EFFECTS OF MINIMUM QUANTITY LUBRICATION (MQL) ON TOOL LIFE IN
DRILLING AISI 1018 STEEL

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It has been reported that minimum quantity lubrication (MQL) provides better tool life compared to flood cooling under some drilling conditions. In this study, I evaluate the performance of uncoated HSS twist drill when machining AISI 1018 steel using a newly developed lubricant designed for MQL (EQO-Kut 718 by QualiChem Inc.). A randomized factorial design was used in the experiment. The results show that a tool life of 1110 holes with a corresponding flank wear of 0.058 mm was realized.
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CHAPTER I
INTRODUCTION

Heat is generated during machining in considerable amounts because of the cutting action and friction created by the tool, the workpiece and the chips. It is important to reduce the heat generated to improve the tool’s life and its dimensional accuracy, to increase the material removal rate, to reduce the cutting forces and to improve the surface roughness of the workpiece. Coolant or cutting fluid is used to take away the heat and to lubricate the machined surface. Cutting fluid should promote the tool life, improve the surface integrity of the workpiece, flush the chips from the cutting zone and protect the surface from corrosion [1]. Traditionally, the machining of parts uses flood cooling in which the jet of coolant is directed toward the cutting zone. Here, the coolant is deployed in large quantities. There are several disadvantages to using this method. The first one has to do with the cost of machining and its disposal. Approximately fifteen percent of total cost in machining is incurred by the coolant and its disposal [2]. The second one deals with a safety issue for the operators. One problem that exists for operators is that when they stay in contact with the coolant for a long time, it may cause skin problems. The third one is the effect on the environment. After machining, the chips produced are mixed with the cutting fluid and they cannot be disposed of directly as regular trash. At the same time, coolant should be filtered before being reused and after several more uses, the coolant also needs to be disposed.
The chips and the used coolant are disposed as hazardous waste—a practice that is costly to any industry. Hence, using the coolant in large quantities is a costly proposition that is not user friendly nor environmental friendly. The alternative solution is to machine with a minimum quantity of lubrication (MQL). MQL is also known as near dry machining or spatter lubrication [1,4].

MQL technique uses a small quantity of oil or lubricant. It is mixed with compressed air to generate a mist or an aerosol. The mist particles provide lubrication and the compressed air helps to reduce the temperature during machining. The range of oil flow rate in MQL usually varies from 1oz to 8oz in 8 hour [3, 4]. This quantity is very small compared to flood cooling. The air pressure varies from 0.2MPa to 6-bar. The selection of the parameters basically depends on the type of tool material, the work piece material and the processes.

Figure 1 MQL system.
MQL can be applied internally or externally as shown in Figure 2 and 3 respectively. In the internal way of applying MQL, mist is passed through the spindle, tool holder and tool. There are two basic approaches for applying MQL internally. In one method, oil and compressed air are mixed in an external unit and passed through the spindle and tool holder. In the other approach, the oil and the compressed air are mixed inside the spindle and passed through the tool holder. In the external way of applying MQL, the oil is mixed with the compressed air in one external unit and is deployed through an external jet. This system is simple, less expensive and effective for drilling shallow holes and low speed processes like gear cutting and broaching [3].

Figure 2 Internally applied MQL.
Figure 3 Externally applied MQL.

The benefits of MQL over flood coolant system [4]:

- Promotes longer tool life by reducing friction, ranging from 25 to 500 percent.
- Increases productivity in terms of reducing machining time by allowing machining with higher feed rates.
- Chips are clean and dry.
- No need to re-circulate the old or foul smelling coolant.
- Minimum disposal cost as mostly mist evaporates during machining.
- Machine as well as machining area remains clean and hence a much safer working area.
- No coolant tank for coolant and no significant filtering system is required.
- The entire process is environmentally friendly, as the fluid does not need to be treated, recycled or disposed of.
AISI 1018 steel has many applications. One of them is the manufacturing of bolts, gears, pinions, shafts, ratchet, machine parts, and axles. Most these parts are produced through machining processes such as turning, drilling, milling, shaping and grinding. It has been noticed that 70-80% of the manufactured parts need machining before the actual applications [5]. In machining, cooling and lubricating methods play an important role in minimizing the heat-affected zone. Traditionally, a flood cooling system is used to reduce the temperature of the cutting tool during the machining process. Due to high cutting forces and tool-work piece interface temperature, both work materials and tool materials may diffuse into each other. Either the chips take away the tool’s material or the chip particles diffuse onto the tool tip. As a consequence, many failures such as flank wear, thermal cracks and chipping occur on the cutting tool. In a flood cooling system, a large amount of coolant is required which increases the cost of machining. It is also hazardous in industrial applications. Nowadays, industries opt for Minimum Quantity Lubrication (MQL) system. In a MQL system, mist is generated and the flow of mist is regulated for optimum results. This system has proved to be more efficient and more economical compared to the flood coolant system [6,7].

The application of MQL is found more effective than flood cooling lubrication systems in grooving operations. Air supply plays a vital role in mist transportation to the tool and work piece interface area.
Obikawa et al. [8] conducted an experiment in 2005 on 0.45% carbon steel with TiC/TiCN/TiN triple layer coated carbide tool. The comparison was done between a P35 coated cemented carbide tool and a P25 uncoated cemented carbide tool. In the experiment, a P35 tool was used for a 3000 m cutting length and a P25 tool was used for a 1000 m cutting length. Two cutting speeds were used: 4 m/sec and 5 m/sec. The feed rate was 0.12 mm/rev. MQL was applied at the rate of 7 ml/h and the flow rate for the controlled-oil-mist directed grooving tool (COD tool) was set to 2.4 ml/h. The corner edge-wear and flank wear was measured in dry, wet and MQL cooling conditions. Three different air pressures were used: 0.3MPa, 0.5MPa and 0.7MPa. When the cutting speed was 4 m/sec, the feed rate was set to 0.12 mm/rev and the air pressure was set to 0.7MPa. The corner wear and flank wear for the P35 and P25 tools under dry; wet and MQL cutting are listed on Table 1.

Table 1 The corner wear and flank wear for P35 and P25 tool under different cutting environment [8].

<table>
<thead>
<tr>
<th></th>
<th>Corner wear</th>
<th>Flank wear</th>
<th></th>
<th>Corner wear</th>
<th>Flank wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>P35 tool</td>
<td></td>
<td></td>
<td>P25 tool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MQL</td>
<td>0.05mm</td>
<td>0.03mm</td>
<td>MQL</td>
<td>0.24mm</td>
<td>0.19mm</td>
</tr>
<tr>
<td>Wet</td>
<td>0.12mm</td>
<td>0.06mm</td>
<td>Dry</td>
<td>0.22mm</td>
<td>0.16mm</td>
</tr>
<tr>
<td>Dry</td>
<td>0.15mm</td>
<td>0.08mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From these results, it can be said that the wear is minimum in MQL compared to wet cooling and dry cutting conditions for P35 tool. There is not much difference in wear for the uncoated carbide tool. To see the effect of cutting speed, the experiment was
further run with a P35 coated carbide tool and the cutting speed being set at 4 m/sec and then 5 m/sec. The data obtained is listed on Table 2.

Table 2 Effect of different cutting speed on wear [8].

<table>
<thead>
<tr>
<th>Cutting speed</th>
<th>Corner wear</th>
<th>Flank wear</th>
<th>Cutting length</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m/sec- MQL</td>
<td>0.06 mm</td>
<td>0.04 mm</td>
<td>3300 m</td>
</tr>
<tr>
<td>5 m/sec- Dry</td>
<td>0.17 mm</td>
<td>0.08 mm</td>
<td>2700 m</td>
</tr>
<tr>
<td>4 m/sec- MQL</td>
<td>0.14 mm</td>
<td>0.06 mm</td>
<td>2600 m</td>
</tr>
<tr>
<td>5 m/sec- Dry</td>
<td>0.16 mm</td>
<td>0.10 mm</td>
<td>2100 m</td>
</tr>
</tbody>
</table>

From Table 2, it can be said that at the higher cutting speed of 5 m/sec, the corner wear in dry cutting increased suddenly due to the loss of coating layers. MQL reduced the wear to a large extent even at high cutting speed of 5 m/sec. The results also showed that by increasing the air pressure in MQL from 0.3 MPa to 0.7 MPa, flank wear and corner wear reduced drastically with a constant supply of MQL by 7ml/h.

The application of MQL in turning operation reduces tool wear, surface roughness and cutting temperature at the tool-chip-work piece surface contact as reported by Dhar et al. [9], who conducted an experiment on the turning of AISI 4340 steel. Here, Machining was done with carbide inserts at a cutting speed of 110 m/min, a feed rate of 0.16 mm/rev and a depth of cut of 1.5 mm. The turning operation was done under a dry, wet (flood cooling) and MQL environment. In MQL, the air pressure was set to 7-bar and the flow rate at 60 ml/h. The machining was done for about 45 min. During the experiment, the average principal flank wear, average auxiliary flank wear and surface roughness were
measured for different cutting lengths. Table 3 lists the results for a 45 min cutting length:

Table 3 Effect of cutting environment on flank wear and surface roughness [9].

