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EFFECT OF OIL FLOW RATE ON PRODUCTION THROUGH-TOOL DUAL CHANNEL MQL DRILLING

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ABSTRACT

Minimum quantity lubrication (MQL) drilling has been known for decades, but limited knowledge is available on two-channel through-tool MQL drilling due to the lack of accessibility to production systems. A common problem in MQL drilling is the absence of a rational approach to select the oil flow rate. The limited entry and exit area, and fixed energy available to the flow make the behavior complicated. This study leverages the capabilities in Ford's manufacturing lab to abridge the research gap. Four different oil flow rates (0 ml/h, 15 ml/h, 30 ml/h and 60 ml/h) and two different drills (twist drill and straight drill) were used to find out the influence of oil flow rate on the cutting performance. Tool life, tool wear, cutting force and torque were monitored as the cutting performance indicators. It was concluded that, the common belief of higher oil flow rate providing better tool life, does not hold true for through-tool MQL drilling. The tool life for 30 ml/hr. oil flow rate appeared to be the highest compared to all the other cases for both the drills. Increasing the oil flow rate above 30 ml/hr. decreased the tool life. However, it is to be noted that the optimal oil flow rate values may be specific to the case.

Keywords: Minimum quantity lubrication, drilling, two-channel MQL, tool wear, cutting force and torque

1. INTRODUCTION

Drilling is the most common metal removal process in the manufacturing industry, specifically in the automotive industry. The effectiveness of the drilling process is heavily dependent on the tool geometry and cooling technique used for the process. Multiple studies have been conducted on finding the optimum tool geometry for cutting [1-3]. Drilling provides very minimum access to the cutting zone and thus the delivery of the coolant/lubricant to the cutting zone is a challenge. Externally applied systems which are commonly used in turning, facing and grinding are not effective for drilling [4-6]. Therefore, through-tool channels are provided in the drill bit to ensure effective delivery of the coolant/lubricant to the cutting zone. Through-tool channels exit on the flank face of the drill and are placed very close to the cutting edge. This placement provides direct application of lubricant/coolant to the cutting zone and reduces the tool temperature due to lubrication, conduction and convection. There are multiple methods of providing the coolant/lubricant to the cutting zone. The most widely applied methods are flood cooling and minimum quantity lubrication (MQL).

In flood cooling, a water-based coolant is supplied to the cutting zone. The pressure of the fluid is in the order of 20 bar and the flow rate is 20-80 l/min. The coolant forces the chips away from the cutting zone and carries away the heat generated to keeps the temperature in control. This helps in maintaining the tool hardness and also the dimensional accuracy of the holes produced. While, in MQL, lubricant and pressurized air are used to create an aerosol and supply it to the cutting zone. The small droplets increase the contact surface area to volume ratio and thus a lower quantity of lubricant is required [7, 8]. The lubricant flow rate typically ranges from 10 to 100 ml/h and air pressure typically is around 4-6 bar in practical applications. When the total machining costs of the both the cooling/lubrication processes are compared, it was found that MQL has potential to save about 20% of the total machining costs[6, 9-11]. However, these savings are only possible if the process parameters and the tool geometry are optimized. In a MQL process, apart from the cutting parameters, the oil flow rate, air pressure and nozzle location are important parameters to be optimized. Studies have been conducted to optimize these parameters [12-20]. However, most of these studies are for turning, milling and grinding processes where the application of MQL is comparatively easier than drilling. This leads to lack of knowledge for drilling process.

Studies have been performed to investigate the performance of MQL. It has been concluded from these studies that higher input air pressure produces smaller droplets, and a higher flow rate of lubricant provides longer tool life [21, 22]. Also, the heat generation on the cutting edge was found to be non-uniform [23, 24]. However, most of the work was for externally supplied systems and, only a little information is available on oil flow rate effect using through-tool MQL drilling [25-29]. Furthermore, most of the available work was performed on lab scale setups which may not replicate every aspect of the full scale production machines. Unlike the externally applied system, the flow path of an internally applied system has a lot of restrictions and has to pass through small gaps. If the channel path is not designed properly, the lubricant may not reach to the desired location. This effect is critical for multi-diameter drills. Hughey and Stephenson, studied the distribution of the oil flow at different locations in multi-diameter drills, they found that most of the lubricant flows out from the larger holes at the top of the drill which are far from the primary cutting edge [30]. Using these results, they proposed a resistance-capacitance analogy to balance the flow distribution at multiple locations of the drills. However, the industrial solution of the problem was to increase the flow rate so that the required amount of fluid is obtained at the primary cutting edge. This increase in flow at the primary cutting edge meant a proportional increase in the flow at other locations, which increases the wastage of the lubricant and defeats the purpose of MQL. Recent studies have also shown a reduction in the average flow velocity with an increase in the oil flow rate [26]. The decrease in the flow velocity and excessive oil can worsen the cutting performance.

