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ANALYSIS OF THE INFLUENCE OF THE HOLE DEPTH ON THE GEOMETRIC QUALITY OF THE MACHINED PART, WHEN THE CUTTING FLUID AND THE MACHINING PARAMETERS ARE VARIED

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Abstract. *The purpose of this work is to study the effect of the length of the hole on the surface roughness (Ra and Rz parameters), thrust force (Fz) and torque (Mz) in drilling of gray cast iron FC 300. Blind holes of 10 mm of diameter were drilled with five different drilling lengths (10, 15, 20, 25 e 32 mm) under different cutting speeds and feed rates. Twist drills coated with TiAlN were used in tests using different lubri-cooling systems: atmospheric air (dry cutting), minimum quantity lubrication-MQL and flood cooling. Analysis of Variance (ANOVA) with a reliability index of 95% was employed to detect and classify the input variables that are statistically significant for the roughness parameters, thrust force and torque. The lubri-cooling, in general, was the second most important variable affecting all the output variables studied. MQL and flood cooling systems presented similar surface roughness when drilling shallow holes (10 and 15 mm). However, for deep holes (25 and 32 mm) the MQL system produced better surface roughness than the flood cooling.*

Keywords: *Hole length, lubri-cooling system, surface roughness, thrust force, torque, gray cast iron machining*

1. INTRODUCTION

It is well known that the drilling process faces difficulties in terms of accuracy. Small form errors and good surface finish is essential in many parts, such as: bearing surfaces, surfaces that require painting, surfaces where fluids and gases flow, surfaces where visual brilliance is required, surfaces that should reflect lights, among others (Machado et al., 2011). The surface finish is influenced by various machining parameters, including: the geometry of the cutting tool, part geometry, machine tool rigidity, workpiece material, cutting conditions and tool material (Costa et al., 2015; Costa et al., 2009; Nakayama, 1966; Shouckry, 1982).

Deep holes are not ease to machine and one of the reasons is the difficulty that the externally applied cutting fluid has to gain access to the cutting region to exert its functions and help the chip to come out of the hole. As a result, the friction in the cutting regions increases and consequently augmenting the machining forces, that compromise the hole quality (Ramos et al., 2017; Costa, 2004; Santos, 2002).

The cutting force, which is directly related to the shear strength of the work material, is predominantly responsible for the torque acting on the drill. The thrust (or feed) force, which is also related to the shear strength of the work material, depends mostly on the performance of the chisel edge for extruding the material in the center of the drill (allowing penetration of the drill into the workpiece). The friction of the drill margins and the chips onto the hole wall also contribute to increase the thrust force and torque. This contributions depend on the quality of drill surfaces (obtained by grinding) and on the cutting fluid used (Costa et al., 2015, De Castro, 2001; Sandvik Coromant, 1994; Teixeira, 1995).

Unfortunately, application of cutting fluids in machining processes affects the environment (polluting the air and local areas) and may cause risks to the health of workers, requiring concerns from the production sectors. As a result of this common problem in the shop floor, two lines of research are revealed quite strongly. Firstly, the development of new cutting fluids, environmentally friendly that do not harm the health of the operators, last longer in the machine and do not need to be frequently replaced. Secondly, the development of processes that do not require cutting fluid or the use of smaller amounts, for example, Minimum Quantity Lubrication (MQL) system (Sales et al., 2001; Jayal et al., 2010; Costa et al., 2015).

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

This paper aims to examine how the hole length affects the surface roughness (Ra and Rz parameters), the thrust force (Fz) and the torque (Mz) when varying the lubri-cooling system, the cutting speed and the feed rate, besides the drilling length itself.

2. METHODOLOGY

2.1. Strategies for the drilling tests

The experiments consisted of machining blind holes in gray cast iron FC 300 using HSS/cobalt twist drills coated with TiAlN with 10 mm of diameter and 130º of point angle. Five different hole lengths (10, 15, 20, 25 e 32 mm) were drilled in a 3-axis vertical machining center, Discovery 760 Romi-Bridgeport, with 9 kW of power and maximum spindle speed of 10,000 rpm.

The work material was the pearlite FC 300 gray cast iron with addition of 0.2 % of Mo and refined graphite in the form of plates with dimensions of 240 mm x 400 mm x 36 mm. It has an average hardness of 217 HB and UTS of 283 MPa.