<table>
<thead>
<tr>
<th>Environment</th>
<th>Avg. principal flank wear (µm)</th>
<th>Avg. auxiliary flank wear (µm)</th>
<th>Surface roughness Ra (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>475</td>
<td>375</td>
<td>52</td>
</tr>
<tr>
<td>Wet</td>
<td>500</td>
<td>450</td>
<td>60</td>
</tr>
<tr>
<td>MQL</td>
<td>350</td>
<td>325</td>
<td>45</td>
</tr>
</tbody>
</table>

From Table 3, it can be said that the wear rate and the surface roughness value were lesser in MQL compared to dry and wet cooling conditions. The growth rate of the flank wears decreased in MQL because of the reduction in temperature at the tool-chip interface area near the flank surface of the tool. Reduction in temperature helped to reduce abrasion wear by retaining tool hardness and also helped to reduce abrasion and diffusion types of wear—which are highly sensitive to temperature. The surface finish of the work piece and the dimensional accuracy depend on the auxiliary flank wear [9].

In 2005, Attanasio et al. [10] applied MQL technique on rake surfaces and flank surfaces of the tool to see the effect of wear on the tool. The turning operation was done on 100Cr6-normalized steel with feed rates of 0.2 mm/rev and 0.26 mm/rev, a cutting speed of 300 m/min, a depth of cut of 1mm, and cutting lengths of 50 mm and 200 mm. Three different lubrication systems were used: dry, MQL on flank surface and MQL on rake surface. In MQL, ester oil with EP additive (COUPEX EP46) was used with an air
pressure of 2.5 bar and an oil flow rate of 20 mg/h. Tool life was recorded in minutes for different combinations of feed rates, cutting lengths and lubrication systems.

Table 4 Effect of different cutting speeds and feed rates on tool life under different lubrication environment [10].

<table>
<thead>
<tr>
<th>Lubrication Environment</th>
<th>Tool life when feed rate: 0.2 mm/rev and cutting length: 50 mm</th>
<th>Tool life when feed rate: 0.26 mm/rev and cutting length: 50 mm</th>
<th>Tool life when feed rate: 0.20 mm/rev and cutting length: 200 mm</th>
<th>Tool life when feed rate: 0.26 mm/rev and cutting length: 200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cutting</td>
<td>10.04 min</td>
<td>8.17 min</td>
<td>10.10 min</td>
<td>7.86 min</td>
</tr>
<tr>
<td>MQL on Rake</td>
<td>9.75 min</td>
<td>8.58 min</td>
<td>9.28 min</td>
<td>9.36 min</td>
</tr>
<tr>
<td>MQL on Flank</td>
<td>10.36 min</td>
<td>9.16 min</td>
<td>11.44 min</td>
<td>9.68 min</td>
</tr>
</tbody>
</table>

From Table 4 it was observed that the maximum tool life was obtained when MQL was applied on the flank surface of the tool with a feed rate of 0.2 mm/rev. As feed rate increased to 0.26 mm/rev, the tool life was reduced to 9.68 min. The tool tips were observed under scanning electron microscope (SEM). On the rake surface crater wear, the inner notching and outer notching were observed. Under energy dispersive x-ray (EDS) analysis, elements like sulphur and calcium were observed on the tip used in flank MQL. Those elements were not present on the tip used in rake MQL. This indicates that MQL was not able to reach at the cutting area when it was applied on the rake surface. The team had concluded that MQL gives some advantages during the turning operation but it has some limitation due to the difficulty of the lubricants reaching the cutting surface.
Dhar et al. [11] showed that MQL helps to reduce the cutting temperature and dimensional inaccuracy when turning of AISI 1040 steel was cut by an uncoated carbide insert. The results obtained in MQL were compared with dry cutting and wet cooling conditions. Different sets of cutting speeds and feed rates were used to compare the effectiveness of dry, wet and MQL cooling conditions. The air pressure of 7-bar and a flow rate of 60 ml/h were used in MQL. Cutting speeds were: 64, 80, 110 and 130 m/min and feed rates were: 0.1, 0.13, 0.16 and 0.2 mm/rev. The effectiveness of the cooling media was observed by measuring the tool-chip interface temperature, the chips’ shapes and color, the chip reduction co-efficient and the dimensional deviation at different cutting speeds and feed rates. The tool-chip interface temperature was observed to be the lowest when machining was done with a feed rate of 0.1 mm/rev and a cutting speed of 130 m/min under MQL. When the feed rate was set to 0.2 mm/rev, the temperatures were recorded as 790°C, 775°C and 760°C for dry, wet and MQL conditions respectively. The trend of cutting temperature decreased when the feed rates and cutting speeds were decreased. To determine the dimensional accuracy, the experiment was run at the cutting speed of 110 m/min, a feed rate at 0.2 mm/rev and a depth of cut at 1mm. It was observed that for a cutting length of 425mm, the dimensional deviation was minimum (about 70µm) under MQL and maximum (95µm) under dry cutting condition. The study concluded that MQL provides benefits mainly due to the reduction in cutting temperature, which improves the tool-chip interaction and maintains the sharpness of the cutting edges. MQL reduced tool tip wear and damages and because of this, dimensional accuracy improved.
In 2006 Dhar et al. [12] again investigated the effects of MQL in turning AISI 1040 steel at high cutting speeds. During the experiment the factors: cutting forces, cutting temperature, chip reduction coefficient, average flank wear, auxiliary flank wear, surface finish and dimensional accuracy were measured to see the effect of MQL with different sets of cutting speeds and feed rates. The experimental conditions are listed in Table 5.

Table 5 Cutting parameters used in the experiment [12].

<table>
<thead>
<tr>
<th>Work material</th>
<th>AISI 1040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting tool material</td>
<td>Carbide inserts</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>72, 94, 139 and 164 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.10, 0.13, 0.16, 0.20 mm/rev</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>1.5mm</td>
</tr>
<tr>
<td>Air pressure in MQL supply</td>
<td>8 bar</td>
</tr>
<tr>
<td>Flow rate of MQL supply</td>
<td>200ml/h</td>
</tr>
<tr>
<td>Cutting environment</td>
<td>Dry and MQL method</td>
</tr>
</tbody>
</table>

It was observed in the experiment conducted by Dhar et al. [12] that MQL helped to reduce the cutting temperature approximately by 5-10% compared with dry cutting for each combination of cutting speed and feed. The general trend indicates that with an increase in cutting speed, cutting temperature is also increased, but the cutting temperature in MQL is lesser than that of dry cutting. Cutting force and feed force play vital role for power and energy consumption, product quality, and life of other members.
such as the tool holder, the fixtures and other machine parts. It was observed that as cutting speed increased, the magnitude of both of these forces reduced. In comparison between dry cutting and MQL, MQL helped to reduce these forces. During the machining, the shear strength of the material increases due to compression and straining. If cutting temperature is high enough shear strength of the material decreases due to softening effect. Overall cutting forces depend on the type of material, the cutting temperature, the fixtures and the mountings. MQL helps to reduce the cutting temperature and hence, results in reduced forces. The tool life affects the productivity and economy of manufacturing. When tool inserts were observed, the rake surface and the clearance surface had crater wear and flank wear respectively due to the continuous interaction and rubbing action between chips and the work surface. The flank wears, surface roughness and dimensional deviation were found to be lesser with the use of MQL compared to dry cutting. Overall it was observed that when MQL was used in the turning of AISI 1040 steel, tool life was increased. At the same time, cutting forces, flank wear, surface roughness and dimensional deviation were decreased.

Dhar et al. [13] conducted another study on AISI 1060 steel in which all the parameters were kept the same as in the previous study except for the work piece material, the air pressure and the flow rate of MQL. Here, air pressure was set at 7-bar and flow rate was set at 60 ml/h. The experiment was run under dry cutting and MQL cutting environments. It was observed that MQL helped to reduce the average cutting temperature by 5% to 12% depending upon the process parameters (i.e. feed rate and cutting speed). The authors also discovered that as the cutting speed increased, the
accumulation of chips made it difficult for the proper amount of MQL to reach the cutting zone. In conventional machining, the tool generally failed by gradual wears due to abrasion, adhesion, diffusion, chemical erosion and galvanic action that depend on the type of tool, the tool material and the work piece material. The growth of average flank wear under MQL was lesser than that of dry cutting condition. But as the machining time increased, the flank-wear also increased. Dimensional deviation and surface roughness were also found to be more in dry cutting than under MQL cutting. Overall, MQL gave better results for cutting forces, tool wear, surface roughness and dimensional deviation.