From previous work form the authors, it was found that the lubricant does not distribute homogeneously across the channel cross-section[10]. Moreover, the heat generation is also non uniform throughout the cutting edge. Therefore, the problem of selecting the optimal oil flow rate is far more complex than it looks. A rational approach to decide the MQL oil flow rate is required and this paper attempts to generate information required. Experiments for four different oil flow rates and two different types of drills are performed and the tool wear, tool life, cutting force and cutting torque were analyzed to evaluate the cutting performance. All these experiments were performed on a production scale CNC machine at Ford Motor Company's Global Powertrain Manufacturing Engineering Lab.

To structure this paper, first section includes the background and motivation. Second section provides the material and the methodology used for the study. Section three includes the results obtained. Section four provides discussion about the results. Lastly, section five provides the conclusions

2. MATERIALS AND METHODS

2.1 Experimental Setup

Two different types of carbide drills (i) Twist/ 30° helix angle and (ii) Straight/ 0° helix angle drill were used for the study. The twist drill is a margin less drill with a very small chisel width and the straight drill is a double margin drill with spilt point design. Using two drills was to generalize the effect and make sure the results obtained were not case specific. Both the drills were standard off the shelf drills with 10 mm diameter produced by Kennametal (Latrobe, PA). The drills were of 5×D length, the point angle of the twist drill was 140º and that of straight drill was 130º. The diameter of through-tool channels were 1.5 mm for both the drills while, the pitch circle diameter of through-tool channels was 5 mm for twist drills and 4 mm for straight drills. Carbide drills were used for the study because they provide longer life than HSS tools and are the standard tools used in high volume automobile production. Drill geometry apart from helix angle were not considered since no direct comparison between different types of drill was to be carried out. Majority of the parts produced for automobiles are made of Aluminum (Al); therefore, it makes sense using Al as the workpiece material. However, drilling Al produces Built-up-Edge (BUE) which can reduce the performance of the drills, irrespective of the tool wear. This may hinder the motive of the study, since the main goal of the study is to evaluate the influence of MQL lubrication on the tool wear and BUE can change the tool failure mode. Therefore, Cast Iron was used as the workpiece material for the drilling tests, which is the material used for making larger V8 engine blocks and will provide gradual tool wear which is easy to track.

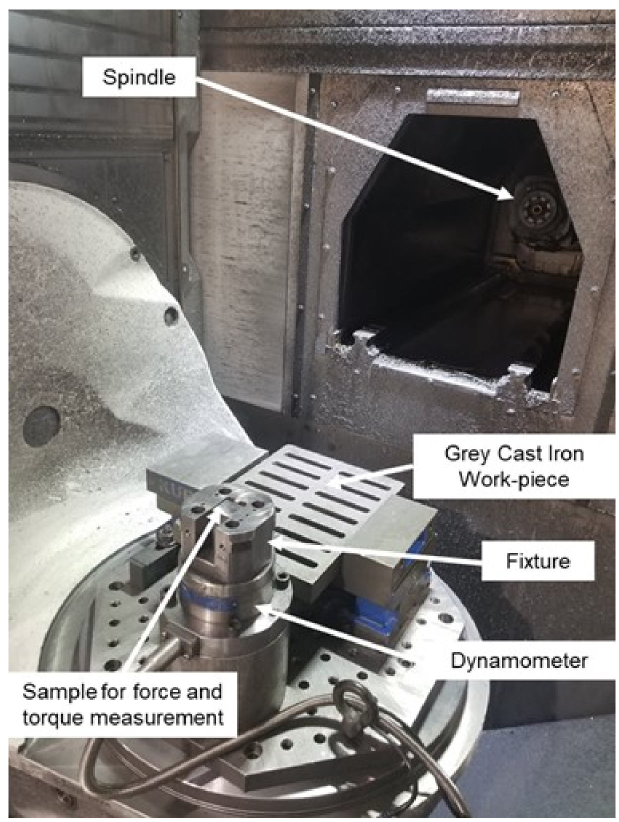

FIGURE 1: MQL DRILLING SETUP ON GROB 515 5-AXIS CNC

The drilling tests were performed on GROB-515, a production scale 5-axis CNC machine developed by GROB-WERKE