Besides the drilling length, the following input parameters were varied: the lubri-cooling system (dry, minimum quantity lubrication-MQL and flood cooling-FC), the cutting speed (15 and 25 m/min) and the feed rate (0.1 and 0.2 mm/rev). Analysis of variance (ANOVA) with a reliability index of 95% was used in order to have statistically reliable results. For this analysis, the STATISTICA® 12.0 software was used.

Combination of the input variables resulted in 60 different cutting conditions, or 60 tests. Considering that each test consisted of three holes in sequence (test and two replicas), a total of 180 holes were machined, with a distance of 12 mm between the centers of the holes. Tab. 1 shows details of the variables investigated.

Table 1. Input and output variables of the drilling tests.

VARIABLES			VALUE
INPUT	drilling length (mm)		10, 15, 20, 25, 32
	lubri-cooling system	atmospheric air (dry cutting)	-
		minimum quantity lubrication-MQL (ml/h)	22
		flood cooling-FC (conventional overhead) (930 L/h)	930
	cutting speed (m/min)		15, 25
	feed rate (mm/rev)		0.1, 0.2
OUTPUT	surface roughness	parameter Ra (µm)	
		parameter Rz (µm)	
	cutting efforts	thrust force-Fz (N)	
		torque-Mz (N.m)	

The three different lubri-cooling systems (atmospheres) employed were dry machining, minimum quantity of lubricant (MQL) and conventional overhead flood cooling, both applied externally to the tool.

For the MQL system, a neat vegetal base oil (Accu-Lube LB2000, manufactured by ITW Chemical Products Ltda) was used at a flow rate of 22 ml/h. This fluid, biodegradable and non-toxic, is a chemical mix of vegetable oils (soybean, corn and canola) and anticorrosive additives. The oil spray device used was the O2AO-STD model, manufactured by ITW Chemical Products Ltda, which works with a continuous flow of compressed air, set around 0.5 MPa (5 bar) of pressure. Fig. 1 shows the position of the MQL nozzle during a test.

The flood cooling system used a vegetal oil-based micro-emulsion (Vasco 7000®, manufactured by Blaser Swisslube Inc.) at concentration of 8%, with an average flow rate of 930 L/h, delivered by the Machining Center pumping system.

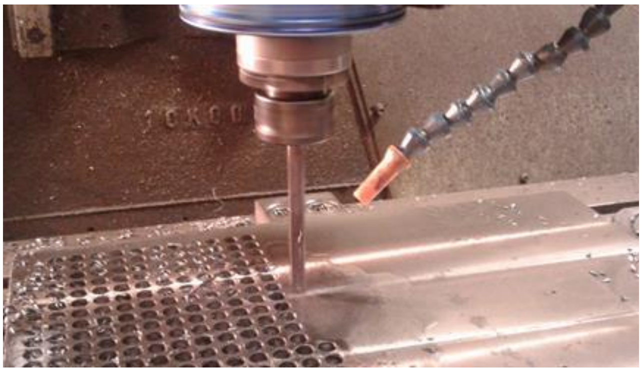


Figure 1. Application of minimum quantity of lubricant (MQL) in the flow rate of 22 ml/h.

2.2. Evaluated parameters - Output variables

The Ra and Rz roughness parameters were measured by a portable digital roughness tester. This equipment was the Surtronic3+ 112/1590 model, manufactured by Taylor Hobson®, with resolution of 0.01 µm and probe tip radius of 5 µm.

The cut-off value (Lc) used was 0.8 mm, resulting in a 4 mm measurement range (5x0.8). The roughness was measured in the central region of the hole wall in two diametrically opposite positions. The mean value of the two analyzed regions was the roughness value assigned to the hole.

The thrust force (Fz) and torque (Mz) were measured by a system composed of a rotating piezoelectric dynamometer, model 9123C, with a signal amplifier (conditioner), model 5223B, both manufactured by Kistler, a data acquisition board USB 6000 and Labview 7.6 software (both by National Instrument). The thrust force and torque signals were acquired during the machining of the entire length of each hole, with a rate of 1 kHz. Fig. 2 shows schematically this measuring system.

As three holes were machined for each test, the mean response value (Ra, Rz, Fz, and Mz) was assigned to the test.