The location of MQL jet also plays a major role during machining. The position of the nozzle affects the cutting temperature during machining. To determine the effect of angle at which the MQL nozzle is set on the machining temperature, Ueda et al. [14] conducted one study on the continuous and intermittent turning and milling of AISI 1045 steel. The cutting temperature was measured using a two-color pyrometer for both operations. Vegetable oil was used for mist, as it is harmless for the operator compared to conventional cooling. The airflow rate was set at 210 ml/min and the oil flow rate was set at 40 ml/hr. It was observed that the tool temperature was lesser by 60°C than that of dry turning. For instance, temperature at the cutting speed of 300 m/min was 1060°C in dry turning and with MQL it was 1000°C. This difference in temperature (i.e. 60°C) is equivalent to a cutting speed difference of 50 m/min. High machining efficiency can be achieved in MQL. In intermittent turning operation, the difference of temperature was 70°C when machining was done in dry and MQL condition at the cutting speed of 300 m/min. The location of MQL nozzle played an important role on cutting temperature. In
turning, the position of the nozzle at 45° vertically and horizontally gave better results on rake surface temperature. In end milling, MQL was supplied on flank face of the cutter. The tool temperature was resulted to be 660° in dry cutting and 580° in MQL cutting.

In one another study, Dhiman et al. [5] studied the machining behavior of AISI 1018 steel under dry cutting during the turning operation. The steel bar was turned with spindle speeds of 83 to 508 rpm, feed rates of 0.09, 0.12, 0.16 mm/rev and depths of cut of 0.2, 0.8 and 1.2 mm. The effect of different spindle speeds was analyzed on cutting temperature at different feed rates and depths of cut. It was found that as the speed increased, cutting temperature also increased. When spindle speed increased from 83 to 508 rpm, feed rates to 0.16 mm/rev and depths of cut to 1.2 mm, the tool tip temperature was found to increase from 60°C to 200°C. At 0.2 mm depth of cut, surface roughness was more at 83 and 508 rpm spindle speed. Surface roughness was the same for all feed rate at 224 rpm and 320 rpm. With increase in depth of cut, chips produced are thicker, shear plane angle reduces, shear plane area increases, contact length increases and cutting force increases. The influence of the depth of cut reduces at higher feed rate.

The study conducted by Anshu Jayal et al. [16] explains the effect of cutting fluid application on tool life and tool wear. In their experiment, AISI 1045 steel was turned with a high cutting speed of 400 m/min, a feed rate of 0.35 mm/rev and a depth of cut of 2mm. The mean tool life was observed under a) dry cutting, b) MQL (Mineral oil-based soluble oil concentrate) with flow rate of 30 ml/h and 0.6 MPa air supply, c) MQL-EP (ester + EP additives) with flow rate of 30 ml/h and 0.6 MPa air supply, and d) flood coolant (soluble mineral oil) supplied at 9 l/min. Three types of cutting tools were used:
flat-faced single layer TiN PVD coated cemented tungsten carbide, flat-faced multi layer TiN/Al₂O₃/TiCN/TiN CVD coated carbide and grooved single TiN PVD coated carbide. The tool life for flat-faced PVD tools and grooved PVD tools are listed in Table 6.

Table 6 Effects of cutting environment on tool life of flat-faced PVD tools and grooved PVD tools [16].

<table>
<thead>
<tr>
<th></th>
<th>Dry cutting</th>
<th>MQL</th>
<th>MQL-EP</th>
<th>Flood cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean tool life for flat-faced PVD tools (sec)</td>
<td>6.5</td>
<td>10.5</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Mean tool life for grooved PVD tools (sec)</td>
<td>11</td>
<td>12</td>
<td>7.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

From Table 6, it can be seen that dry cutting is not as effective as in high speed turning. Flood cooling condition showed better results. For both tools, crater wear was noted. Crater wear was more prominent in dry cutting for flat-faced PVD tool. Crater wear was observed more in MQL-EP cutting condition for grooved face PVD tool. Flank wear was higher for both types of tools under dry cutting condition. Turning under MQL condition proved beneficial for AISI 9310 steel [17]. The average cutting temperature was reduced up to 10% compared to dry and wet cutting. Remarkable improvement in tool life and productivity (in terms of material removal rate) was observed under MQL cutting. Surface finish was observed to improve under MQL cutting.

Saluena-Berna et al. [18] conducted an experiment in milling operation. He showed that surface roughness was improved with the application of MQL compared to dry cutting and wet cooling conditions. Along with CVD coated inserts, MQL is
advisable for stainless steel milling when feed rate per tooth is higher than 0.06 mm/min. Tool life depends on machining parameters in milling such as cutting speed, feed rate per tooth, tool geometry, depth of cut, work piece hardness, cutting tool material, material and lubricant and lubrication methods. To know the effect of factors such as helix angle of cutter, work piece hardness, milling orientation and MQL on tool life and surface roughness, Iqbal et al. [19] conducted an experiment on high-speed milling of AISI D2 material. In the experiment, the cutting speed was set to 250 m/min, the feed rate was set to 0.1 mm/tooth, and the radial depth of cut and axial depth of cut were set to 0.4mm and 5mm respectively. The flat end carbide cutters with PVD TiAlN coated tool having two different helix angles were used: 30° and 50°. Two different lubrication methods were used: dry and MQL. When tool life is concerned, it was concluded that tool life in high-speed milling can be maximized for AISI D2 material having hardness between 52 to 62 HRc by using end mill having higher helix angle (50°) along with down milling and MQL cooling system. For surface roughness, it was suggested that the tool having helix angle of 45° could be used with down milling and MQL to minimize the surface roughness value. The surface roughness value for 52HRc material was obtained 0.3 to 0.35µm and 0.45 to 0.5µm for 62 HRc materials. The cutting edge was damaged by micro chipping and adhesion wear. Rake face was not damaged by any wear mechanism even though the work piece chips were found to diffuse onto the rake face. The portion near the cutting edge was damaged by diffusion wear and the area far from cutting edge showed more oxidation wear. Adhesion and diffusion wear damaged the flank face of the tool. To improve the tool life, coating material on tool plays major role. The coating of
TiAlN showed better tool life and longer cutting length compared to the uncoated WC-Co tools proved by Si Tae et al. [20].

Cutting speed and feed rate are important in high-speed milling. Tool-wear and tool life are major concerns in high-speed milling. To investigate the effects of MQL in high-speed milling, Y. S. Liao et al. [21] conducted an experiment in which AISI P21 steel was milled with a TiAlN/TiN coated carbide insert at cutting speeds of 300, 400 and 500 m/min and feed rates of 0.10, 0.15 and 0.20 mm/tooth. The axial depth of cut and radial depth of cut were 0.3 and 5 mm respectively. The tool life (in meter), cutting force (in N) and surface roughness (in µm) were measured under dry cutting and under MQL cutting with different cutting speeds and feed rates. The achieved tool life results are listed in Table 7.

Table 7 Effects of cutting speeds and feed rates on tool life under dry and MQL cutting environment [21].

<table>
<thead>
<tr>
<th>Cutting speed (m/min)</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>Cutting condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>11</td>
<td>6</td>
<td>4</td>
<td>Dry</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>11</td>
<td>5.5</td>
<td>MQL</td>
</tr>
<tr>
<td>0.15</td>
<td>12</td>
<td>5.5</td>
<td>3.5</td>
<td>Dry</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>10</td>
<td>4.5</td>
<td>MQL</td>
</tr>
<tr>
<td>0.20</td>
<td>9</td>
<td>4.5</td>
<td>3.25</td>
<td>Dry</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>8.5</td>
<td>3.75</td>
<td>MQL</td>
</tr>
</tbody>
</table>

From the data in Table 7, MQL was effective at a cutting speed of 300 m/min and a feed rate of 0.10 mm/tooth. As cutting speed and feed rate increased, the effectiveness
of lubrication decreased. MQL seems to provide extra oxygen to chip-tool interface so as to promote the formation of a protective layer of oxides. At optimal cutting speeds this layer is stable and creates the barrier for diffusion, which aids in the wear resistance of the cutting tool and increases the tool life significantly. At high cutting speed, the formation of this layer becomes unstable and tool life decreases. Cutting force and surface roughness were measured for different cutting speed when feed rate was 0.15 mm/tooth and depth of cut was 0.3 mm, and are shown in Table 8. From the data shown in Table 8, it can be said that cutting forces and surface roughness values were smaller for MQL compared to dry cutting.

Table 8 Effects of cutting speeds on cutting force and surface roughness in dry and MQL cutting environment [22].

<table>
<thead>
<tr>
<th>Cutting speed (m/min)</th>
<th>Cutting force (N)</th>
<th>Surface roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>MQL</td>
</tr>
<tr>
<td>300</td>
<td>47.5</td>
<td>44</td>
</tr>
<tr>
<td>400</td>
<td>46</td>
<td>44</td>
</tr>
<tr>
<td>500</td>
<td>45</td>
<td>43</td>
</tr>
</tbody>
</table>

The results in Table 8 indicate that MQL proved to be beneficial to tool life for AISI D2 cold work steel in high-speed milling when WC-Co carbide was coated with TiAlN/TiAlSiN [22].

