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An Experimental Study on the effect of Minimum Quantity Lubrication on Drilling AISI 1040 Steel

A.M.M. Nazmul AHSAN[1,♠] , Md. Golam KIBRIA[1], Md. Raju AHMED[2]

[1] *Department of Industrial Engineering and Management, Khulna University of Engineering & Technology, Khulna-9203, Bangladesh.*

[2] *Pabna Sugar Mill Ltd., Dashuria, Ishurdi, Pabna, Bangladesh.*

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ABSTRACT

The growing demand for higher productivity, product quality, and overall economy in manufacturing by drilling particularly to meet the challenges thrown by liberalization and global cost competitiveness, insists high material removal rate, high stability, and long life of the cutting tools. However, high production machining with high cutting velocity, feed, and depth of cut is inherently associated with the generation of large amount of heat and this high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface finish of the part. The dry drilling of steels is an environmentally friendly machining process, but has some serious limitations like higher cutting temperature, tool wear, and greater dimensional deviation. Conventional cutting fluids (wet machining) eliminate such problems but have some drawbacks. Cutting fluids possess a significant portion of the total machining cost. Thus, machining under Minimum Quantity Lubrication (MQL) condition has drawn the attention of researchers as an alternative to the traditionally used wet and dry machining conditions with a view to minimizing the cooling and lubricating cost as well as reducing cutting zone temperature, tool wear, surface roughness, and dimensional deviation. In this paper, the effects MQL on dimensional deviation, drilling force, and torque during drilling AISI 1040 steel are examined and compaired with drilling under dry and wet conditions.

Key Words: *MQL, Cutting Zone Temperature, dimensional Deviation, Drilling Force, Torque.*

1. INTRODUCTION

During drilling process, the most important factor affecting the cutting tool performance and work piece properties is cutting temperature that emerges between drill bit and chip. The cutting temperature directly influences hole characteristics such as diameter, perpendicularity and cylindricity as well as surface roughness and tool wear [1]. Drills often experience excessive temperatures because the drill is embedded in the work piece and heat generation is localized in a small area. The magnitude of the cutting temperature increases in different degree with the increase in cutting velocity, feed and depth of cut. At such elevated temperature the cutting tools if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased

♠Corresponding author, e-mail: ahsan.ipe@gmail.com

cutting force, dimensional inaccuracy of the product and shorter tool life [2]. This problem increases further with the increase in strength and hardness of the work material.

A major portion of the energy is consumed in the formation and removal of chips. The greater the energy consumption, the greater are the temperature and frictional forces at the tool–chip interface and consequently the higher is the tool wear [3]. Drill wear not only affects the surface finish of the hole but also influences the life of the drill bit. Wear on drill bit dictates the hole quality and tool life of the drill bit [4]. Worn drills produce poor quality holes and in extreme cases, a broken drill can destroy almost all finished parts. A drill begins to wear as soon as it is placed into operation. As it wears, cutting force increases as well as the temperature rises. And this accelerates the physical and chemical processes associated with drill wear and therefore drill wears faster. Force and torque depend upon drill wear, drill size, feed rate and spindle speed [5].

In case of drilling, thrust and torque depend upon drill wear, drill size, feed rate and spindle speed. A study shows that tool breakage, tool wear and work piece deflection are strongly related to cutting force [5]. Bhowmick and Ahmet [15] showed that the conventional uncoated HSS drill generated the highest levels of torque and thrust force in dry conditions, due to the formation of a large BUE and torque and thrust forces are expected to increase during drilling with uncoated HSS.

A large amount of heat is created in dry machining because of rubbing between cutting tool and work piece interface. Dry machining has not fully established itself in drilling technology, mainly because of extremely high thermal load on the drilling tools resulting in accelerated tool wear and unsatisfying overall process stability [6]. The optimization of cutting conditions to make them more suitable for dry cutting is performed through the increase in feed and decrease in cutting speed. With this, roughly the same amount of heat is generated, but the area of the tool which receives this heat is bigger, making the temperature lower and the amount of chip removed per minute constant (without increasing cutting time). This action may damage the work piece surface finish due to the increase in feed [7]. Moreover, in dry drilling, the drilling tool has to withstand harsh environment including high temperatures, frictional forces and large mechanical and thermal loads [1].

The application of cutting fluid during machining operation reduces cutting zone temperature and increases tool life and acts as lubricant as well [8]. Without cooling and lubrication, the chip sticks to the tool and breaks it in a very short cutting time. It reduces cutting zone temperature either by removing heats as coolant or reducing friction as lubricant. In addition to that it serves a practical function as a chip-handling medium [9]. On the other hand, the cooling and lubricating effects of cutting fluid influence each other and diminish with the increase in cutting velocity [2].

