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EFFECTS OF MQL ON WORKPIECE TEMPERATURE AND HOLE QUALITY IN DEEP DRILLING OF SAE4144M STEEL

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Abstract. *Drilling of deep and small boreholes using twist drills is a challenging task due to difficult chip removal and accumulated heat during the process. Pressurized fluids are often used to overcome these problems, however they add costs to the process, increase the environmental impact and represent occupational health risks. Minimum quantity lubrication (MQL) is a more ecological alternative to conventional flood cooling, however it has limited effect in terms of cooling the cutting edge and chip evacuation. This study compares MQL and conventional lubrication condition in deep drilling taking in consider the workpiece temperature and hole quality. The workpiece material is SAE 4144M forged quenched and tempered steel with hardness of 39 HRC. Solid cemented carbide drills with 4 mm diameter were used to drill 96 mm depth holes. A single channel unit was used as minimum quantity lubrication system. LubriOil E47 was selected for MQL tests, the pressure in the pipeline was 10 bar and oil flow rate was approximately 20 ml/h. EcoCut 610B pressurized to 50 bar was used in flood application tests. The results showed that the workpiece temperatures are higher for MQL in comparison to pressurized oil condition. There was a small variation of the hole diameter, however it was possible to observe that values were higher for the MQL condition. Roundness values were higher for MQL and surface roughness values were close for the both lubrication conditions.*

Keywords: *MQL, drilling, twist drill*

1. INTRODUCTION

SAE 4144M is a low alloy steel widely used in the manufacture of injection holders which carry fuel from the high-pressure pump to the combustion chamber. Drilling of deep and small holes of this material is a challenging task. It often presents problems related to chip clogging, tool breakage and low workpiece quality (Wosniak , *et al*., 2010). For these cases it is necessary to use special machines and tools, and pressurized fluids to enhance chip removal, with cooling and lubricating properties that meet stringent requirements. This complexity adds costs to the process, increases the environmental impact and the health risks for the operator. Minimum quantity lubrication (MQL) is a more ecological alternative to conventional flood cooling. In MQL systems an oil with low viscosity is pumped into the venturi nozzle of the generator. The smallest droplets interact with the inner wall by forming an oil film and a spatterflow is generated in addition to the spray flow. Spatter and spray flows then interact with the tool/workpiece interface resulting lower friction (Cabanettes, *et al*., 2016). MQL can provide better lubrication, however it has limited effect in terms of cooling the cutting edge, once the generated heat is not dissipated by coolant as conventional wet machining. Moreover, the chips are not removed away from the cutting zone by coolant. The accumulated heat can lead to premature tool wear and thermally distort the workpiece (Biermann *et al*., 2012). Therefore, it is important to select proper cutting conditions in order to minimize heat generation and produce small chips for better chip evacuation. Additionally, the use of polished tools is beneficial for MQL once results in less friction and easy chip flow on the flutes. Special drill point geometries and coolant holes grinding also contribute for reduction of heat generation during the process.

Zeilmann and Weingaertner (2006) studied the workpiece temperature behavior during drilling of the titanium alloy Ti6Al4V and conclude that the measured temperatures with application of MQL internally through the tool were 50% smaller than those obtained with MQL applied with an external nozzle. Sato *et al*. (2013) applied a pyrometer system for the measurement of the temperature at the bottom surface of a hole. They found that the temperature increases as drilling progresses, and it increases considerably near the bottom surface of the carbon–steel workpiece. Biermann *et al*. (2012) implemented a finite-element-(FE)-based simulation in consideration of the material removal on deep-hole drilling using twist drills and MQL. They founded that due to the material removal the heat flow into the workpiece increases when machining with higher cutting speed and feed values, while the measured and simulated temperature decreases.

In this paper deep drilling of SAE4144M with cemented carbide twist drill under MQL and pressurized oil condition is evaluated taking in consider the workpiece temperature and hole quality.

2. MATERIALS AND METHODS

The material is SAE 4144M forged quenched and tempered steel with hardness of 39 HRC used in unit pump bodies designed to raise the pressure and inject diesel in the diesel injection system from the diesel engines. Its chemical composition measured by a spectrofotometer Spectrolab Analytical Instrument is shown in Tab. 1.