In most of the turning and milling processes, a tool makes the contact on the outer surface of the work piece. So the cutting temperature can be reduced easily. Chips can be segmented and flown over the tool. But in drilling operation, it is difficult to reduce the
temperature when a drill cuts the material. The chip removal is also one of the concerns during drilling operations. As drilling proceeds during machining, there is rubbing action among the cutting edge of the tool, the machined surface and the chips. This results in high temperature due to friction. It is necessary to decrease the temperature of the tool and the work piece through an effective cooling system to achieve better tool life and surface finish. Due to the high temperature, machined surface becomes less brittle and rigid. There are more chances that both, tool material as well as the work piece material diffuses into each other. Much research is done on machining AISI 1018 steel. In 2004, Makiyama Tadashi et al. [23] conducted an experiment of drilling on 0.5% carbon steel. Holes were drilled with a TiAlN coated solid carbide twist drill with a cutting speed of 120 m/min and a feed of 0.2 mm/rev. Holes were drilled under wet cutting, dry cutting condition and minimum quantity lubrication (MQL). Ester oil was used in MQL with two different flow rates of 5 ml/h and 10 ml/h. The air pressure was set at 0.5MPa in MQL. The tool life and hole size deviation were measured to analyze the effect of MQL, flood cooling and dry cutting condition. In dry cutting condition, tool life was found to be 31.7 m, (equivalent to 1554 holes). In wet cutting condition, tool life was found to be 61.1 m (equivalent to 2995 holes). The tool life in MQL with 5 ml/h was found to be 78.3 m (equivalent to 3838 holes) and with 10 ml/h, tool life was found to be 215.4 m (equivalent to 10559 holes). The tool life was found maximum in MQL with a 10ml/h flow rate. In dry cutting, the largest cutting torque was recorded with an irregular surface. Hence, tool life was found to be the shortest. Wet cutting had the highest cooling effect and smallest hole-diameter deviation. The MQL with 5ml/h flow rate had medium effect
of cooling and the largest enlargement of hole-diameter. The finished hole-surface had regular feed marks without burnishing effect. That might be the reason for the lower torque. MQL with 10ml/h flow rate had the largest tool life with larger enlargement of drilled holes and had a smaller cutting torque. The results indicate that there is a relationship between the enlargement of diameter of the drilled hole and tool life.

In 2005, Heinemann et al. [24] analyzed the effect of MQL on tool life of small twist drills in deep-hole drilling. The study was done on 0.45% plain carbon steel. Four types of drill were used: a) uncoated high speed steel (HSS), b) uncoated Co-HSS, c) TiN coated Co-HSS and d) TiAlN multilayer-coated Co-HSS. Three different types mist were used in MQL: SETOL ST-SHAD 20A (Synthetic ester + additives + alcohol 20%), SETOL ST-SHAD (Synthetic ester + additives) and SETOL SOE (Oil free synthetic lubricant + 40% water). The cutting speed was 26 m/min and the feed rate used was 0.26 mm/rev. The objective was to study the effect on tool life when MQL was to be applied in continuous form and discontinuous form. The experiment was run further with different kind of MQL. When drilling was carried out under continuous supply of MQL with a flow rate of 18 ml/h, tool life (number of drilled holes) for different drills were as follows: a) uncoated HSS drilled 558 holes, b) uncoated Co-HSS drilled 536 holes, c) TiN coated Co-HSS drilled 709 holes and d) TiAlN coated HSS drilled 966 holes. When MQL was applied discontinuously (MQL supply resumed during withdrawal after drilling hole), tool life dropped drastically. Uncoated Co-HSS drilled only 13 holes (98% drop), TiN coated Co-HSS drilled 411 holes (42% drops) and TiAlN coated Co-HSS drilled 709 holes (27% drop). To see the effect of different MQL, experiment was run
again with uncoated HSS drill under 18ml/h flow rate of MQL. It was found that 558 holes were drilled with SETOL ST 20A lubricant, 689 holes were drilled with SETOL ST SHAD lubricant and 1117 holes were drilled with SETOL SOE lubricant. It can be concluded from the results that MQL with high cooling capability is advantageous for deep-hole drilling.

In 2010, Shaikh and Boubekri [25] evaluated the performance of high-speed steel (HSS) drill on AISI 1018 steel. The experiment was conducted on AISI 1018 steel work pieces. With three different cutting speeds: 80, 100, and 120 SFM and two different feed rates: 0.004 and 0.003 IPR. Aculube 6000 vegetable oil was used as MQL. The study was conducted to measure the tool life of drill in terms of number of holes and surface finish of the drilled hole. After collecting the hole-size of diameter and surface finish, regression models were generated for both the inner diameter and the surface finish in terms of cutting speed and feed rate. The tool life at different cutting speed and different feed rate are shown on Table 9.

Table 9 Effect of cutting speeds and feed rates on tool life [25].

<table>
<thead>
<tr>
<th>Feed Rate (IPR)</th>
<th>Cutting speed (SFM)</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.003</td>
<td></td>
<td>880</td>
<td>490</td>
<td>530</td>
</tr>
<tr>
<td>0.004</td>
<td></td>
<td>430</td>
<td>390</td>
<td>280</td>
</tr>
</tbody>
</table>

It was observed that at lower feed rate (i.e. 0.003 IPR), as cutting speed increased, the surface roughness of drilled hole also increased and for higher feed rate (i.e. 0.004
IPR), as cutting speed increased, the surface roughness was decreased [25].

Summary

From the literature review we can conclude that extensive research has been conducted in machining steel. Most of the operations including turning, milling, drilling, grinding and grooving are performed under MQL. Flood coolant machining failed to reach at the tool-chip-work piece interface and hence cutting temperature was observed to be high. In MQL, mist particles helped to reduce cutting temperatures, cutting forces and surface roughness. In machining, tool material also plays an important role in achieving a good tool life. It has been observed that tools having TiAlN/TiN coating improve the tool life as these coatings improve heat resistance during machining. MQL was proved more effective than flood cooling machining for speed ranging from 50 m/min to 130 m/min, feed rate ranging from 0.1 mm/rev to 0.2 mm/rev. MQL also proved to be better for high speed turning and milling.

Problems observed during drilling operations were the removal of chips and the high cutting temperatures. Due to the high temperature, tool life decreases with increases in cutting forces, surface roughness and power consumption. Many experiments were conducted with dry cutting (i.e. without the use of cutting fluid). The flood coolant delivery technique helped to remove the chips from the drill hole but it was ineffective in reducing the temperature of the tool-work piece interface. MQL system was more effective than the flood cooling system, because a reduction in temperature was achieved at the tool-work piece interface due to mist particles reaching this interface. The usage of coated twist drill along with MQL cooling system provided better results for tool life,
tool wear and surface finish. The effectiveness of the MQL depends on the type of lubrication used, cutting speed, feed rate, tool material, flow rate of MQL and air pressure in MQL. A study in 2010 by Shaikh and Boubekri [25] on drilling 1018 steel explains the effect of MQL with combination of different cutting speeds and feed rates. The effects were measured in terms of tool life (number of holes drilled) and surface roughness (μm). Tool life was decreased as cutting speed increased and surface roughness decreased when cutting speed increased.
CHAPTER III
EXPERIMENTAL METHOD AND PROCEDURE

This chapter describes the experimental process and measurement procedure for this research. It also describes the objective of the study, sample preparation, work piece, machine tool and cutting tool descriptions and data analyses.

Objectives

The main objectives of this study are:

- To evaluate the performance (in terms of number of holes drilled) of uncoated HSS twist drill when drilling AISI 1018 steel at cutting speeds of 80 and 120 SFM, feed rates of 0.003 and 0.004 IPR using a newly developed lubricant designed for MQL system. It is different lubricant than the lubricant used by Shaikh and Boubekri [25].
- To compare the study results with those obtained by Shaikh and Boubekri [25] when AISI 1018 steel was drilled with uncoated HSS drill and Acculube 6000 vegetable oil for mist.
- To characterize the tool wear using tool maker microscope.

Design of Experiments

The experiment was carried out with two independent variables: speed and feed rate and one dependent variable, hole size. The experiment was carried out based on a randomized factorial design. The hole-depth was one inch for entire drilling operation.
Four cutting speed and feed rate combinations were selected to determine the effects of mist cooling on the tool life of the HSS twist drill. The designs of experiment treatments are shown in Table 10. The speed and feed rates are in feet per minute (SFM) and inch per revolution (IPR) respectively.

Table 10 Speed and feed rate combination.

