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Resource consumption and process performance in minimum quantity lubricated milling of tool steel

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Abstract

The use of cutting fluids has driven performance improvements in metal machining. However these fluids have drawbacks including resources consumed and possible negative environmental consequences. Thus the study of coolant delivery rates is important. This work investigated the use of minimum quantity lubrication (MQL) in solid carbide milling of tool steel. A tool life improvement of 60 percent was demonstrated in comparison to dry cutting. Based on measurements and calculations made, MQL consumed cutting fluid at a rate less than 5 percent of that of a typical flooding coolant system, and was a low-consumption option in terms of electrical power.

Keywords: minimum quantity lubrication; milling; machining; power consumption; energy; tool wear

1. Introduction

In this first section, the background to the study is explained. The main reasons for the use of cutting fluids in machining are provided, then the impact of cutting fluid use is examined. The information gathered leads to the motivation for this study.

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Nomenclature

MQL	minimum quantity lubrication
rpm	revolutions per minute
T	tool life

1.1. Use of cutting fluids to enhance machining

For over 100 years, fluids have been used to improve the performance of metal machining processes such as milling, turning and drilling. For further reading about cutting fluid technology the recent works by Astakhov and Joksch [1] and by Brinksmeier et al. [2] can be consulted. The main purpose and benefits of cutting fluids are as follows.

The application of a cooling medium lowers the temperatures occurring in the cutting zone and also stabilizes the temperature of the cutting process, compared to when cutting dry. Due to a lower operating temperature it is possible to machine with a reduced tool wear rate when using cutting fluids, or indeed to machine with the same tool wear rate at a higher level of productivity. The lowering of peak temperatures lowers the fire risk when machining reactive materials such as titanium [3] and magnesium [4]. Thermal stability over time improves dimensional accuracy for precision machining, as there is less thermal expansion and contraction during and after processing. Furthermore a fluid flow will transport swarf (the chips of cut metal) away from the cutting zone. This reduces the tool and part damage which can be caused by swarf re-cutting and scratching.

A higher-density water-like fluid can perform two additional functions. The first is where high-pressure delivery of the cutting fluid into the tool-chip interface breaks up long swarf into manageable fragments. This is particularly useful where there are long periods of uninterrupted cutting contact such as in turning and drilling. Manageability of the swarf is important for automated removal from the machine and ease of recycling. Secondly, at lower cutting speeds it is possible to reduce frictional forces significantly via lubrication.

The points above represent the positive aspects of cutting fluid application in metal machining.

1.2. Resource consumption considerations

In addition to the factors above, there are hazards associated with cutting fluids which relate to operator health and accidental release to the environment [5]. Many such fluids are corrosive and can cause dermatitis if workers' skin is exposed to them. The kinetic energy produced in machining converts cutting fluids partially into mist form, if the mist is not effectively contained by the machine tool it will be released into the air of the machining shop floor. Regular inhalation of certain cutting fluid mists over a prolonged period of time can have a negative effect on workers' lungs. If at any point cutting fluids are released to the natural environment due to leakage or spillage this is potentially harmful to plant and animal life. Negative health effects and negative environmental effects can be avoided by risk assessment, training and by implementing good practices and controls, which come with an associated operational cost. It should be recognized that fossil fuels are consumed in creating the energy to manufacture [6] and deliver, maintain and dispose of lubricants. Fossil fuel consumption contributes to the phenomenon of global warming.

There is a causal relationship between cutting fluid flow rates for a machining process and the volume of cutting fluid required to run that process. Higher flow rates mean that more foaming and heating and evaporation of the fluid occur during machining. These effects at high flow rate are most easily minimized by increasing the available amount of fluid, i.e. the sump size. Thus the cutting fluid flow rate is a variable which should be considered and decided for specific machining cases, rather than being accepted unchallenged at an across-the-board value. The risks associated with the hazards named in the previous paragraph all reduce when fluid flow rates are reduced. A balance must be struck between maximizing manufacturing rates (which tends to lead to higher cutting fluid delivery rates) and the potential negative impact on operator health and the natural world (which drives towards lower fluid delivery rates).