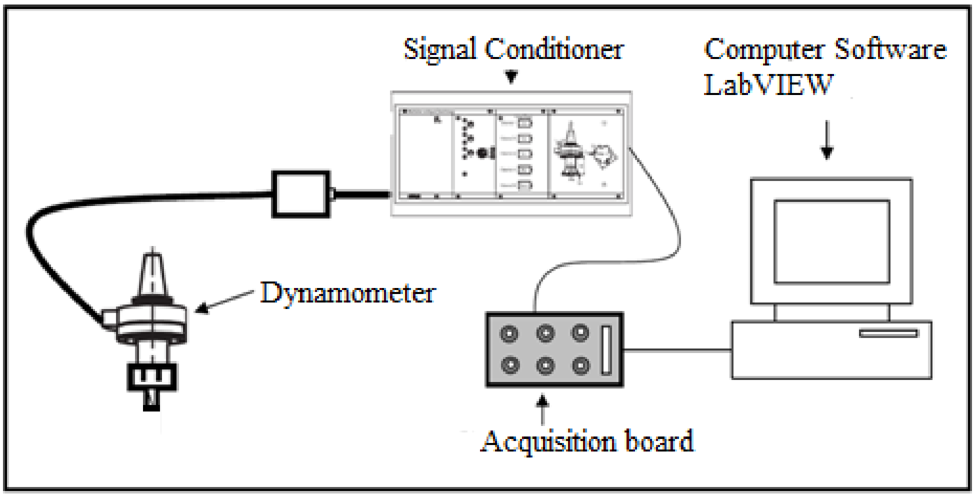


Figure 2. Schematic diagram of the thrust force and torque measuring system.

3. RESULTS E DISCUSIONS

The ANOVA results (with a reliability index of 95%), showed that the most significant input variables that affect the Ra/Rz roughness parameters was the hole length and for the thrust force and torque the feed rate. On the other hand, the lubri-cooling system proved to be, in general, the second or third most important variable for Ra/Rz and Fz/Mz, Tab. 2. The “p-value” shown in the table means maximum error probability. A parameter is statistically significant, for a reliability index of 95%, when $p < 0.05$. The smaller the "p-value" the greater the effect of the parameter.

Table 2. Order of parameters (input variable) statistically significant in the output variables.

OUTPUT VARIABLE		Statistically Significant Parameter (p-value)		
		1st	**2nd**	**3rd**
Surface Roughness	**Ra**	drilling length (0,00000)	lubri-cooling system (0,00896)	feed rate (0,02712)
	Rz	drilling lenth (0,00000)	lubri-cooling system (0,01102)	-
Cutting Force and Torque	**Fz**	feed rate (0,00000)	lubri-cooling system (0,00200)	-
	Mz	feed rate (0,00000)	cutting speed (0,00004)	lubri-cooling system (0,00033)

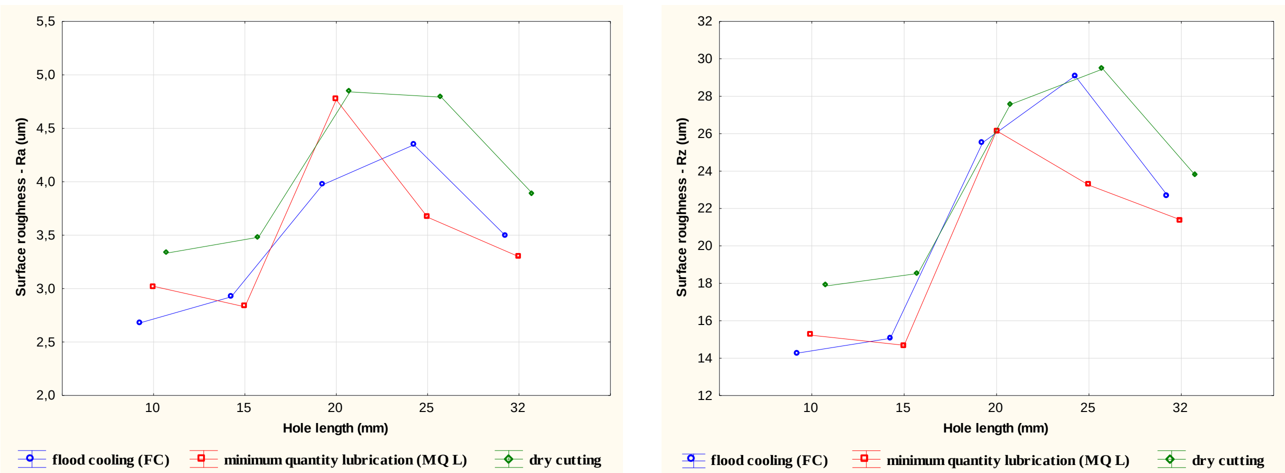
The thrust and cutting forces in drilling are basically originated from the resistance of penetration and cutting of the drill. Thus, there is a direct relationship between the increase in feed rate with the increasing cutting energy needed to extrude and shear the work material in drilling region (Sandvik Coromant, 1994; Teixeira, 1995; Costa 2004; Costa et al. 2015).