<table>
<thead>
<tr>
<th>Number of experiment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination of cutting speed and feed rate</td>
<td>C1, F1</td>
<td>C1, F2</td>
<td>C2, F1</td>
<td>C2, F2</td>
</tr>
<tr>
<td></td>
<td>80, 0.003</td>
<td>80, 0.004</td>
<td>120, 0.003</td>
<td>120, 0.004</td>
</tr>
</tbody>
</table>

The experiment was randomly conducted. There were two levels of cutting speed: 80 SFM (C1) and 120 SFM (C2), and two levels of feed rate: 0.003 IPR (F1) and 0.004 IPR (F2). Based on these, four combinations of cutting speed and feed rate were established. The experiment was conducted as follows:

1. Any one combination of the cutting speed and feed rate out of four was selected randomly and inserted manually in CNC program.
2. Randomly work piece was selected from the stack and 30 holes were drilled in each work piece until the twist drill failed as per the failure criteria.
3. The hole-diameter was measured for every 10th, 20th and 30th hole.
4. Once the tool was failed, replaced the failed tool with the new tool.
5. Inserted new combination of the cutting speed and feed rate and continued the process for all four combinations.
Cutting Tool

The cutting tool used for the drilling operation was a solid straight shank drill made of regular high-speed steel. It was ordered in a batch of 10 assuming that tools were assumed to be identical. The tools were ordered from Guhring Inc. with following specifications:

- Company: Guhring Inc.
- Part Number: 00205DIN 338R-N
- Tool Material: HSS
- Tool Diameter: 0.5in
- Tool Length: 5.944in
- Flute Length: 3.976in
- Drill type: Solid drill with straight shank
- Cutting point angle: 118°

![Figure 4 HSS drill.](image)

Coolant

Synthetic cutting fluid was used for mist generation along with compressed air.
“EQO-KUT 718” by QualiChem Inc. was used as a coolant. The properties of the fluid were as follows:

- Appearance: Light yellow
- Density: 7.67 lbs/gal
- Flash point, COC: 360°F (180°C)
- Viscosity, SUS @ 100°F (38°C): 175
- Fat: Synthetic
- Chlorine and Active Sulfur: None

The cutting fluid was mixed with the compressed air in the unit called “Mister” (Figure 5). The mister is attached outside of the machine. The mist was applied externally on the cutting tool as shown in Figure 6. The air pressure was set to 0.15MPa. The coolant flow rate was set to 12 ml/hr.
Sample Preparation

Before starting the drilling experiment, the material was cut to make samples for the experiment. The material was ordered from a local vendor. The four bars of 10 feet length were cut using a band saw machine as shown in Figure 7. Because of the limitation of clamping device in CNC machining center, the diameter of the work piece was restricted to 4 inches. The samples were made as follows:

1. The bar was placed the roller bed of the band saw machine.
2. The bar was clamped tightly between the clamp and first cut of 0.5 inch was made on the bar to make the surface perpendicular to the bed.
3. If specified with the results of step 2 above, 1.75inch thick blanks were cut from the bar and placed on the wooden pallet (Figure 8)

4. To transform 1.75inch thick blanks in to 1.5inch thick sample, the blanks were processed in a CNC lathe machine for a facing operation on each surface.

5. The 1.75 inch blank was clamped in hydraulic operated chuck

6. During the facing operation on one surface, 0.075inch of material was removed from that surface (Figure 9)

7. The processed blank was then clamped on opposite surface to process the other surface

8. On this opposite surface, a total of 0.175inch material was removed in a similar manner as done on the first surface of the blank (Figure 10)

9. On the same surface, the blank diameter was reduced to 3.950inch up to 0.75 inch in length through a turning operation (Figure11).

10. A chamfering radius of 0.1659inch was machined on same side. The purpose of reducing the diameter and chamfering was to locate and clamp the work piece securely in a CNC machining center.

The first facing operation was done via one program and another facing, turning and chamfering operation was via a second program in the CNC lathe. All the unprocessed work pieces were kept on a wooden pallet near to the CNC machining center.
Figure 7 Band saw cutting (Source: MFET Lab, UNT).

Figure 8 Blank from bar.
Figure 9 Facing on first face.

Figure 10 Facing on opposite surface.
Before the drilling experiment, a number of layouts were drawn on paper. The layout selected was one in which a maximum number of holes were fitted. The program was written and uploaded into the CNC machining center as per the selected layout. The program was written for 30 holes of 1 inch depth and 0.5 inch diameter. The pattern of the hole was symmetric. To identify the first drilled hole, one slot was machined at an edge of the work piece using an end mill cutter. Dry runs were conducted to check the program correctness. The layout is shown in Figure 12. During dry runs, the position of nozzle for mist application was set. The air pressure and coolant flow rate was set at the time of dry runs only.
Figure 12 Work piece layouts.
Vertical machining center used to drill the holes. The machine specifications are as follows:

- Machine make: Mori Seiki Dura Vertical 5060
- Controller: CNC Fanuc controller MSX-504 III
- Maximum Spindle speed: 10000 RPM
- Travel range in X-Axis: 23.600 inches
- Travel range in Y-Axis: 20.900 inches
- Travel range in Z-Axis: 20.100 inches
Work Piece Material

AISI 1018 was used as the work piece material. It has fair machinability, good hardening properties and can be readily welded and brazed. This material is mostly used for shaft, axel, sprocket assemblies, spindles, screw and bolts. The material is available in cold rolled round, square, flat bar or hexagonal shape. Because of its hardening ability and Manganese content, 42 RC-hardness can be achieved even in thin sections. The chemical composition of AISI 1018 steel is shown in Table 11.

Table 11 Chemical composition of AISI 1018 steel (Source: Lokey Metals, FW).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Carbon</th>
<th>Manganese</th>
<th>Phosphorus</th>
<th>Sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>0.16-0.20</td>
<td>0.6-0.9</td>
<td>0.04 max</td>
<td>0.05 max</td>
</tr>
</tbody>
</table>

The mechanical properties are as follows:

Table 12 Mechanical properties of AISI 1018 steel (Source: Lokey Metals, FW).

<table>
<thead>
<tr>
<th>Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (Rockwell C)</td>
<td>42</td>
</tr>
<tr>
<td>Yield Tensile strength (psi)</td>
<td>45000</td>
</tr>
<tr>
<td>Ultimate Tensile strength (psi)</td>
<td>65300</td>
</tr>
<tr>
<td>Modulus of elasticity (ksi)</td>
<td>29000</td>
</tr>
<tr>
<td>Shear modulus (ksi)</td>
<td>11600</td>
</tr>
</tbody>
</table>
Drilling Procedure

Before starting the drilling operation, check for:

1. The mist lubrication oil tank for the proper level of oil in the mist generator device.
   (The device is attached to the backside of the machine.)
2. Check the air knob and the power supply switch.

Keep the pallet of all the previously machined samples near by the machine. Follow the following steps.

1. Insert the control panel key and door keys
2. Turn on the machine by pressing the POWER ON button on control panel.
3. Select and insert the correct program. Select any one combination of cutting speed and feed rate from the Table 10 and type in the selected program.
4. Check and make sure that all the values fed are correct in the program
5. Open the door of the machine by pressing DOOR OPEN button.
6. Clean the three jaw chuck with brush to remove the chips from the clamping area
7. Place the sample and tight the sample with the mallet and ensure that sample is tightened enough.
8. Close the door of the machine
9. Press START button on control panel. Center drilling will start.
10. After completion of center drilling, machine stops because of the optional stop command in program. Check visually for all center drilled holes.
11. Press START button for further drilling operation.
12. After drilling every three holes, machine stops because of optional stop. Open the door and remove the accumulated chips from the drill as well as from the work piece.

13. Close the door and again press START button to continue drilling operation.

14. Repeat steps 13 and 14 till the program completion.

15. After completion of 30th hole, machine stops again and press START button again for the milling process.

16. Open the door and with the help of the file, remove the burr from milled surface for safety purpose.

17. Unclamp the work piece from the chuck with chuck-key and mallet.

18. Clean the work piece with compressed air to remove the accumulated chips and coolant in the drilled holes.

19. Measure the 1st hole with the help of digital vernier caliper and then measure every 10th, 20th and 30th hole of every work piece as per the inner diameter measuring procedure.

20. Record all the values of each measurement in the spreadsheet.

21. Repeat steps from 7 to 21 until the tool fails as per the data collection method.

Once the tool fails, remove the tool from ATC. Unclamp the tool from the tool holder and clamp a new tool for the next combination of cutting speed and feed rate.

Before replacing the new tool clean the tool holder for coolant. Do the tool length compensation\(^1\) for the new tool to make work piece top surface as a datum for the tool.

\(^1\) Tool length compensation steps are given in following page.
Repeat the same steps whenever the tool needs to be changed for all the combinations of cutting speed and feed rate.