It is possible to carry out machining without any kind of cooling, which is commonly referred to as dry cutting. Near-dry machining involves very low flowrates of the cooling medium, this condition is also known as minimum quantity lubrication or MQL. For a detailed discussion of MQL, the paper by Sharma et al. [7] can be consulted.

It has been mentioned that fossil fuels are consumed to facilitate the life cycle of a cutting fluid, this includes the generation of electrical power which is required by machine tools' cutting fluid delivery systems. Aramcharoen and Mativenga [8] summarized approaches taken to date to model energy consumption in machining processes. They identified the power required to drive the pumps of a machine tool cutting fluid delivery system. Lee et al. [9] measured the power consumption required to operate six different types of numerically-controlled lathe, evaluating the power required for each subsystem. For each of the six lathes tested, the cutting fluid delivery system was not dominant in terms of machine power consumed but neither was the power consumption for fluid delivery negligible.

Mulyadi [10] investigated the energy consumed by a machine tool, and the effect of MQL in this respect. He found that for the end milling of annealed H13 tool steel with an inserted carbide tool at 350 m/min surface speed and a feed rate of 0.05mm/tooth, flood delivery of cutting fluid yielded the longest tool life at 30 minutes, followed by MQL cutting (25 minutes) then dry cutting (15 minutes). Mulyadi showed that MQL and dry machining reduce the total direct energy requirement for machining by 30% and 35% respectively, in comparison to the use of flood coolant. This reduction was due to the energy demand from the flood coolant delivery system. Elfizy [11] carried out milling of hardened H13 tool steel using solid carbide coated cutting tools at 400 m/min surface speed and with a feed rate of 0.06 mm/tooth. He showed that dry air at room temperature delivered to the cutting zone under 7 bar pressure was marginally more effective than MQL, in terms of the rate of tool wear measured under these conditions.

1.3. Motivation for the current study

The above sections demonstrate that cutting fluid flow rates should be carefully considered for a given machining process. Research work is already underway regarding the usage of MQL in milling of tool steels. This paper investigates novel aspects in terms of tooling, material condition and test hardware configurations to build on the work done. Experiments are carried out to investigate tool wear performance and device power consumption.

The remainder of this document is composed as follows. Section 2 describes experimental work in terms of the hardware used, the machining process run and the measurements made. Section 3 presents and discusses results and observations, then section 4 concludes with the study's main findings and ideas for future research.

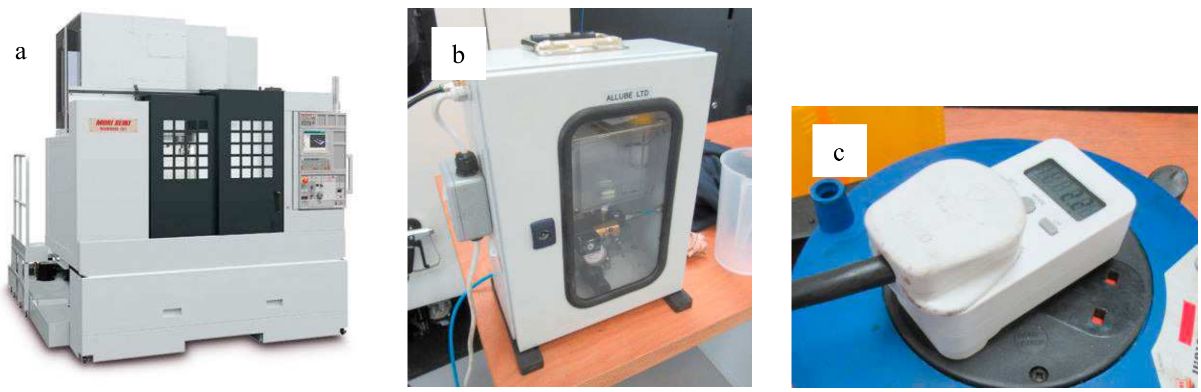

Figure 1. Trials hardware: (a) 3-axis milling machine tool; (b) MQL fluid delivery unit and (c) measurement of MQL unit mains power consumption.

