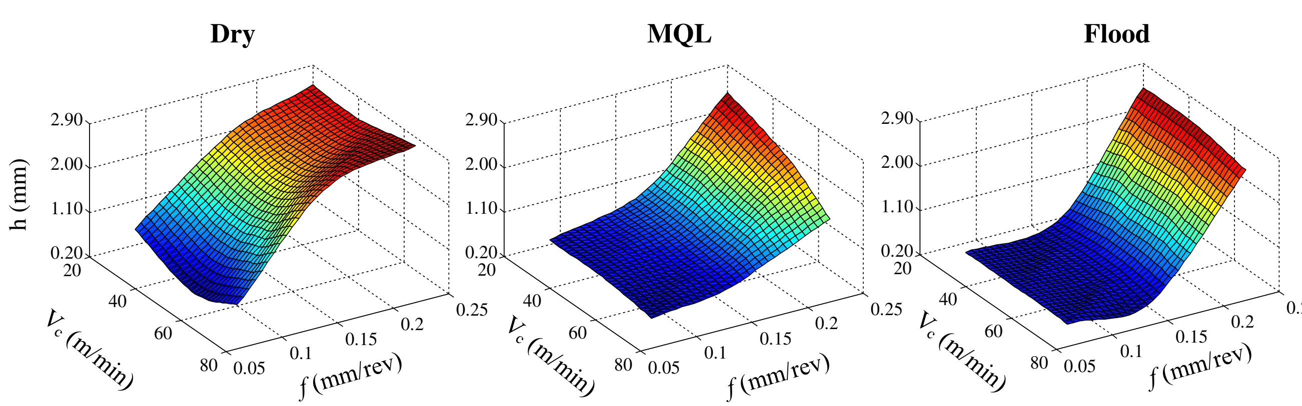


Fig. 5 3D graphics of the burr height as a function of the feed and cutting speed for dry, MQL, and flooding drilling

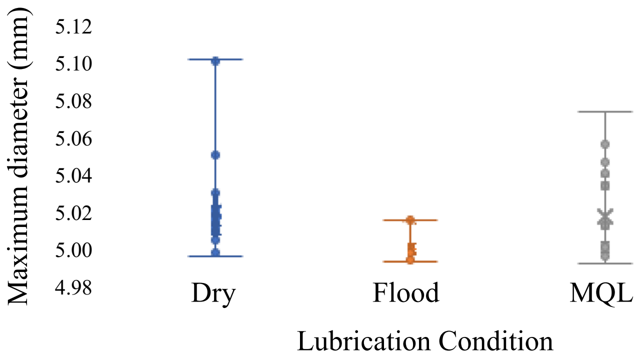


Fig. 6 Maximum deviation for copper drilling in three lubrication conditions

3 Results and discussion

In Table 1, the detailed results for specific cutting pressure, burrs, and maximum diameter are shown. With respect to the drill wear, due to the reduced number of drilled holes, the wear measurement was excluded. In the results, it can be observed that a reduction in feed force, burr height, and maximum diameter is obtained in general for all methods of coolant application when compared to the dry method.

Table 2 shows the statistical analysis for all results obtained. The analysis of variance (ANOVA) was carried out to verify if the influences of the main parameters and/or their interactions together are statistically significant with a confidence interval of 95%. *p* values lower or equal to 0.05 show that the main factor or the interaction significantly affects the responses; those values lower than 0.05 are underlined in Table 2. *R*-squared (R^2) is the coefficient of determination; this indicates the variability of the dependent variables and can be explained by the controllable factors (independent variables) and their interactions [23]. The R^2 values obtained in this study indicate that the models fitted the data properly.

As far as the specific cutting pressure (SCP) and burr height results are concerned, it can be noted that this parameter is statistically affected by lubrication condition as well as feed and their interactions. However, only by burr height the lubrication and cutting speed interaction is relevant. In the case of maximum diameter, just lubrication condition has a significant statistical influence on the result.