Tool length compensation steps for the new tool:
1. Clamp the work piece in the vice and the tool in tool holder
2. Bring the work piece under the tool axis manually
3. Bring the tool on the work piece surface manually
4. Maintain the gap of page thickness by inserting the page in between the work piece and the tool
5. Record the value of Z-axis and insert the value in tool length compensation tab for Z-axis

Data Collection Method

Tool is considered as failed when
- The reading of three consecutive holes is greater than or equal to 0.510 inches
or
- The reading of any hole is less than the first-hole reading.

Inner Diameter Measurement Procedure
1. Measure every 10th, 20th and 30th hole with digital vernier caliper. Record all the readings in spreadsheet
2. If hole reading goes equal or greater than 0.510 inches, measure previous two consecutive holes diameter. If all readings are greater than equal to 0.510 inches then tool is considered to have failed.
3. If previous two holes readings do not repeat the condition of greater than equal to 0.510 inches then continue the drilling process for next 30 holes.

4. If hole-diameter reading is less than the first hole then the tool is considered as failed.

Data Analysis

After collecting all the data for hole-size, an analysis of Variance (ANOVA) was conducted by using Design of Experiment-8 software. The purpose of ANOVA was to determine if there was any significant difference in hole-size due to a specific combination of cutting speed and feed rate. For ANOVA test, the independent variables were cutting speeds and feed rates and dependent variable was hole-size. The following steps were performed for ANOVA:

- Organize the data properly in spreadsheet for all combination readings
- Inspect the F-value, to determine if the model is significant
- Determine if the interaction and main effects for independent variables are significant
- Check R-squared value for the regression model. If required perform transformations to get better values of R-squared
- Plot the required graphs

To characterize the tool wear, analyze all collected failed tools under the toolmakers microscope. The value of flank wear is the distance between the peak and valley on the flank edge of the tool as shown in Figure 14. Measure the flank wear on both the edge of the tool and take the average value.
All failed tools were analyzed for its failure pattern. The tools were observed under toolmakers microscope. The flank wear and chipping areas were observed and measured under 20X magnification lens. The photographs were taken using moticam software.

Main Assumption of Study

- Drilling load had negligible effect on tool life
- Mixture of oil and compressed air and flow rate of mist was continuous throughout the drilling operation
- Work piece samples are identical
- Cutting tool used are identical
• Procedure of hole-diameter measurement with digital vernier caliper was consistence throughout the experiment
• ANOVA was the proper statistical tool to analyze the model
• Machine tool rigidity did not affect the tool life
• Only the numbers of hole drilled by the drill bit decided the tool life of drill
In this study, all collected data was recorded in a Microsoft excel file. This data was then transferred to the Design Expert 8 statistical tool software for Analysis of Variance (ANOVA) and regression analysis. The assumptions for the ANOVA are that within each group, the individual measurements and associated residuals are normally distributed, the groups compared should exhibit equal variance, and the individual measurements and associated residuals in one group are independent from those found in another group.

Hypothesis

The hypothesis tested is the following:

Null Hypothesis:

There is no significant difference in the hole-diameters (responses) by changing the cutting speed and feed rate combinations (input variables).

Alternative Hypothesis:

There is significant difference in the hole-diameters (responses) by changing the cutting speed and feed rate combinations (input variables).

The diameters of the hole obtained from the drilling on AISI-1080 steel were transferred into the Design Expert 8 software. To determine the suitability of the data for
ANOVA analysis, various graphs were plotted for this analysis (e.g., a normal plot of the residual alone and a plot of the residuals versus the predicted values). The residual is the difference between actual value of hole-diameter and predicted value of the hole-diameter. In the analysis of variance plot, the normal probability distribution of residuals is expected. The normal plot of the residuals is shown in Figure 15. A plot of the internally normalized residuals versus the normal % probability approximates a straight line, indicating normal distribution behavior of these normalized residuals. As the data is normalized, the diameters of the hole can be said to be suitable for ANOVA analysis as they follow a normal distribution.

Figure 15 Normal probability plot.
For the assumption of constant variance, the graph of residual versus predicted value was obtained from the design of expert software. The graph of residuals vs. predicted is shown in Figure 16. The graph shows equally distributed random behavior about the centerline indicating constant variance.

![Residuals vs. Predicted](image)

Figure 16 Predicted vs. residual graph.

Table 13 shows the ANOVA results for hole-diameters based on the data obtained from drilling. A two factor randomized factorial design was used for the analysis of variance. In the table, term A is noted for the varying of cutting speeds group, term B is noted for the varying of the feed rates group and term AB is noted for interaction between
cutting speeds and feed rates. ANOVA table contains sources, sum of squares, degree of freedom (df), mean square and p-value. The model F-value of 340.18 implies the model is significant. There is only a 0.01% chance that a “Model F-Value” could be large due to noise. The ANOVA indicates that there is a significant difference between the two groups A and B. Values of “Prob > F” less than 0.0500 indicate that A and B terms are significant. Values greater than 0.1000 indicate that A and B are not significant. The software regression results indicate that the variables A, B, and AB interaction are significant and thus have an effect on the surface diameter of the hole.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7.53E-04</td>
<td>3</td>
<td>2.51E-04</td>
<td>340.18</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>A-Speed</td>
<td>1.18E-05</td>
<td>1</td>
<td>1.18E-05</td>
<td>16.04</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>B-Feed</td>
<td>3.47E-04</td>
<td>1</td>
<td>3.47E-04</td>
<td>470.32</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>1.76E-04</td>
<td>1</td>
<td>1.75E-04</td>
<td>237.96</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>Pure Error</td>
<td>2.07E-04</td>
<td>280</td>
<td>7.37E-07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>9.59E-04</td>
<td>283</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Std. Dev. | 8.59E-04 | R-Squared | 0.7847 |
| Mean      | 0.5      | Adj R-Squared | 0.7824 |
| C.V%      | 0.17     | Pred R-Squared | 0.7786 |
| PRESS     | 2.12E-04 | Adeq Precision | 41.998 |

<table>
<thead>
<tr>
<th>Factor</th>
<th>Coefficient</th>
<th>df</th>
<th>Standard Error</th>
<th>95% CI Low</th>
<th>95% CI High</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.51</td>
<td>1</td>
<td>5.77E-05</td>
<td>0.51</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>A-Speed</td>
<td>2.31E-04</td>
<td>1</td>
<td>5.77E-05</td>
<td>1.17E-04</td>
<td>3.44E-04</td>
<td>1.24</td>
</tr>
<tr>
<td>B-Feed</td>
<td>1.25E-03</td>
<td>1</td>
<td>5.77E-05</td>
<td>1.14E-03</td>
<td>1.36E-03</td>
<td>1.07</td>
</tr>
<tr>
<td>AB</td>
<td>-8.90E-04</td>
<td>1</td>
<td>5.77E-05</td>
<td>-1.00E-03</td>
<td>-7.76E-04</td>
<td>1.28</td>
</tr>
</tbody>
</table>
As mentioned before, the software also shows the linear regression results for the data used in the ANOVA. The R-Squared value is the value, which shows how well the data fits the linear regression model. Its value lies between 0 and 1. The value towards 1 indicates a perfect fit for the linear regression model. There are many variations in the process like human error, cutting forces, material variation, coolant flow and measuring error that can prevent the data from fitting the model perfectly. The R-squared value for the selected regression model of surface diameter hole size is 0.7847. It means that this regression model is able to predict 78.47 percent variations in the process. The remaining 21.53 percent is unaccounted for. The predicted R-Squared value measures how well the regression model is predict the response value. The adjusted R-Squared value measures the amount of variations from the mean. The values of predicted R-squared value and adjusted R-Squared value for the hole-diameter are 77.86 percent and 78.24 percent respectively. The table also shows the value of “Adequate Precision”. It measures the ratio of the signal to noise. The ratio value greater than 4 is always good. For this model, Adequate Precision value is 41.998 hence this model can be used to navigate the design space.

The regression equation obtained is:

\[ \text{Hole Diameter} = 0.51 + (2.310\times10^{-004} \times \text{Cutting speed}) + (1.251\times10^{-003} \times \text{Feed rate}) - (8.896\times10^{-004} \times \text{Cutting speed} \times \text{Feed rate}) \]
Correlation Analysis

A plot between hole-diameter versus number of hole drilled for combination of the cutting speed of 80 SFM and the feed rate of 0.003 IPR is shown in Figure 17. It was observed that there is increase in diameter size from 0.5020 inches to 0.5052 inches up to hole-number 360. There was a sudden fall in hole-size from 0.5052 inches to 0.5022 inches. The chipping off might have caused this from flank surface of the tool. Figure 18 and Figure 19 shows the trend line for first 100 holes and the last 100 holes drilled. For the first hundred holes, diameter was increased and hence the trend line was in the upward direction. For last hundred holes, the diameter size was decreased from 0.5032 inches to 0.5018 inches, resulting in downward trend line. The tool life was 1110 holes for the combination of 80 SFM cutting speed and 0.003 IPR feed rate. The diameter for 1st hole was measured as 0.5020 inches. The diameter for 1120th hole was 0.5018 inches, which was less than the first hole and at this occurrence; the tool was declared as having failed.