2. Experimental work

2.1. Trials configuration

The machine tool used for experiments was a Mori Seiki NV5000α1, a 3-axis vertical milling machine with a maximum spindle speed of 10,000 rpm and a size 40 spindle interface. The machine has a built-in flood cooling system delivering fluid through nozzles external to the spindle. An auxiliary pump system was fitted which produces 30 bar pressure, delivering fluid through the spindle and through the tool body. These two cutting fluid delivery systems were not used in milling trials, as only dry and MQL machining were tested. The machine tool can be seen in Figure 1a.

The work piece material machined was H13 tool steel. H13 is a chromium-molybdenum steel commonly found in die casting moulds and extrusion dies. Further information about the alloy can be found at [12]. The material was milled in the hardened and tempered condition, its nominal hardness in this condition is 53 HRC. The work piece was prepared into a 200 mm by 120 mm by 120 mm cuboidal form prior to trials, and fixed to the machine bed with a manual vice.

The cutting tools used were 8mm diameter, 4 flute coated carbide ball-nosed milling tools from Mitsubishi Carbide, product type VF-4MB R4. These are commonly used for the machining of moulds and dies. The tools have a micro-grain cemented tungsten carbide substrate coated with a single-phase nano coating which is composed of various nitrides. The tools were held in a Nikken chuck, code NC5-63-C25-70, using a collet. Run-out was ensured to be less than 10 microns for all tools tested. The main machining parameters were 250 m/min surface speed and 0.05mm/tooth feed rate, in down milling. This leads to 9,947 rpm spindle speed and 1989 mm/min linear feed rate. The radial depth of cut (the step-over) was set at 0.75mm, with an axial depth of cut of 10 mm. These are considered roughing parameters based on the depths of cut. The surface speed and feed rate were selected after running a screening exercise. After a cutting pass on the work piece the stated parameters caused no visible tool damage, a visually acceptable surface finish, an acceptable swarf colour (discussed later) and no evidence of poor chip ejection or vibration.

High-flowrate emulsion type coolants were not employed for use with this type of milling tool as a high cooling rate leads to high-amplitude cycling of the cutting edge temperature against time with each revolution of the tool. The cutting tool supplier advised that the thermal shock effect from this temperature cycling could lead to cracking at the cutting edge. This combination of machining operation, material and cutting tool type lends itself well to a study of near-dry machining. The MQL delivery unit is pictured in Figure 1b. Dials on the unit were set to provide an air pressure of 5 bar and full MQL fluid flowrate. The air flow was provided by the shop floor pneumatic supply. The cutting fluid type was undiluted Unist Coolube 2210. This fluid is formulated based on plant oil and is non-toxic. The MQL mixture of air and fluid droplets was delivered through a plastic tube with a 1.5 mm inner diameter. The end of the tube was located 20mm from the milling tool, and pointed towards the cutting region of the tool by the use of a magnetic clamp stand. The tube had no nozzle feature at the end. Figure 2 shows what could be observed when the milling operation was taking place with MQL application.

2.2. Power consumption of MQL system

Whilst the MQL system was operating, its electrical supply was plugged into a mains power measurement device which was plugged into a mains electrical socket. The steady state power consumption of the MQL system could be read from a display on the measurement device. The power supply and power measurement arrangement can be seen in Figure 1c.

2.3. Cutting fluid flow rates

Cutting fluid flowrates were measured via a high flow rate and low flow rate method. The first method involved filling a large graduated vessel located inside the machine tool, during 30 seconds of running the coolant supply. The second method for the MQL system involved running the MQL flow for 30 minutes with the supply tube directed into a small sealed measuring cylinder.