Many of the fluids, which are used to lubricate metal forming and machining, contain environmentally harmful or potentially damaging chemical constituents. These fluids are difficult to dispose and expensive to recycle and can cause skin and lung disease to the operators and air pollution. Also the increasingly stricter environmental regulations and their enforcement are eliminating much of the flexibility in the use of cutting fluids. While the cutting fluid manufacturers are developing new formulations, for e.g. without Pb, or S, or Cl elements which improves machinability but detrimental from a health and environmental point of view. It is a long way before the cutting fluids can be considered totally harmless and acceptable. The costs associated with the use of cutting fluids are estimated to be several billion dollars per year. Consequently, reducing the use of cutting fluids, if possible, can be a significant economic incentive. Due to several negative effects, a lot of efforts have been pronounced in the recent past to minimize or even completely avoid the use of cutting fluids.

When dry cutting is not an option because of its drawbacks and difficult cutting conditions and wet machining is not an option because of unfavorable consequences of cutting fluids, minimum quantity cooling and lubrication may be an alternative. It helps decrease production costs by 10–50% as well as minimizing environmental and health hazards. Minimum quantity cooling and lubrication (MQL) cutting or minimum quantity fluid (MQF) cutting, also refers to as quasi-dry cutting, can be characterized by a small quantity of cooling and lubricating fluid supplied to the cutting zone – the amount usually does not exceed 50 ml/h [10,11]. Minimum Quantity Lubrication (MQL) has many advantages compared with traditional wet machining and dry machining. Many researchers have suggested that MQL shows potential competitiveness in terms of tool life, surface finish and cutting forces in turning, milling, drilling, reaming and taping [12].

Minimum quantity lubrication (MQL), an economic and efficient lubrication process, is based on the principle that a drop of liquid is split by an air flow, distributed in streaks and transported in the direction of flow of air. In MQL machining, a small amount of vegetable oil or biodegradable synthetic ester is sprayed to the tool tip with compressed air. The consumption oil in industrial applications is in the range of approximately 10 - 100 ml per hour [13]. Conventional cutting fluid can also be used instead of vegetable oil or biodegradable synthetic ester because of its unavailability and expensiveness.

Cutting fluids or vegetable oils can reduce coefficient of friction at chip-tool interface and thus could reduce cutting forces and increase tool life to some extent. Liaoa et al. [14] found that there was a considerable reduction in cutting force in milling cutting for MQL as compared with dry cutting and flood cooling conditions, especially at low cutting speed (such as 75 m/min) . The results demonstrated that MQL might be regarded as an economical and environmentally compatible lubrication technique for low speed, feed rate, and depth of cut condition. On the contrary, MQL seemed to have no effect on the improvement of tool performance in high-speed milling such as 125 m/min.

In this study, we develop an MQL system in-house. The performance of MQL provided through this developed system is experimentally evaluated during drilling AISI 1040 steel and compaired with dry and wet drilling.

2. EXPERIMENTAL INVESTIGATIONS

Under MQL condition, the lubricating agent needs to be supplied at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the requirements for the present work and the uninterrupted supply of MQL at constant pressure, an MQL delivery system is designed and fabricated. The schematic view and the experimental setup of the fabricated MQL system are shown in Figure 1 and Figure 3 respectively. The thin but high velocity stream of MQL is projected in such a direction that the coolant can reach as close to the chip-tool and work-tool interfaces as possible.

The developed MQL system consists of the following four major parts.

1. Compressor
2. Lubricating Oil Reservoir
3. Mixing chamber
4. Final nozzle

In MQL system, air and cutting fluid mixing is the basic function of the system. This function requires three main parts such as compressor, reservoir, and mixing chamber. A compressor which is used to supply compressed air to the cutting fluid/oil reservoir and mixing chamber. The cutting/lubricating oil passes down due to the pressure of compressed air in the reservoir and thus the oil flows through the transmission pipe from reservoir to the mixing chamber. The compressed air from compressor also directly passes through the transmission pipe and reaches the mixing chamber. Thus, the compressed air from compressor is divided into two sections using a T-junction, one to supply to the mixing chamber directly and the other to supply to the oil reservoir.

Oil Reservoir has two inlets and one outlet. One of These inlets is used to provide compressed air into the oil reservoir to give feed to the lubricating oil and the other inlet is used to refill the reservoir. The pressure feeded oil goes to the mixing chamber embedded in the nozzle.