(Munich, Germany). For clamping the drills HSK-63A tool holders were used which rigidly clamp the tool using shrink fit. The machine tool was equipped with a through-tool Bielomatic two-channel MQL system integrated into the machine. The Bielomatic MQL system allowed the control of oil flow rate from 0 ml/h to 500 ml/h with an accuracy of at-least 85%. Whereas the air pressure was controlled externally using gauge and valve. A Kistler (Winterthur, Switzerland) Model-9275 force and torque dynamometer along with a National Instruments (Austin, TX) DAQ was used to measure the cutting force and torque. The workpiece sample was mounted coaxially on the dynamometer using a fixture to obtain most accurate force and torque data. The tool wear was measured using Smartscope optical microscope (Optical gaging Products, Rochester, NY). The machining setup can be seen in Fig. 1.

To understand the influence of oil flow rate on the tool wear, four different oil flow rates were chosen i.e. 0 ml/h, 15 ml/h, 30 ml/h and 60 ml/h. A full factorial design of experiment was developed with 4 levels of oil flow rate and 2 different types of drills. For the 0 ml/h. oil flow rate condition, the air flow was still kept on to aid with chip evacuation. For each case a new drill was used to ensure the comparability between the experiments. The drills were purged before using to ensure instantaneous flow of the fluid as soon as the MQL system is turned on. All other machining and MQL parameters except for oil flow rate were kept constant throughout all the experiments. The input air pressure was set at 4.13 bar (60 psi) which is the standard pressure used by North American auto plants. The max cutting velocity was kept to be 80 m/min which translated to a spindle speed of 2540 RPM for a 10 mm diameter drill. The feed rate was kept as 0.18 mm/rev which was based upon the parameters used by Ford Motor Company in production and the hole depth was 30 mm. The MQL lubricant used was Castrol A1536 which is a fatty alcohol lubricant with a viscosity of 28 cP at 40°C and the standard lubricant for MQL operations.

2.2 Methodology and Measurement

A new drill was fit into the HSK tool holder and setup into the machine after ensuring that the tool was wear and damage free using images captured by Smartscope Optical microscope. The hole layout as seen in Fig. 2 was setup in such a manner that there is a minimum of 2 mm gap between adjacent holes. This ensured that the hardened layer created at the periphery of the hole during drilling of one hole does not affect the second hole. Furthermore, to allow the tool to cool down and mimic actual part production process, where a drill is used for drilling specific number of holes in a part and then has a certain time lag before being used for the next part, a dwell of 15 s was kept after each row of holes. This led to a total of 264 holes on each workpiece. The first hole drilled after every change of workpiece was on a sample placed in the fixture over the dynamometer for cutting force and torque measurement. Therefore, the tool forces and tool wear were monitored after every 265 holes. The sampling frequency for the DAQ was kept as 100Hz and a MATLAB® code was used to calculate the average values. The start of cutting was identified using a filter and the average thrust force and torque were obtained by averaging all the values starting from 1 sec after the start of the cut to 3 s after the start of cut. This is demonstrated in Fig. 3.

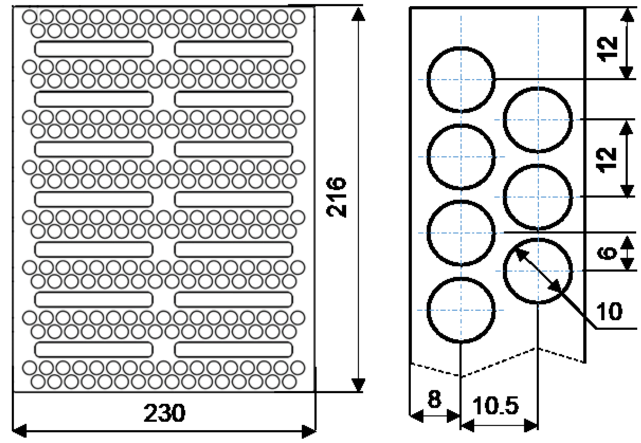

FIGURE 2: HOLE LAYOUT (ALL UNITS ARE IN MM)