2.4. Tool life testing

An NC program was created to run multiple straight-line shoulder milling passes on the H13 block, stepping over 0.75mm with each pass. Tool wear was measured for every 10 to 25 passes made, which permitted a high resolution profile of tool wear evolution to be obtained over the life of the cutting tool. The tool wear measurement method was as follows. The tool flank for each of four teeth was imaged with a USB microscope then the images were analyzed using software. Lines and points were overlaid onto the images to yield distance values in mm. The dimension of wear scars was measured down the tool flank perpendicular to the cutting edge, at six points along each cutting edge. The individual values were averaged. 0.25 mm of average flank wear was decided to be the point of tool failure.

3. Results and discussion

3.1. Relative consumption impact of the MQL system

The consumption impact of the MQL unit was assessed from the rate of use of cutting fluid and electrical energy.

In Table 1 the fluid consumption impact of the MQL unit is compared against the other cutting fluid delivery options available on the milling machine tool. The MQL unit studied has 800 ml of storage capacity, corresponding to 50 hours of use before a refill. The fluid is used once and it should ideally evaporate to leave no residue on the surfaces of the work piece and machine tool. In terms of higher-flowrate emulsion cutting fluid options, the machine tool sump has 220 litres of fluid storage capacity, corresponding to around 5.5 minutes of fluid circulation when running with flood delivery.

Flood and higher-pressure coolant systems continuously recirculate cutting fluids between the machine sump and the cutting zone so the actual fluid consumption rate is much lower than the flow rate. Fluid is circulated for typically between 6 months and 2 years before disposal. A more like-for-like measure of fluid consumption rates for flood and higher-pressure coolant is as follows. As an example a 220 litre sump may be cleaned out and the fluid changed on an annual basis due to fluid degradation over time. If the machine tool spends 3 hours each day with a program running over 220 days in a year, then the cutting fluid consumption rate is 330 ml for each hour where the program is running. The consumption rate for the MQL system featured in this work was still less than 5% of that value.

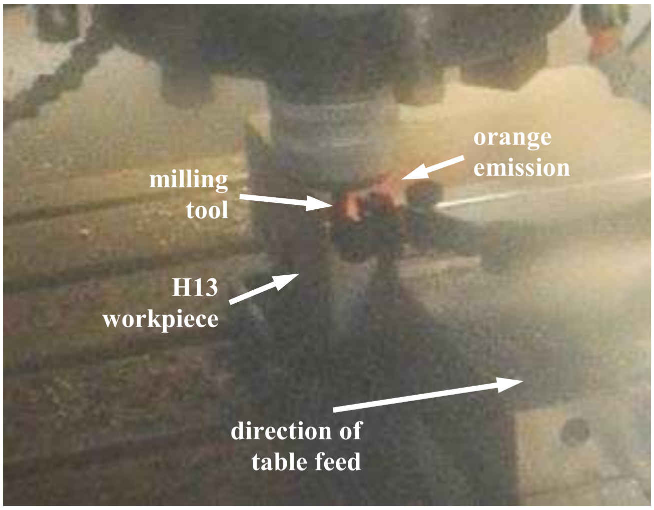

Figure 2. Image from a trials video shows the steel test piece being milled using MQL.

Table 1. Comparison of cutting fluid delivery options in terms of fluid flow rates.

Cutting fluid delivery method	Fluid flowrate (l/min)
MQL	270×10^{-6}
Flood	38.8
30 bar through-tool	24.5
Flood and 30 bar through-tool	63.3

In terms of electrical energy, the MQL unit consumed 8 W of power when running at steady state. 8 W powers the supply of cutting fluid droplets into an air flow, whilst the pressurized air comes from a centralized shop floor compressor. Multiple machine tools are supplied from a single compressor, a power consumption of further tens of Watts could be ascribed to supplying the air flow. Mulyadi [10] attributed 50 W to the supply of pressurized air for an MQL system.