Mixing chamber has two inlets connected to the compressed air supply and outlet of reservoir, respectively. At first, the compressed air enters a sub-chamber through the inlet and then passes through eight openings to reach the mixing chamber. From the other inlet, the pressure feeded oil reaches the mixing chamber through four openings. The final nozzle is attached to the mixing chamber. The air-oil mixture is sprayed to the cutting zone through the opening of this nozzle. The schematic diagram of the nozzle attached to the mixing chamber is shown in Figure 2.

The nozzle assembly of the MQL system is mounted on a drill machine. The experimental conditions for Dry, Wet, and MQL machining environments under which the drilling experiments are carried out are briefly given in Table 1. Considering common interest and time constraint, only HSS drill bits are used for the investigation. The drilling tests are carried out while drilling AISI-1040 steel on a Radial drill machine (RM-U9 Radial Drill Machine, Sweden) by HSS drill under dry, wet and MQL conditions. A total of 30 holes for each of three different environments at each of three different spindle speeds are drilled in the AISI 1040 Steel work-piece in rows with a horizontal, center-to-center spacing of 12 mm between the adjacent holes.

The force exerted by the rotating drill bit on the part surface referrers to drilling force. A force measuring device (dynamometer) is used to measure the drilling force and torque. Each drilling cycle has a duration of approximately 5 seconds between the initial contact and the complete retraction of the drill bit. More specifically, the average torque (in Nm) is calculated from the difference in torque between the onset of chip clogging and the drill's retraction. The average thrust force is also calculated from the onset of chip clogging to drill retraction. The effect of MQL condition on drilling force and torque is investigated at different spindle speed.

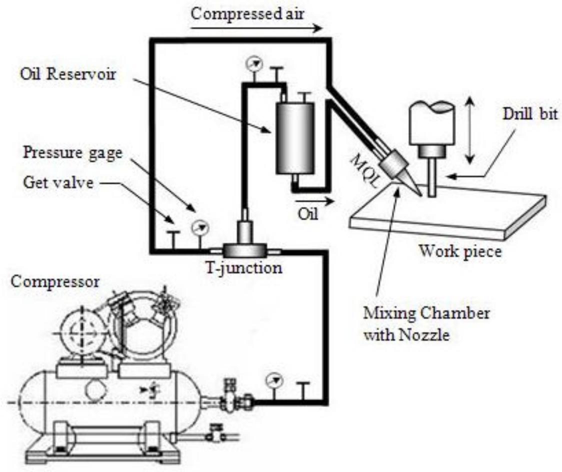
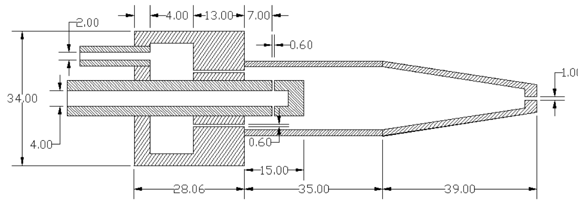
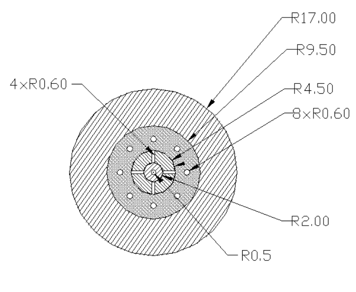


Figure 1. Schematic view of MQL setup



(a) Lateral sectional view



(b) Transverse sectional view

Figure 2. The schematic diagram of the nozzle attached with mixing chamber (dimensions are in millimeter).

Figure 3. Experimental setup of MQL system

Table 1. Experimental conditions

Parameter	Dry and Wet Machining Condition	MQL Machining Condition
Machine tool	RM-U1, Radial Drill Machine, Sweden, 1.5kW.	RM-U1, Radial Drill Machine, Sweden, 1.5kW.
Work material	AISI-1040 [C-0.40%, plain carbon steel]	AISI-1040 [C-0.40%, plain carbon steel]
Cutting tool	High speed steel (HSS), diameter: 6mm, 8 mm.	High speed steel (HSS), diameter: 6 mm, 8mm.
Process parameters Spindle speed Depth of cut	 200 rpm, 440 rpm & 670 rpm. 19.5 mm	 200 rpm, 440 rpm & 670 rpm. 19.5 mm
Cutting fluid supply	1.2 litter/min (Wet condition)	Air: 6 bar, Flow rate: 90 ml/min (through nozzle tip).
Environment	Dry and Wet (with cutting fluid)	MQL