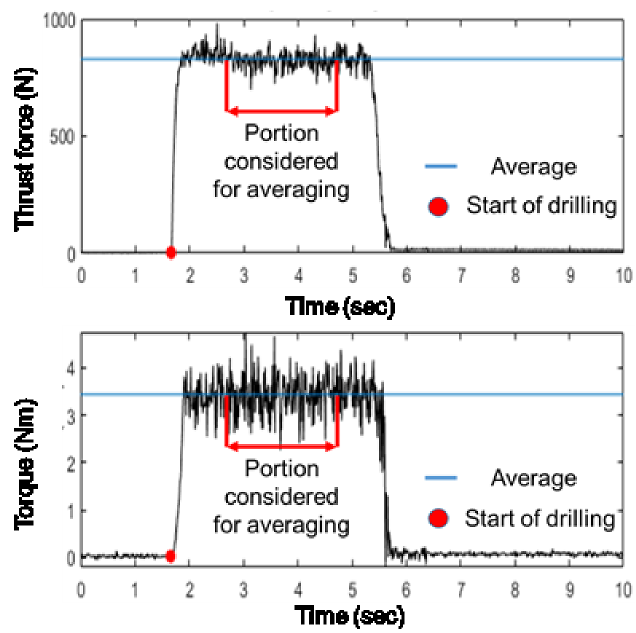

FIGURE 3: AVERAGE THRUST FORCE AND TORQUE CALCULATION

The same measurement frequency was used for monitoring the tool wear. The drilling tests were terminated after a reduction of more than 20 µm in the hole diameter or when the drill broke, whichever happened earlier. This consideration was based upon the reduction in the functionality of the hole produced due to the loss of size or the incapability of the drill to produce holes. The wear measurement was carried using Smartscope optical microscope. Two tool wear locations were measured and named as shown Fig. 4.

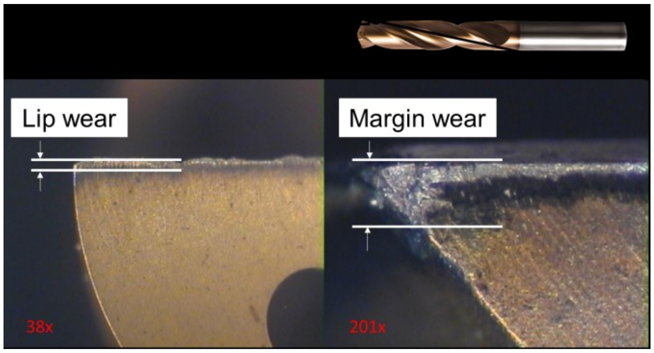

FIGURE 4: TOOL WEAR MEASUREMENT LOCATIONS

3. RESULTS

3.1 Tool Life

As stated previously, a tool is considered worn whenever it was incapable of drilling holes or the hole produced were more than 20 µm undersized. This criteria was setup based upon the incapability of the drill to produce more holes or the loss in the functionality of the hole because of the reduction in the size. Maximum lip wear and maximum margin wear were measured at specified intervals. The wear values were measured on both the cutting edges and the average value was used. The tool life obtained in the unit of no of holes drilled is shown in Table 1. The hole size was measured using pin gauges after every 100 holes. For all the cases, the end of tool life came because the holes produced were undersized by at-least 20 µm. The 0 ml/h condition gave the least tool life which was expected because of the absence of the lubricant. Using 15 ml/h oil flow rate, the tool life increased by 100 holes in case of twist drills and 200 holes in case of straight drills. A further increase in the oil flow rate from 15 ml/h to 30 ml/h improved the tool life by 500 holes in twist drill and 600 holes in straight drill. However, increasing the oil flow rate to 60 ml/h did not further improve the tool life, and in fact an adverse effect was seen in the case of straight drills, where the tool life drops by about 100 holes.