The effect of the feed rate on the surface finishing is well known in machining. The height of the peaks and the depth of the valleys in a machined surface tend to increase with the square of the feed rate (Machado et al., 2011).

The conditions of the chip-tool interface have great influence in the machining process. In the sliding region/zone, which is observed in the periphery of the chip-tool contact area, the local atmosphere has access to the interface and can influence the machining forces and tool wear. The use of a cutting fluid, with good lubricating action, reduces the chip-tool contact area and diminishes the machining force, this can also improve the surface roughness. However, when a coolant action prevails, the cutting fluid may increase the machining force by promoting an increase in the shear strength of the work material in the shear zones, which can also lead to an increased surface roughness (Machado et al., 2011).

3.1. Influence of hole length and lubri-cooling system on output variables

The influence of the hole length and lubri-cooling system on the surface roughness parameters Ra and Rz can be seen in the plots of Fig. 3. It is clear that the variation of the drilling length up to 15 mm, regardless of the lubri-cooling system used, slightly changes the Ra/Rz values were observed. From the hole length of 15 mm up to 25 mm, , the values of Ra and Rz generally increased significantly. However, when machining a hole with 32 mm of length the Ra/Rz values decreased considerably.



b)

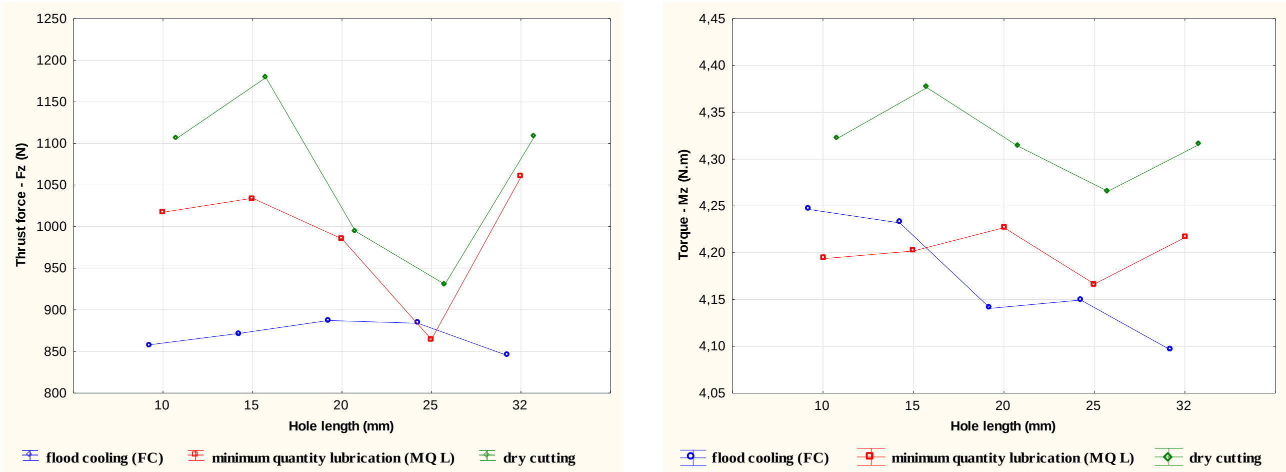
Figure 3. Influence of hole length and lubri-cooling system on the results of the surface roughness. a) Ra roughness parameter; b) Rz roughness parameter.

When drilling in dry condition the holes produced showed the poorest surface roughness, regardless the lengths of them. MQL and flood cooling systems presented similar surface roughness when drilling shallow holes (10 and 15 mm), but in deep holes (25 and 32 mm) the MQL system produced better surface roughness than the flood cooling. This result suggests that as the hole length increases the penetration of the cutting fluid becomes more difficult and the MQL system, by having the oil transported by a flow of air at a pressure of 5 bar, is more effective than the flood cooling in reaching the cutting zone and exert their functions properly.

The influence of the drilling length and lubri-cooling systems on the thrust force (Fz) and torque (Mz) are shown in the plots of Fig. 4. Similar to what happened to Ra/Rz, the highest Fz/Mz values were recorded for the dry drilling.