![Figure 17 Hole-diameter vs. number of holes (80SFM, 0.003IPR).](image)

Figure 17 Hole-diameter vs. number of holes (80SFM, 0.003IPR).
Figure 18 Hole-diameter for first hundred holes (80SFM, 0.003IPR).

Figure 19 Hole-diameter for last hundred holes (80SFM, 0.003IPR).
When X, the number of holes, was plotted against Y, the diameter of the holes, an attempt was made to determine the linear equation that best fits the data for the following groups. The overall gathered data for a combination, the first hundred holes for a combination and the last hundred holes for a combination. For the first combination, Table 14 lists the results.

Table 14 Coefficient of correlation for the Combination 1.

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Coefficient of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>For over all data</td>
<td>Y = 0.5033 – 3*10^{-7}X</td>
<td>-0.1183</td>
</tr>
<tr>
<td>For first hundred holes</td>
<td>Y = 0.5024 – 9*10^{-6}X</td>
<td>0.4107</td>
</tr>
<tr>
<td>For last hundred holes</td>
<td>Y = 0.5016 – 1*10^{-5}X</td>
<td>-0.2350</td>
</tr>
</tbody>
</table>

From the Table 14, it is observed that the coefficient of correlation for the first hundred holes is positive and for the last hundred holes it is negative. The overall correlation coefficient is negative. The coefficient of correlation -0.118 indicates a slight negative correlation exists between the variables diameter of the holes and the number of holes. If coefficient of correlation is -1.0 then there is a perfect negative correlation between these two variables. When one variable increases, another variable decreases. If the coefficient of correlation is 0, there is no correlation between these two variables. If the coefficient of correlation is 1.0, there is a perfect positive correlation between these two variables. When one variable increases, another variable increases too. When one variable decreases, the other variable decreases too.
The correlation analysis for the combination of another cutting speed and feed rate is shown in Figure 20. The cutting speed was the same, 80 SFM, but the feed rate was increased from 0.003 IPR to 0.004 IPR. The maximum number of holes drilled with this combination was 530. The hole-diameter for the first hole was recorded as 0.5060 inches. The value for 530th hole was 0.5047 inches, which was less than first hole and hence the tool was declared as failed. Compared to the first combination, the tool life here was less for the second combination. Due to the higher feed rate, the cutting force and the cutting temperature might be higher here, which may have shortened the life of the tool. The trends for first hundred and last hundred hole-diameters are shown in Figure 21 and 22, respectively. For last hundred holes, the data shows a sudden fall in hole-diameter from 0.5085 inches to 0.5047 inches. This indicates that the diameter being reduced may be due to flank wear or crater wears on the tool surface. The wear on tool surface can be investigated under toolmakers microscope. The largest hole-diameter in this combination was recorded to be 0.5087 inches.
Figure 20 Hole-diameter vs. number of holes (80SFM, 0.004IPR).

Figure 21 Hole-diameter for first hundred holes (80SFM, 0.004IPR).
Figure 22 Hole-diameter for last hundred holes (80SF, 0.004IPR).

For the second combination, an attempt to fit X, the number of holes to Y, the diameter of holes, in a linear model resulted in values listed in Table 15.

Table 15 Coefficient of correlation for the Combination 2.

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Coefficient of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>For over all data</td>
<td>Y = 0.5075 – 2*10^{-7}X</td>
<td>-0.0535</td>
</tr>
<tr>
<td>For first hundred holes</td>
<td>Y = 0.5069 – 8*10^{-6}X</td>
<td>0.4110</td>
</tr>
<tr>
<td>For last hundred holes</td>
<td>Y = 0.5016 – 2*10^{-5}X</td>
<td>-0.5876</td>
</tr>
</tbody>
</table>

From the Table 15 shows the equations and coefficient of correlation for over all data, the first hundred holes and the last hundred holes for the second combination. The correlation is not strong correlation for over all data.
In the third combination, the maximum cutting speed of 120 SFM and minimum feed rate of 0.003 IPR was used. The tool lasted up to 870 holes. The maximum diameter measured here was for hole-number 580. The hole-diameter here was 0.5083 inches. It was observed from Figure 23, the diameter did not vary much up to 400 holes. After that, the hole-diameter reached maximum and tool failed on hole-number 870. The diameter for hole-number 870 was measured 0.5028 inches. Compare to the combination of the lowest cutting speed and highest feed rate i.e. 80 SFM and 0.004 IPR; this combination has more tool life. The correlation for first hundred and last hundred is shown in Figure 24 and 25, respectively. The hole-diameter increased from 0.5038 inches to 0.5063 inches for the first hundred holes and for the last hundred holes, hole-size decreased from 0.5048 inches to 0.5028 inches. The correlation coefficient values for the third combination are shown in Table 16.

23 Hole-diameter vs. number of holes (120SFM, 0.003IPR).
Figure 24 Hole-diameter for first hundred holes (120SFM, 0.003IPR).

Figure 25 Hole-diameter for last hundred holes (120SFM, 0.003IPR).
For the third combination, an attempt to fit X, number of holes to Y, the diameter of holes, in a linear model resulted in values listed in Table 16.

Table 16 Coefficient of correlation for the Combination 3.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Coefficient of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>For over all data</td>
<td>Y= 0.5056 – 6*10^-7X</td>
</tr>
<tr>
<td>For first hundred holes</td>
<td>Y= 0.5051 – 8*10^-6X</td>
</tr>
<tr>
<td>For last hundred holes</td>
<td>Y= 0.5087 – 5*10^-6X</td>
</tr>
</tbody>
</table>

The correlation for the overall data is negative. For the first hundred holes correlation is positive between the number of holes and hole-diameter. The proposed linear equations are not a good fit for this data.

The correlation analysis for last combination of cutting speed and feed rate is shown in Figure 26. With this combination, a total of 290 holes were drilled. The maximum hole-diameter measured was 0.5078 inches. There was overall variation found in the hole-diameters. In this combination, maximum cutting speed and maximum feed rate was used to drill the holes. Due to higher feed rate, cutting forces and temperature might be higher in cutting zone. The flank wears or crater wear was quickly and tool failed quickly. No particular pattern was observed in hole-diameter over the number of hole. The correlation analysis for first hundred holes and last hundred holes is shown in Figure 27 and 28, respectively. The trend of hole-diameter in the first hundred holes is increasing and for last hundred holes is decreasing. The hole-size for 290th hole, 0.5040 inches was smaller than first hole, 0.5043 inches, which indicated failure of the tool.
Figure 26 Hole-diameter vs. number of holes (120SFM, 0.004IPR).

Figure 27 Hole-diameter for first hundred holes (120SFM, 0.004IPR).
Figure 28 Hole-diameter for last hundred holes (120SFM, 0.004IPR).

For the last combination, an attempt to fit a linear model to $X$, the number of holes, to $Y$, the diameter of holes resulted in Table 17 values.

Table 17 Coefficient of correlation for the Combination 4.

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Coefficient of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>For over all data</td>
<td>$Y = 0.5065 - 3 \times 10^{-6}X$</td>
<td>-0.2745</td>
</tr>
<tr>
<td>For first hundred holes</td>
<td>$Y = 0.5054 - 2 \times 10^{-5}X$</td>
<td>0.5905</td>
</tr>
<tr>
<td>For last hundred holes</td>
<td>$Y = 0.5081 - 1 \times 10^{-5}X$</td>
<td>-0.5107</td>
</tr>
</tbody>
</table>

Table 17 shows the equations and coefficient of correlation for the fourth combination. The correlation for over all data and for last hundred holes is negative. For the first hundred holes, correlation is positive. The proposed linear models are not a good fit for any of the data sets.
Tool Life Analysis

The tool life comparison is shown in Figure 29. The effect of feed rate on tool life is plotted on the graph for different cutting speeds. It is observed that tool life with lower feed rate and lower cutting speed was maximum. For cutting speed 80 SFM and 0.003 IPR feed rate, tool life was 1110 holes. If the feed rate was increased from 0.003 to 0.004 IPR, the tool life was decreased from 1110 holes to 520 holes and that was equal to a 53% reduction in tool life. For 120 SFM cutting speed tool life was 860 holes for 0.003 IPR. Increasing the feed rate from 0.003 IPR to 0.004 IPR, keeping cutting speed at 120 SFM, the tool life was reduced from 860 holes to 280 holes which was equal to 67% reduction in tool life. The tool life was reduced drastically in combination of higher feed rate and higher cutting speed.