3. RESULTS AND DISCUSSION

Dimensional deviation of holes, torque, and thrust force are important indices of drilling accuracy and hole quality. Dimensional deviation needs to be reduced as much as possible. Minimum Quantity Lubrication condition is expected to give better hole quality as well as accuracy through the reduction in dimensional deviation of holes. The diameters and dimensional deviations of the holes are measured. The summary of data obtained from the experiments carried out under Dry, Wet, and MQL conditions for 6 mm and 8mm drill bits are given in Table 2 and Table 3 respectively. In case of dry drilling, the diameters of the holes are quite apart from nominal hole diameter. This may be due to higher cutting temperature and friction between tool and work-piece. Such high temperature causes dimensional deviation. Hole diameters under MQL condition are the closest to nominal value. During MQL drilling, the cutting fluid reaches inside the hole and consequently more closely to the cutting zone due to high pressure jet of cutting fluid. This ensures effective lubrication and the jet of compressed air and cutting fluid massively increases the heat transfer rate as well. Thus, the cutting zone temperature is significantly reduced and thereby providing lower dimensional deviation. The standard deviation of hole diameters under MQL condition is the lowest as well.

Table 2. Diameters of holes (6 mm) at different rpm under dry, wet and MQL condition

RPM	Machining Condition	Diameter of holes			Standard Deviation
		D_{max} (mm)	D_{min} (mm)	D_{ave} (mm)	
200	Dry	6.3429	6.1529	6.1693	0.0218
	Wet	6.2629	6.1529	6.1467	0.0312
	MQL	6.0850	6.0005	6.0392	0.0256
440	Dry	6.2196	6.1128	6.1693	0.0218
	Wet	6.2.63	6.1096	6.1672	0.0277
	MQL	6.0850	6.0150	6.0532	0.0232
670	Dry	6.2629	6.1863	6.2276	0.0227
	Wet	6.1996	6.0929	6.1346	0.0258
	MQL	6.0850	6.0050	6.02452	0.0240

Table 3. Diameters of holes (8 mm) at different rpm under dry, wet and MQL condition

RPM	Machining Condition	Diameter of holes			Standard Deviation
		D_{max} (mm)	D_{min} (mm)	D_{ave} (mm)	
200	Dry	8.1708	8.0708	8.1234	0.0276
	Wet	8.1208	8.0625	8.0775	0.0151
	MQL	8.0750	8.0005	8.0382	0.0227
440	Dry	8.2825	8.1308	8.2158	0.0374
	Wet	8.1041	8.0625	8.0794	0.0143
	MQL	8.0759	8.0050	8.1716	0.0213
670	Dry	8.2125	8.1291	8.1764	0.0208
	Wet	8.1291	8.0708	8.0955	0.0193
	MQL	8.0850	8.0000	8.0256	0.0213

30 samples for each cutting environment at 3 different rpm are drilled. Diameters of holes drilled with 6 mm and 8 mm drill at 200 rpm in three different environments are shown in Figure 4 and Figure 5, respectively. Hole diameters of all samples are found random in nature. The 3σ limits for hole diameters (6mm, 8mm) found at Dry, Wet and MQL conditions are $6.1693 \pm 3\times0.0218$ mm, $6.1467 \pm 3\times0.0312$mm, $6.0392 \pm 3\times0.0256$ mm, $8.1234 \pm 3\times0.0276$mm, $8.0775 \pm 3\times0.0151$ mm, and $8.0382 \pm 3\times0.0227$ mm, respectively. All hole diameters including the maximum and minimum hole diameters are within the 3σ limits. From these values it can be said that the MQL condition provides better dimensional accuracy of drilled holes.

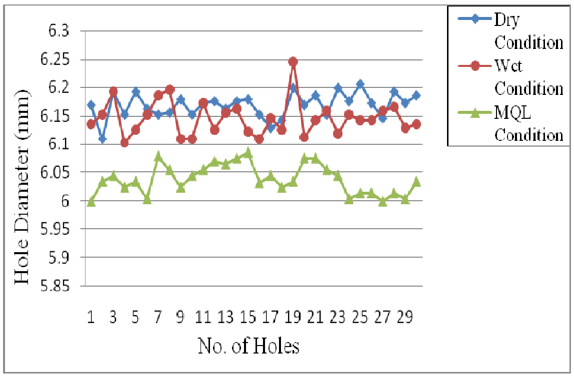


Figure 4. Dimensional deviation under Dry, Wet and MQL conditions at 200 rpm (6 mm drill bit).