TABLE 1: TOOL LIFE IN UNITS OF NO OF HOLES DRILLED

	Twist Drill	Straight Drill
0 ml/h	900	400
15 ml/h	1000	600
30 ml/h	1500	1200
60 ml/h	1500	1100

3.2 Tool Wear

The tool wear for all the tools was measured after every 265 holes. The maximum lip wear and maximum margin wear were measured as shown in Fig. 4. The end state of the tool for twist drills at different flow rate condition are shown in Fig. 5(a), the numbers on the bottom right of each figure states the no. of holes drilled. Figure 5(b) shows the margin wear for all the cases. Margin wear was measured on both the cutting edges and the average value was used for the representation purposes. The 0 ml/h condition showed the maximum and most rapid wear. While the margin wear for 15 ml/h and 30 ml/h was almost the same. The margin wear for 60 ml/h condition was similar to 15 ml/h up to 1000 holes, but at the later stages the wear rate increased and the tool worn out rapidly compared to 30 ml/h where a similar tool life was obtained. Interestingly, the absolute value of margin wear for 30 ml/h and 60 ml/h was higher than that of 15 ml/h but the tool life for 15 ml/h was lower than the other two cases. Figure 5(c) shows the lip wear for twist drills, similar to the margin wear, lip wear was measured on both the cutting edges and average value was used. The tool wear rate is high during the initial stages, but with increase in the no. of holes

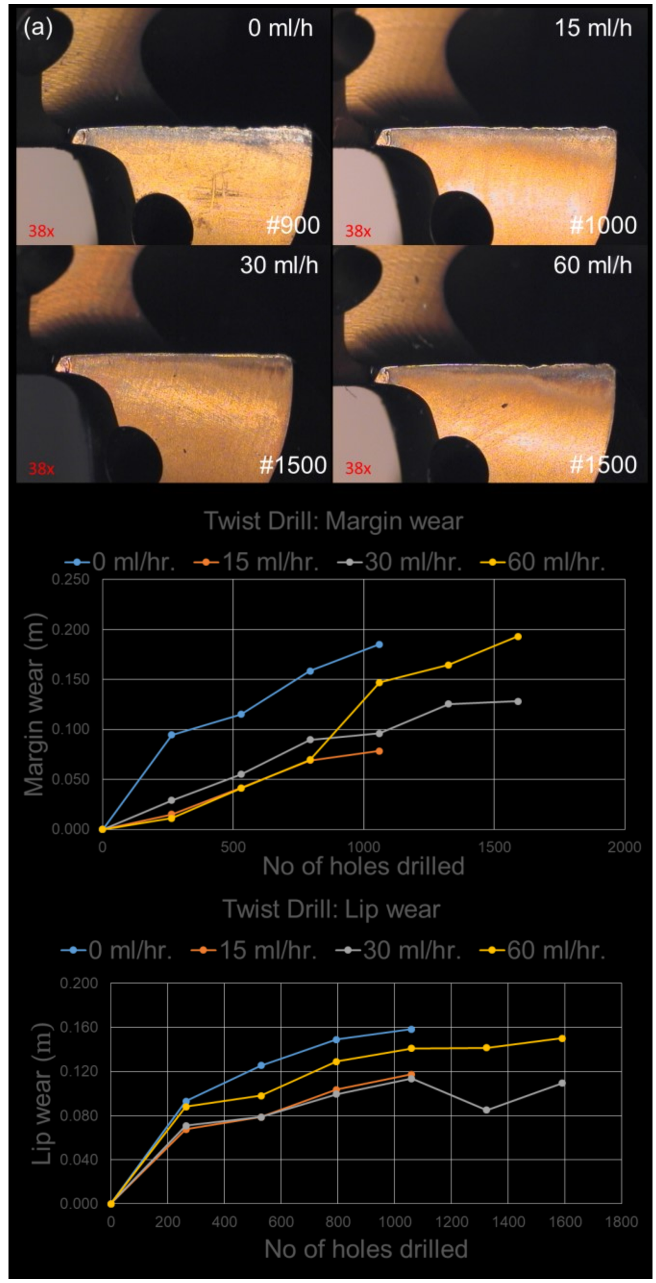

FIGURE 5: TOOL WEAR IN TWIST DRILLS (a) TOOL WEAR OF CUTTING EDGE AFTER THE END OF TOOL LIFE (b) MARGIN WEAR AT DIFFERENT NO OF HOLES DRILLED (c) LIP WEAR AT DIFFERENT NOF OF HOLES DRILLED

drilled a reduction in wear rate was observed for all the cases. The absolute value of wear was maximum for 0 ml/h, closely followed by 60 ml/h, 15 ml/h and 30 ml/h in that order. For the case of 30 ml/h around 1300 holes, a reduction in tool wear is observed. This reduction was because of material accumulation, also known as BUE on the edge. The material filled up the tool wear volume and thus the measured value dropped. But after drilling a few more holes the material got dislodged and the tool surface was exposed again.