Table 1. Chemical composition (%) of SAE 4144M.

Steel	C	Si	Mn	Mo	Cu	Ni	Cr	P	S
AISI 4144M	0.44	0.24	0.95	0.25	0.22	0.17	1.26	0.02	0.02

This study compares MQL and pressurized oil condition, taking in consider their influences on the workpiece temperature, diameter and surface roughness. The tests were performed in a Fanuc Robodrill CNC machine with maximum spindle speed of 24000 RPM with a MAS BT-30 with internal coolant-lubricant supply tool holder. A single channel V7 Lubrix unit was used as minimum quantity lubrication system (Fig. 1). In the tests the pressure in the pipeline was 10 bar and oil flow rate was approximately 20 ml/h. EcoCut 610B (10 cSt at 40ºC) pressurized to 50 bar was used in flood application tests and LubriOil E47 (47 cSt at 40ºC) was selected for MQL tests.

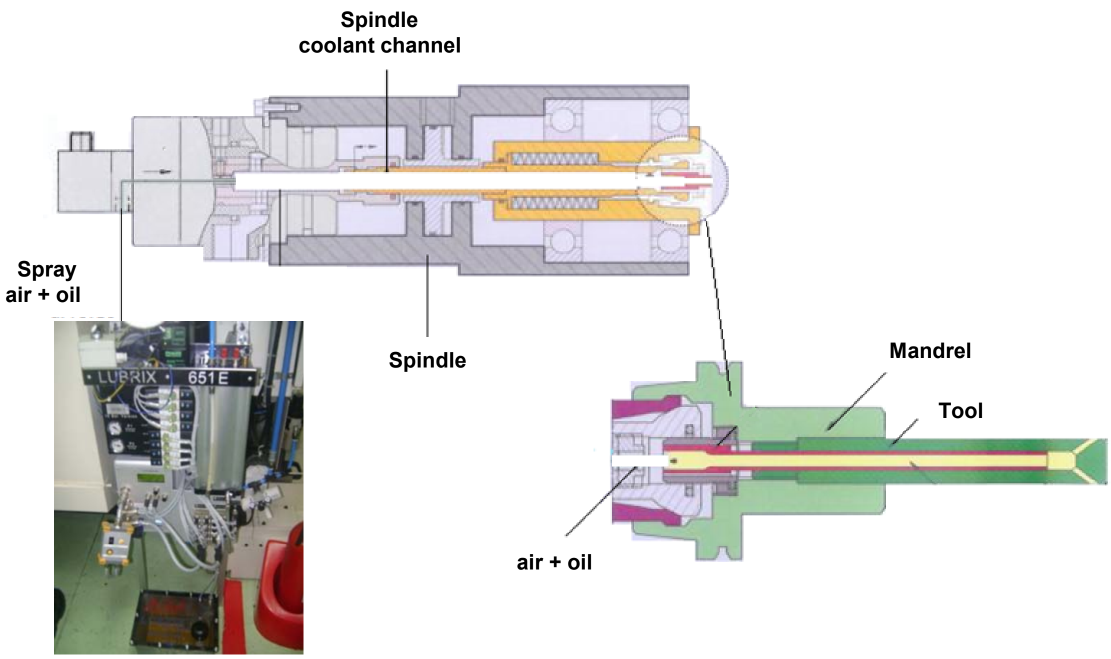


Figure 1. MQL system

Solid cemented carbide drills (K40 class) with 4 mm diameter were used to drill 96 mm depth holes, resulting in a deep drilling condition of L/D = 24. These drills have double margins, polished flutes and TiAlN coating, point angle of 130° and spiral point geometry. The cutting speed was 80 m/min and the feed-rate was 0.085 mm/rev for all tests. In order to assess the superficial integrity of the obtained bores, a Zeiss three-dimensional machine, the Contura model, and a Taylor Hobson roughnessmeter (Form TalySurf Series 2 120i) were used. In order to measure the workpiece temperature, thermocouple sensors (Type K) were positioned at 1mm from the hole wall at four hole depths (Fig. 2) and connected to a data collector (Agilent 34870A).