Figure 29 Feed-rate vs. tool life.
The following Figure 30 shows the relation of tool life based on cutting speeds for different feed rates. At lower cutting speed the tool life was 1110 holes for 0.003 IPR. It was observed that increasing cutting speed from 80 IPR to 120 IPR, tool life was decreased from 1110 holes to 860 holes, which was equal to 22.5% reduction. With higher feed rate, tool life was lesser than lower feed rate. Tool life of 520 holes was observed when drilling was done with 80 SFM cutting speed and 0.004 IPR. When cutting speed was increased from 80 SFM to 120 IPR, tool life was reduced from 520 holes to 280 holes, which was equal to 46% reduction. Tool life was higher at lower cutting speed compared to higher cutting speed.

Figure 30 Cutting speed vs. tool life.
The following Figure 31 shows the graph of tool life obtained by using two different type of mist lubricator: one EQO-KUT 718 and Aculube 6000 vegetable oil [25]. The tool life was compared for all four combinations of cutting speed and feed rate.

![Tool Life comparison based on Mist](image)

Figure 31 Tool-life for different mist lubrication.

It was observed that tool life obtained using EQO-KUT 718 was greater than tool life obtained using Aculube 6000 mist lubrication oil. The combination of lower feed rate with both the cutting speeds (i.e. 80 SFM and 120 SFM) caused the tool life to be increased by 26% and 62% respectively by using EQO-KUT 718 oil. There was not significant difference in tool life at higher feed rate and cutting speeds.
Tool Failure Analysis

All failed tools were analyzed for the flank-wear or crater-wear. A toolmaker microscope was used to analyze the tool. Failed drills were observed under 20X magnification lens. The flank edges were analyzed and pictures were recorded with a moticam camera attached on a microscope. The images were captured on computer.

It was observed that the drill, which was used to drill in combination of 80 SFM and 0.003 IPR has flank wear of 0.058 mm. The material was removed slowly from the flank edge during machining. No chipping was observed on the flank edge. Only gradual wear was observed and this could be because the cutting speed as well as the feed rate was low.

![Tool-failure for first combination.](image)

Figure 32 Tool-failure for first combination.
The tool failure for second combination was shown in Figure 33. On the flank edge, flank wears and chipping were observed. Because of higher feed rate i.e. 0.004 IPR, material from flank edge was chipped off and the tool had failed earlier compared to first combination (cutting speed 80 SFM and feed rate 0.003 IPR). Due to the higher feed rate, temperature as well as cutting forces was probably higher. The flank wear was measured as 0.040 mm.

Figure 33 Tool-failure for second combination.
For the third combination i.e. higher speed of 120 SFM and lower feed of 0.003 IPR, the flank wear was noted about 0.06 mm. When the tool was observed under a toolmakers microscope, the flank wear was observed on flank edges (this could have been attributed to high cutting speeds). The material was also chipped off. Because of it, the tool failed quickly. The flank wears and crater wear was shown in Figure 34 and 35. In the fourth combination, the tool failed due to crater wear. The flank wear was less than the crater wears. This wear could be because of higher cutting speed and feed rate which could indicate high cutting forces and lower cooling effects compared to the other three combinations. The failure was shown in Figure 36. The flank wear was noted as 0.034 mm.

Figure 34 Tool-failure for third combination-a.
Figure 35 Tool-failure for third combination- b.

Figure 36 Tool-failure for fourth combination.
Summary

The experiment of drilling in AISI 1018 steel was done with two different cutting speeds: 80 SFM and 120 SFM and two different feed rate: 0.003 IPR and 0.004 IPR. The drilling operation was done with four combinations of cutting speeds and feed rates. The hole-diameter was measured each time after the tenth hole drilled. The hole-diameter readings were analyzed in Design Expert-8 statistical software version for ANOVA. The correlation analysis was done using excel.

For the combination of 80 SFM cutting speed and 0.003 IPR feed rate, tool life was 1110 holes. The first hole-size was measured as 0.5020 inches. The maximum hole-diameter recorded as 0.5052 inches for 360th hole. The hole-diameter for 1120th hole was measured as 0.5018 inches, which was less than the first hole-diameter and based on this, the tool was declared as having failed. For this combination, an increasing trend was observed in hole-diameter and as machining was continued and a decreasing trend was noted in the last hundred holes. When failed tool was analyzed under toolmaker’s microscope, more flank wear was observed on the flank edges. The average flank wear of 0.058mm was measured.

For the combination of lower speed and higher feed rate i.e. 80 SFM and 0.004 IPR, the tool life of 520 holes was observed. The hole-diameter for the first hole was 0.5060 inches measured. Because of higher feed rate, tool life was lesser than the first combination. The flank wears and crater wear were observed on the cutting edge of the tool. The maximum hole-diameter was measured about 0.5085 inches for 380th hole.
When drilling was done with the third combination, cutting speed was set at 120 SFM and feed rate was set at 0.003 IPR. The tool life for this combination was recorded as 860 holes. This combination was better than the second combination but lesser than first combination. The hole-diameter for the first hole was measured as 0.5038 inches. The maximum hole-size of 0.5085 inches was recorded for 580th hole. The hole diameter for 870th hole was measured lesser than the first hole i.e. 0.5028 inches and thus, the tool was declared as having failed as per the failure criteria set for the experiment. The average flank wears of 0.060 mm was measured with toolmaker’s microscope.

The tool life for fourth combination was measured as 280 holes. In this combination, drilling operation was done with maximum cutting speed of 120 SFM and maximum feed rate of 0.004 IPR. With this combination, less tool life was observed in the experiment. The hole-size for the first hole was measured as 0.5043 inches and 0.5040 inches for 290th hole. The maximum hole-diameter of 0.5078 inches was measured for 60th, 110th and 160th hole. The crater wear was noticed more than the flank wear on the failed tool.

It was observed that for the lowest combination of the cutting speed and the feed rate: 80 SFM and 0.003 IPR respectively, the tool life and flank wear on the tool was maximum: 1110 holes and 0.058mm respectively. For the highest combination of the cutting speed and the feed rate: 120 SFM and 0.004 IPR respectively, the tool life and flank wear on the tool was minimum: 280 holes and 0.034mm respectively.

When the tool life was compared based on the mist lubrication oil used, it was observed that the tool life using EQO-KUT 718 was more than the tool life using
Aculube 6000. For the fourth combination, tool life was same for both the mist lubrication oil. For first combination, the tool life was 26% more for EQO-KUT 718 than Aculube 6000. For the third combination the tool life was increased by 62% for EQO-KUT 718 mist lubrication oil.
CHAPTER VI

CONCLUSION

The experiment was conducted to analyze the effect of mist lubrication on AISI 1018 steel by comparing the tool life based on the lubrication used. The machining was done with four combination of cutting speed and feed rate. Two cutting speeds: 80 SFM and 120 SFM and two feed rates: 0.003 IPR and 0.004 IPR were used. The drilling was done in 3 axes CNC machining center- Mori Seiki. EQO-KUT 718- lubrication oil was used. It was applied externally. The hole-diameter was measured for all the samples and gathered for data analysis. The conclusions were made as follows:

The maximum tool life of 1110 holes was realized using a cutting speed of 80 SFM and a feed rate of 0.003 IPR. When using cutting speed of 120 SFM and 0.003 IPR feed rate, 860 holes tool life was recorded, was less than the first combination. This might be because of possible excessive heat generated at the cutting zone and higher cutting forces resulting in wear and tear of the cutting tool. The flank wear was noticed on the cutting edge and chipping was minor at this combination.

The minimum tool life of 280 holes at a cutting speed of 120 SFM and a feed rate of 0.004 IPR. Because of the higher cutting speed and feed rates, it is hypothesized that there was increase in cutting forces, temperature and wear. As feed rate and cutting speed increased, the cutting edge of tool got blunt which increased friction between tool and work piece. Due to friction cutting temperature increased and tool life decreased.
The ANOVA was conducted based on the hole-size, cutting speed and feed rates. The regression equation indicates that cutting speed, feed rate and the combination of these two are all significant factors based on 95% confidence level. Therefore, the null hypothesis- “There is no significant difference in the hole-size (responses) by changing the cutting speed and feed rate combination (input variables)” is rejected.

Based on the results of this study and those obtained by Vasim and Boubekri [25], the EQO-KUT 718 lubricant is more effective than the Aculube 6000 when drilling was conducted at lower feed rates.

Recommendations for Future Research

Using other possible feed rates and cutting speeds levels, this experiment could be extended. Alternatively, the same experiment could be repeated by drilling into another commonly used metal or by changing to a different type of coolant to determine the tool life or an affectivity of MQL. Other variables in the drilling procedure could be assessed in future research. One of them could be evaluating the temperature variable during cutting. With a laser temperature meter, the temperature effect while cutting could be observed and recorded while cutting. This may lead to a better explanation on how the temperature affects the wear and tear of the tool. This temperature effect could be assessed with and without using a coolant.

Lastly, another possibility is to determine how the strain experienced in the tool during drilling. Also, in this same case, a different measurement of tool life (in terms of strain) could be used and this measurement could also be related to the hole-diameter.
REFERENCES

http://www.masterchemical.com/db-docs/technical-bulletins/Fluid_MQL.pdf