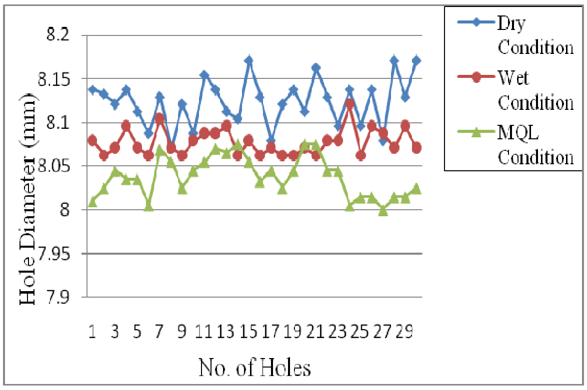


Figure 5. Dimensional deviation under Dry, Wet and MQL conditions at 200 rpm (8 mm drill bit).

Drilled hole diameters found at 440 rpm at three different environments are shown in Figure 6 and Figure 7. The nature of drilled hole diameters are similar to that found at 200 rpm. The 3σ limits for hole diameters (6 mm, 8 mm) found at Dry, Wet and MQL conditions are 6.1693 ± 3×0.0218 mm, 6.1672 ± 3×0.0277 mm, 6.0532 ± 3×0.0232 mm, 8.2158 ± 3×0.0374 mm, 8.0794 ± 3×0.0143 mm, and 8.1716 ± 3×0.0213 mm respectively. The mean values at Wet and MQL conditions at 440 rpm are relatively close to each other and better than that found at Dry condition. Drilled hole diameters found at 670 rpm at three different environments are shown in Figure 8 and 9. The 3σ limits for hole diameters (6 mm, 8 mm) found at Dry, Wet and MQL conditions are 6.2276 ± 3×0.0227 mm, 6.1346 ± 3×0.0258 mm, 6.02452 ± 3×0.0240 mm, 8.1764 ± 3×0.0208 mm, 8.0955 ± 3×0.0213 mm, and 8.0256 ± 3×0.0209 mm respectively. At 670 rpm , the mean diameters are not close to each other.

The drilled hole diameters at MQL condition are closer to the nominal value than that found in Dry and Wet conditions. Dimensional deviations of holes at MQL condition are relatively lower at different spindle speeds as well.

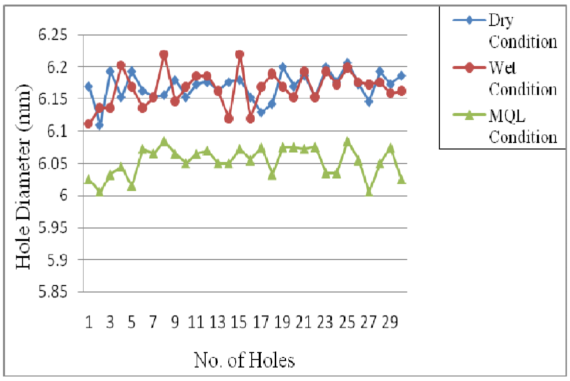


Figure 6. Dimensional deviation under Dry, Wet and MQL conditions at 440 rpm (6 mm drill bit).

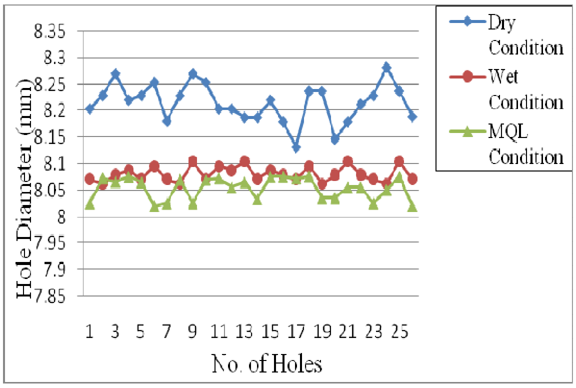


Figure 7. Dimensional deviation under Dry, Wet and MQL conditions at 440 rpm (8 mm drill bit).