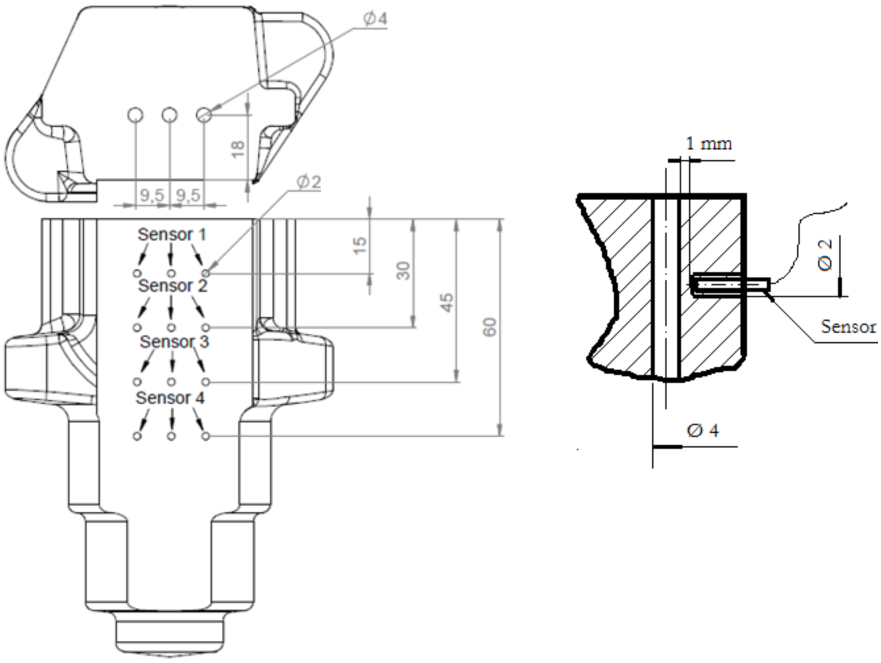


Figure 2. Workpiece temperature measurement setup

3. RESULTS AND DISCUSSIONS

3.1 Workpiece temperature

Figure 3 shows the workpiece temperature behavior measured by the four sensors for the pressurized oil condition. After the machining, cooling occurred at room temperature. It was possible to verify that the sensor 1 registered the lowest temperature. However, there was an anomaly at the beginning of the cooling process and the temperature raised again, exerting some influence on the measurement of sensors 2 and 3, which registered the highest temperatures. A similar effect occurred in the experiment of Zeilmann and Weingaertner (2006), and the reason for that was attributed to tangled chips around the tool. Another fact that helps explaining this behavior is the increase in temperature due to larger contact area between the tool and the hole wall. The highest temperature recorded was 35.5 °C by sensor 3. For the comparison between the lubrication systems an average value of 34 °C was considered.