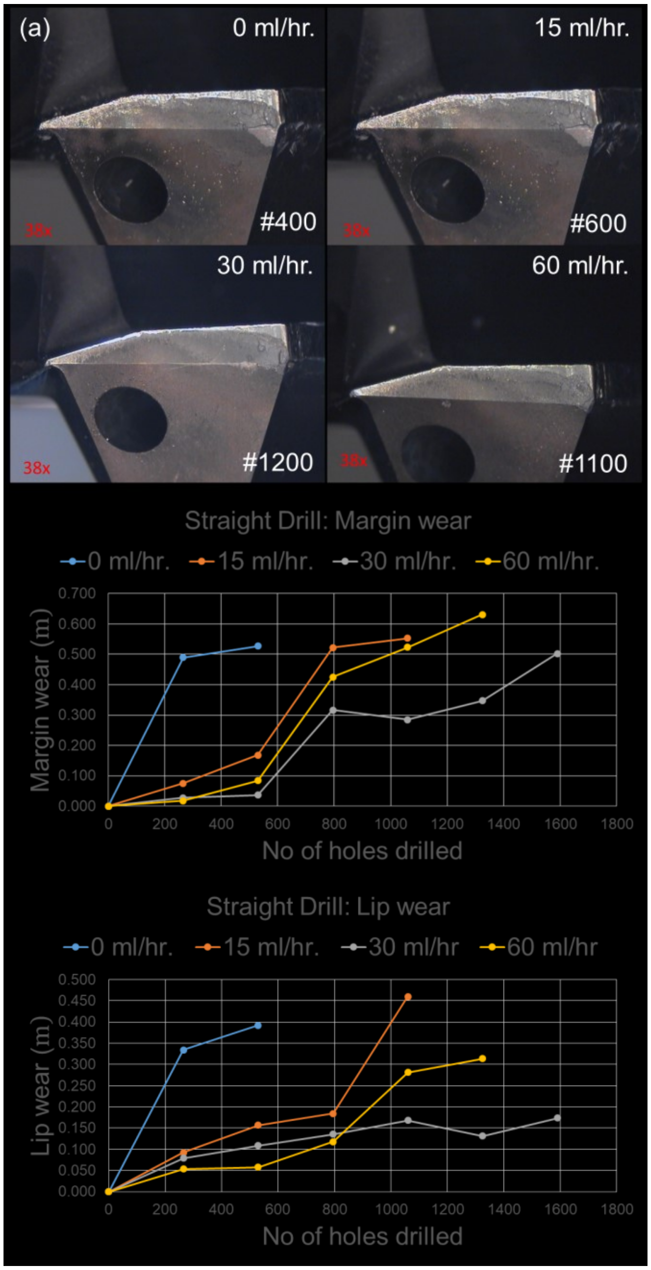

FIGURE 6: TOOL WEAR IN STRAIGHT DRILLS (a) TOOL WEAR OF CUTTING EDGE AT THE END OF TOOL LIFE (b) MARGIN WEAR AT DIFFERENT NO OF HOLES DRILLED (c) LIP WEAR AT DIFFERENT NOF OF HOLES DRILLED

Figure 6(a) shows the end state condition for straight drill at different oil flow rate conditions. The number at the bottom corner represents the no of holes drilled by the drill. The margin wear of the straight drills was measured and is shown in Fig. 6(b). The 0 ml/h condition showed rapid initial wear rate whereas the wear rate of other three conditions was similar and slower. The maximum wear was observed for 0 ml/h condition followed by 15 ml/h, 60 ml/h and 30 ml/h in that order. Also, the absolute value of wear in straight drills was almost twice than that of twist drills. Figure 6(c) shows the lip wear for straight drill. Just like margin wear, the maximum wear was observed in 0 ml/h condition followed by 15 ml/h, 60 ml/h and 30 ml/h. The absolute values of lip wear were almost twice than twist drill.