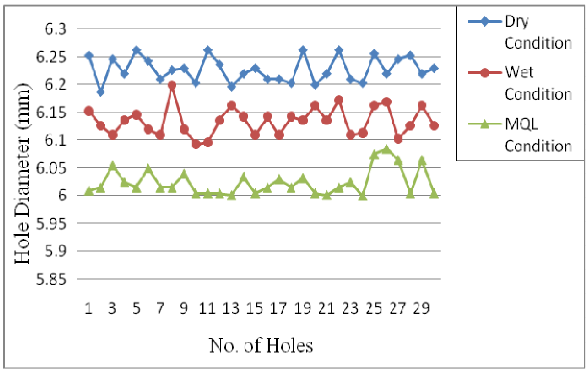


Figure 8. Dimensional deviation under Dry, Wet and MQL conditions at 670 rpm (6 mm drill bit).

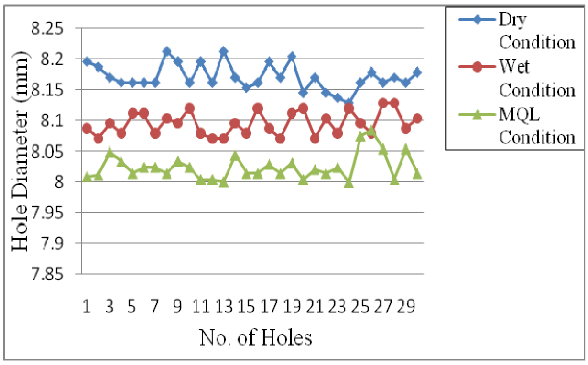


Figure 9. Dimensional deviation under Dry, Wet and MQL conditions at 670 rpm (8 mm drill bit).

The drilling force at drilling zone is important index of drilling capacity of a machine and it is needed to minimize the required drilling force as far as possible. During drilling steel specimens, drilling force decreases with the increase in RPM of the spindle and increases with the increase in depth of cut. The same phenomenon occurs for drilling torque. High drilling force influences the damage of the drill bits, poor machinibility, chip formation mode, tool life, and the life of the machine tool. Hence, it is important to reduce this detrimental drilling force. The present investigation using 6 mm diameter drill bit shows that the torque as well as the drilling force is higher under Dry and Wet conditions than under MQL condition (Figure 10, Figure 11).

From the Figure 10 and Figure 11, it is clear that the drilling force and torque decrease with the increment in RPM. Basically, the torque and force exerted under dry and wet conditions are higher than those under MQL condition. Therefore, the use of MQL helps reduce the drilling force and torque. During drilling under wet condition, conventional cutting fluid fails to penetrate the chip-tool interface and thus cannot remove the generated heat effectively.

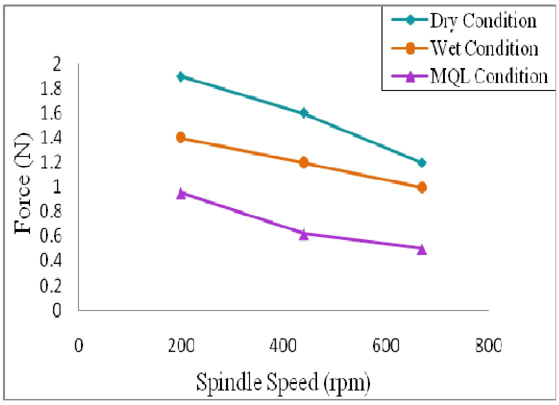


Figure 10. Drilling Force Vs RPM curve (for 6 mm drill bit).

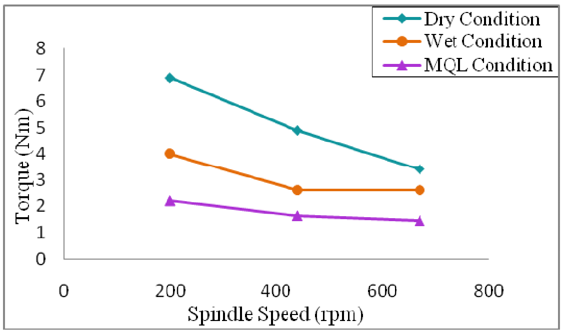


Figure 11. Drilling Torque Vs RPM curve (for 6 mm drill bit).

4. CONCLUSIONS

The experimentally observed performance of MQL in drilling AISI-1040 steel by HSS drill can be summarized as follows:

- Dimensional deviation was smaller under MQL condition compared to dry and wet conditions. When high depth of cut was employed, the drilling with dry condition was not possible because of poor cooling and lubrication action.

- Torque and force exerted under Dry and wet conditions were higher than that under MQL condition. Hence, the use of MQL condition is effective to reduce the drilling force and torque.

- The beneficial effects of MQL may be attributed to effective lubricating action, which prevented chip sticking on the tool and made the cutting favorable.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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