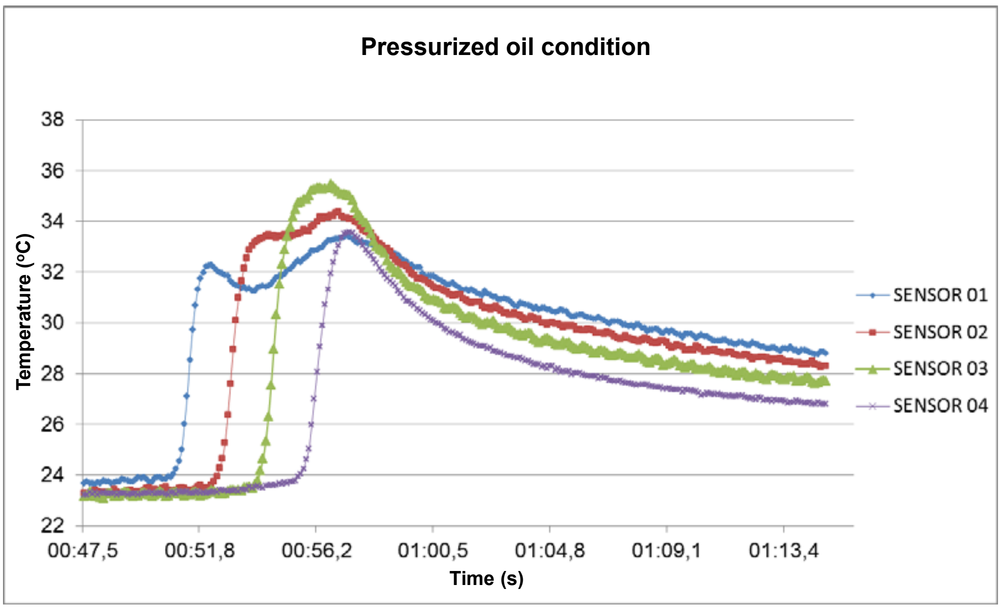


Figure 3. Workpiece temperature for the pressurized oil condition

Figure 4 shows the workpiece temperature behavior measured by the four sensors for the MQL system. The results show an expected behavior, according to the previous discussions. In this case a significant increase of the temperature occurs with the increase of the hole depth. After the measurement made by sensor 1, the temperature continues to increase and sensor 4 registered the highest value. In order to verify the temperature difference between the two lubricating conditions the difference of 5 °C before the beginning of the drilling was taken into account. It can be observed that the average temperature was 11 °C higher in the MQL system. Therefore, drilling with the MQL system generates higher amount of heat and a higher cutting temperature than the pressurized oil condition. Material cutting behavior is affect by temperature, so that with an increase in temperature there is a tendency of reduction of penetration force. According to Astakhov and Galitsky (2008) thrust force is mainly reduced when the optimum cutting temperature is reached. This temperature provides favorable conditions for cutting. Once MQL system generates higher temperatures than pressurized oil condition, the efficiency of the drill coatings is fundamental for deep drilling in order to protect the tool substrate and the integrity of the tool point geometry.

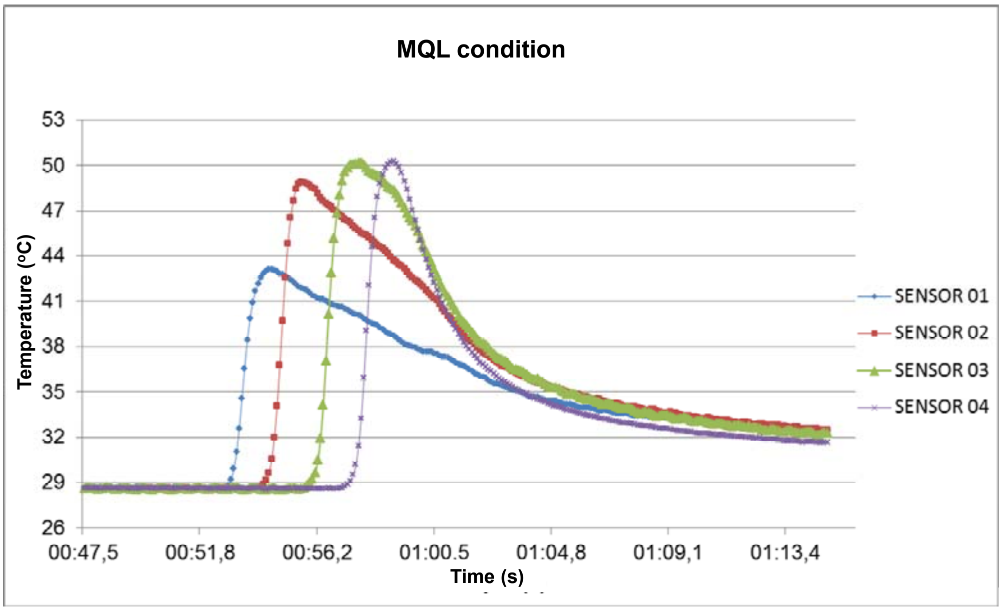


Figure 4. Workpiece temperature for the MQL condition

3.2 Hole quality

Table 2 shows the mesurement results of roundness, surface roughness and diameter of the holes. The surface roughness values were close for the both lubrication conditions. A little bit higher surface roughness R_z and R_t values were obtained for the pressurized oil condition, probably due to the friction between the chips and the hole wall.