3.3 Cutting Force

The cutting force was measured as explained previously and the average cutting force was calculated as shown in Fig. 3. Figure 7 shows the average cutting force for twist drill and straight drill. The value of only thrust force was considered. The thrust force for twist drill (Fig. 7(a)) do not show much variation with respect to oil flow rate. However, increase of about 10% in thrust force was observed with increase in no. of drilled holes. The trend of increase in the magnitude of thrust force was similar in all the cases. Figure 7(b) shows the thrust force for straight drill. The magnitude of thrust force increases steadily with increase in the no of holes drilled. However, unlike twist drill, a difference in the magnitude of thrust force with respect to oil

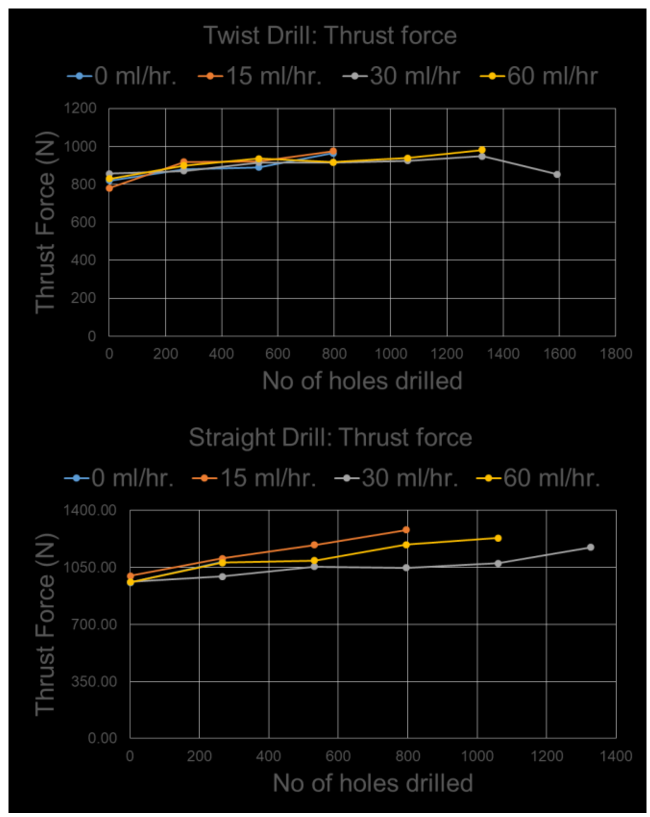

FIGURE 7: (a) AVERAGE THRUST FOR TWIST DRILL AT DIFFERENT CONDITIONS (b) AVERAGE THRUST FOR STRAIGHT DRILL AR DIFFERENT CONSDITIONS

flow rate was observed. The thrust force for 0 ml/h and 15 ml/h overlays on each other and thus the data for 0 ml/h cannot be seen on the plot. The thrust force for 60 ml/h is lower than 15 ml/h but consistently higher than 30 ml/h. The thrust force for straight drills at the end of tool life increases by about 35% as compared to a new drill.

3.4 Cutting Torque

The cutting torque for twist drills and straight drills is shown in Fig. 8(a) and Fig. 8(b) respectively. The cutting torque for twist drill does not show any clear trend. No major change in the magnitude of the cutting torque with respect to oil flow rate or with respect to no of holes drilled was observed. The cutting torque remains fairly constant irrespective of the tool health. However, an increase in cutting torque is expected once enough wear on the tool is observable. The effect of oil flow rate on straight drill was easily observable. The magnitude of the cutting torque was very similar for all the oil flow rate conditions. The cutting torque remains fairly constant irrespective of the oil flow rate. However, whenever a drill gets close to the end of its tool life, the magnitude of cutting torque increased by more than 100%. This sudden increase in torque can be a good indicator for estimating the tool health.