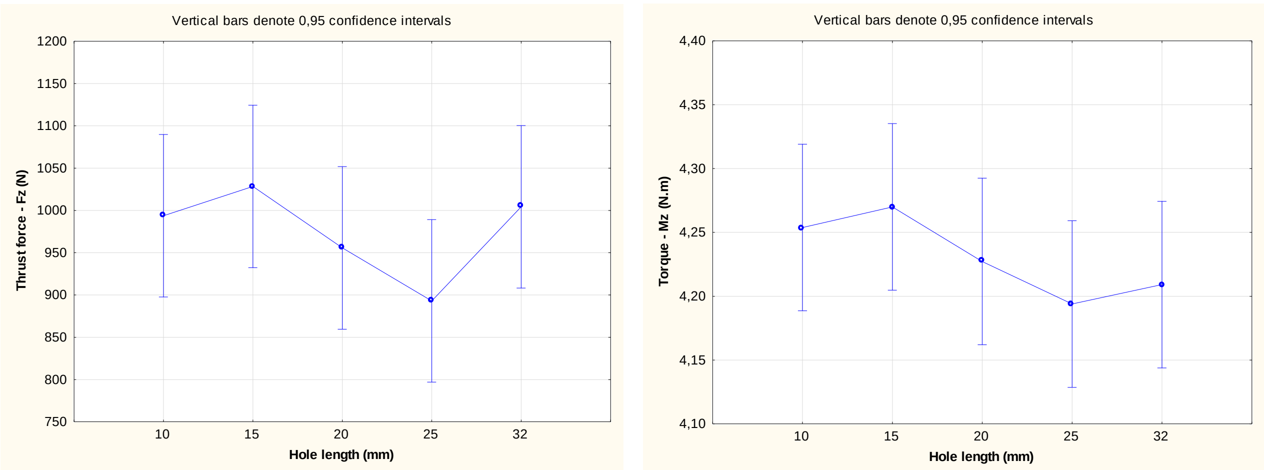
For a general analysis of the Fz/Mz results, drilling with MQL presented intermediate values of Fz/Mz in relation to dry cutting and machining with flood cooling, although in some conditions the MQL system overcame the flood cooling (such as the torque for the hole lengths of 10 and 15 mm, Fig. 4).

Figure 5 shows tendency graphics of the thrust force and torque against the hole length considering all the input variables investigated. Fz/Mz values increased up to the length of 15 mm, when they reach their maximum values, and then decreased to the length of 25 mm, when they reach their minimum values, rising again for the length of 32 mm.



a) b)

Figure 4. Influence of hole length and lubri-cooling system on results of the cutting efforts. a) Thrust force-Fz); b) Torque-Mz.



a) b)

Figure 5. Influence of hole length on the a) Thrust force-Fz; b) Torque-Mz.

The drilling lengths investigated in this work correspond to a range of length/diameter (L/D) ratio of 1 (10 mm) to 3.2 (32 mm). It would be interesting to investigate the behavior of the surface roughness, thrust force and torque beyond this range. The thickness of the workpiece available (36 mm) did not allow drilling blind holes deeper than 32 mm in this case, leaving this suggestion for future works.

4. CONCLUSIONS

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

- The most important input variables and that are statistically significant for the Ra/Rz roughness parameters was the hole length and for the Fz thrust force and Mz torque are the feed rate. On the other hand, the lubri-cooling system proved to be, in general, the second most important variable for both Ra/Rz and Fz/Mz.

- The higher values of surface roughness parameters, thrust force and torque were recorded in dry drilling.
- The Ra/Rz values for drilling shallow holes (10 and 15 mm) with MQL and flood cooling systems are relatively close. However, for the deeper holes (lengths of 25 and 32 mm), drilling with MQL produced better surface roughness than flood cooling.
- In general, the MQL system presented intermediate values of Fz/Mz in relation to dry cutting and machining with flood cooling. Exception was in the machining of shallow holes (lengths of 10 and 15 mm) when the MQL presented smaller torque than the flood cooling system.
- The variation of the hole length did not follow a tendency that allow estimation of output parameters investigated in drilling of gray cart iron FC 300 (surface roughness, thrust force and torque). The behavior of them oscillated with growth of hole lengths.

3. ACKNOWLEDGEMENTS

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5. RESPONSIBILITY NOTICE