Table 2. Experimental results for surface roughness.

Surface roughness	R_a (μm)	R_z (μm)	R_t (μm)
MQL	0,44	4,55	7,31
Pressurized oil	0,43	5,72	7,82

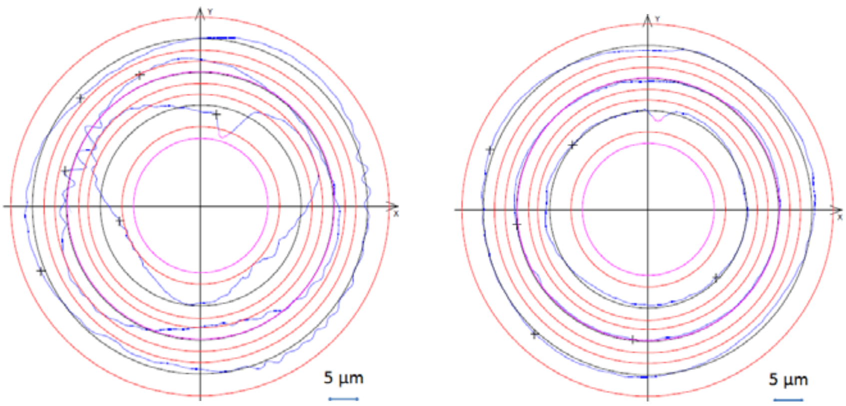
Table 3 shows the mesurement results of roundness and diameter of the holes. There was a small variation of holes diameter, however it was possible to observe that the values were higher for the MQL condition. The increase in diameter of the holes might be related to the temperature of the cutting zone. The temperature generated with MQL is higher than the pressurized oil condition, causing a higher drill thermal expansion, and consequently resulting in larger hole diameter. However there was no significant variation of the hole diameter in function of the hole depth.

Table 3. Experimental results for roundness and diameter of the holes.

	Roundness (μm) at 10 mm	Roundness (μm) at 20 mm	Roundness (μm) at 30 mm	Diameter (mm) at 10 mm	Diameter (mm) at 20 mm	Diameter (mm) at 30 mm
MQL	0,0037	0,0068	0,0106	4,015	4,017	4,017
Oil	0,0025	0,0016	0,0023	4,012	4,011	4,011

The characteristic of the bore that presented greater influence of the coolant system was roundness. Figure 5 has regular reference lines (red) and three irregular lines (blue) showing roundness measurements at three different depths of the hole. Hole roundness was lower when pressurized oil was applied. There was no significant variation of the hole roundness in function of the hole depth for this condition. On the other hand, hole roundness increases as the depth of the hole increases with MQL system. This is associated with the fact that the temperature increases as the hole depth increases. Thus, with the use of the MQL system the frequency of defects in the surface of the hole increases, directly influencing the hole roundness.

These results show that the hole quality suffers greater influence of the MQL system due to the minimal amount of lubricant between the drill margins and the hole wall. In this condition, the temperature increases, causing a reduction in the viscosity of the oil, which in turn increases the friction on the hole wall, causing greater surface damage.



a) b)

Figure 5. Roundness measurements at depths 10, 20 and 30 mm.
(a) MQL system (b) pressurized oil condition

4. CONCLUSIONS

The results showed that temperatures are higher for MQL in comparison to pressurized oil condition. The workpiece temperature increases with the depth of the drilled holes. There was a small variation of the diameter holes. Surface roughness values were close for the both lubrication conditions. Roundness was higher for MQL and it increased with the hole depth due to the higher temperatures. The hole quality suffers greater influence of the MQL system due to the minimal amount of lubricant between the drill margins and the hole wall. In this condition, the temperature increases, causing a reduction in the viscosity of the oil, which in turn increases the friction on the hole wall, causing greater surface damage.

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