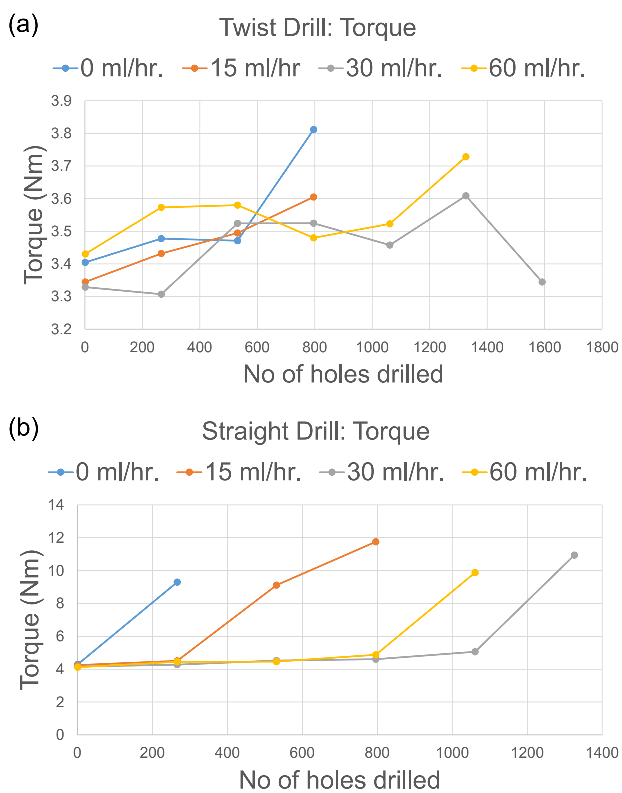

FIGURE 8 : (a) AVERAGE TORQUE FOR TWIST DRILL AT DIFFERENT CONDITIONS (b) AVERAGE TORQUE FOR STRAIGHT DRILL AR DIFFERENT CONSDITIONS

4. DISCUSSION

The effect of oil flow rate on the tool life, tool wear, thrust force and cutting torque was analyzed in this study. The experiments were performed using two types of drills namely, twist and straight. The effect of oil flow rate on twist drills was not that evident because of the geometry of the drill overshadowing the effect of oil flow rate. However, for the case of straight drill, a clear distinction in the tool performance with change in oil flow rate was seen because of the absence of helical flutes to remove the chips. The tool life obtained for both the types of drill initially increased with increase in oil flow rate from 0 ml/h to 30 ml/h but, a further increase in the oil flow rate did not improve the tool life. In fact a reduction in the tool life was observed for straight drill when the oil flow rate was increased from 30 ml/h to 60 ml/h. A similar trend was observed in the tool wear where the 30 ml/h oil flow rate condition always had lower tool wear than all other conditions. For straight drills, the same trend was observed in cutting force and cutting torque. However, the twist drill does not show a clear distinction between different oil flow rates. This makes the straight drills more sensitive to the oil dosage because they rely solely on the pressurized air for chip evacuation.

Oil in MQL provides lubrication and the pressurized air helps in chip evacuation. Both these phenomenon help in reducing the temperature and thereby providing better performance. With an increase in the oil flow rate, the lubrication of the part increases and also mass of the flow increases. This increase in the mass, increases the average droplet diameter and reduces the penetration of droplets to the cutting edge. Also, an increase in the oil flow rate reduces the average flow velocity. Considering all these behaviors, an increase in the oil flow rate improves lubrication and reduces the wear rate. A reduction in wear rate keeps the tool sharper and dimensionally accurate longer. However, the lubrication has a threshold. As long as this threshold value which in this case was 30 ml/h is met, enough lubrication is available at the cutting edge. Increasing the oil flow rate beyond the threshold value does not improve the lubrication but instead hinders with the chip evacuation because of highly viscous oil flooding the cutting zone and clogging the exit paths. This decreases chip evacuation efficiency and increases the time spent by the hot chips in contact with the tool. A longer contact time increases the tool temperature because of the poor capability of MQL to provide cooling. This increase in tool temperature reduces the tool life and performance. Therefore, increasing the oil flow rate beyond threshold does more harm than help.

Lastly, increasing the oil flow rate also increases the usage of the expensive MQL lubricants and leaves a layer of extra oil on the part produced. This layer of oil may hinder the next manufacturing process and requires secondary steps to be cleaned up. These secondary steps increase the cycle time of the part, reduce production efficiency and increase the cost of the process. Therefore, use of an optimal quantity of oil is important.

5. CONCLUSION

MQL has the potential of reducing the machining costs of the parts along with reducing the environmental hazards if, the process has been efficiently designed. The present work analyzed the effect of oil flow rate on the tool life, tool wear, thrust force and torque. It was concluded that for the case of through-tool MQL drilling, where the access to the cutting zone is limited, a higher oil flow rate does not necessarily mean an improvement in the tool life. Also, a higher oil flow rate increases the lubricant costs and defeats the purpose of MQL. Moreover, it was observed that straight flute drills are more sensitive to oil flow rate than twist drills, where the geometry of the drill overshadows the effect of oil flow rate. A significant improvement in the tool life and reduction in cutting cost can be obtained with proper selection of MQL oil flow rate.

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