3.1 Specific cutting pressure

The lubrication condition and feed affected the specific cutting pressure and the interaction lubrication condition × feed. Figure 2 shows the specific cutting pressure response for varying the feed. It is noted that the specific cutting pressure (K_s) for the drilling with MQL is lower than that obtained in the dry and flooding drilling. This is because the cutting temperature for MQL is higher than that of the flooding. And then, there is a small loss of workpiece strength caused by the temperature, which influences in order to reduce the cutting force and the specific cutting pressure. In dry machining, the temperature is higher, which leads to the heating of the workpiece e difficulties the shear. With increasing of feed, the pressure tends to decrease, in accordance with Eq. 1 [13]. Figure 3 shows the three-dimensional surfaces of the cutting-specific pressure as a function of the feed and cutting speed for three lubrication conditions. What has been said previously can be confirmed. And also, the cutting speed did not contribute to change in specific cutting pressure.

3.2 Burr height

Table 3 shows the burrs obtained for copper drilling. For dry drilling, the burr height was bigger, the type of crown. When using cutting fluid, the friction coefficient between the tool and workpiece is lower, which could limit the plastic deformation and favor the copper shear. For higher feeds, more material is removed and this leads to severe plastic deformation, and in consequence bigger burrs. In general, with increasing of cutting speed, the burr height tends to decrease.

Figure 4 shows the interaction plot for the burr height. The lubrication condition and feed affected significantly the burr height as well as the interaction lubrication condition × cutting speed and lubrication condition × feed. Note that uniform and transient burrs were formed for dry and lubrication conditions. Figure 5 details

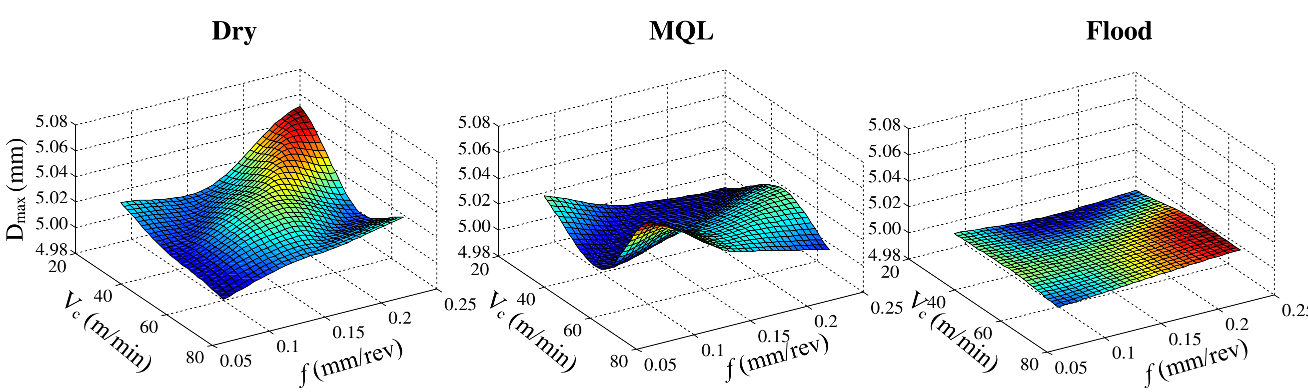


Fig. 7 3D graphics of the maximum diameter as a function of the feed and cutting speed for dry, MQL, and flooding drilling

the 3D graphics of the burr height as a function of the feed and cutting speed for dry, MQL, and flood drilling.

3.3 Maximum diameter

Figure 6 shows the variation of the maximum diameter resulting from the different lubrication conditions. Only the lubrication conditions have a significant effect on the maximum diameter. The maximum diameter is less affected when using flooding, because the temperature in the workpiece is lower. On the other hand, for dry machining, the temperature is higher and the hole is more deformed. The temperature has decreased directly proportional to the amount of lubricant. At last, the results to MQL showed values between the ones for dry and flooding machining.

Figure 7 shows the three-dimensional surfaces of the maximum diameter as a function of the feed and cutting speed for three lubrication conditions.

4 Conclusions

Electrolytic copper was drilled in order to compare the performance of three different lubrication conditions on the specific cutting pressure, burr height, and maximum diameter. The experimental work involved different feeds and cutting speeds. The influence of each cutting parameter on the quality of the drilling was determined by ANOVA analysis. It is possible to draw the following conclusions from the work presented:

- The parameters lubrication, feed, and their interaction lubrication × feed showed influence in the specific cutting pressure. MQL represented the best lubrication condition in the drilling of copper.
- The parameters lubrication, feed, and the interaction condition lubrication × cutting speed and lubrication × feed affected the burr height. For burr height, the lower burr was obtained using flood and MQL.
- Only the parameter condition lubrication influenced the maximum diameter. The use of the flood showed the best result.

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