Hardware to measure the power consumption of the machine tool was not readily available, so for comparison purposes the public literature was consulted. There are numerous measurements made of the power consumed by higher-flowrate machine tool flood and high pressure coolant delivery systems [8], [9], [10]. System power consumption was in the range from 200 to 2400 W. The MQL fluid supply power measured in this work was less than 5% of these values. This basic calculation does not take into account the additional energy requirements for maintenance, cleaning and disposal which are associated with 220 litres of cutting fluid stored in a machine tool sump. For example a regular top-up is required to replace water lost by misting and evaporation. Machined parts may require an additional degreasing step to meet end user requirements.

3.2. MQL performance regarding tool wear

Dry and MQL milling trials were run, the resulting tool wear profiles against cutting time are displayed in Figure 3. Compared with dry cutting it was possible to trade 16 ml/ hour of MQL cutting fluid for an additional 47 minutes (or 60 percent) of tool life, which increased from 73 to 120 minutes. This certainly makes financial sense as the milling tools cost hundreds of pounds whilst 120 minutes' worth of MQL fluid costs less than one pound. The consumption of fluid and energy resources are presented and discussed in section 3.1.

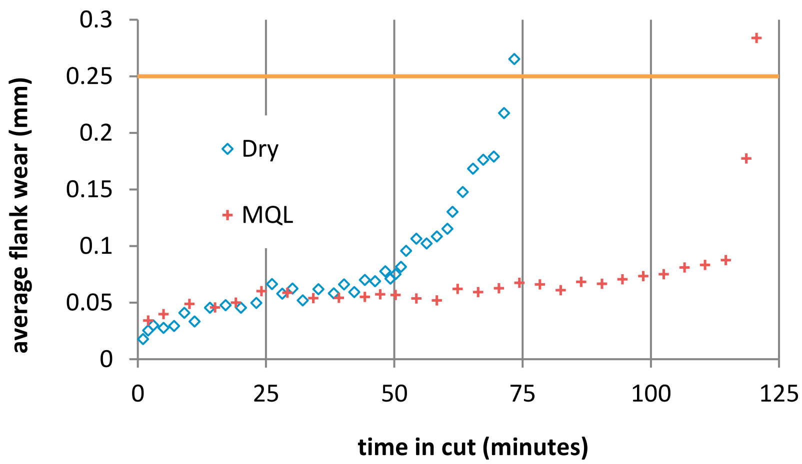

Figure 3. Tool wear progression against time for dry and MQL cutting.

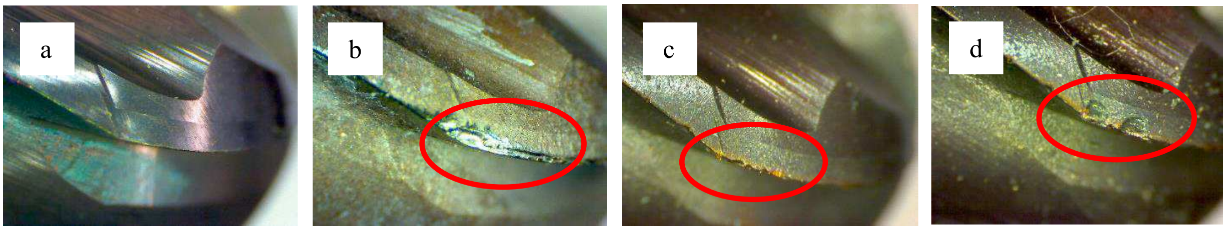

Figure 4. Tool condition images, with damage highlighted (red ellipses): (a) before machining; (b) after 73 minutes dry cutting; (c) after 115 minutes MQL cutting; (d) after 121 minutes MQL cutting.

The images captured in Figure 4 show the features of tool damage which occurred during cutting. Figure 4a shows the tool condition of supply prior to cutting. Figures 4b and 4d show tools at the point of failure based on flank wear, corresponding to Figure 3. The tool which was worn by dry cutting (Figure 4b) had a shiny region at the cutting edge, which is a sign of work piece adhesion. When adhered material is removed by the action of the tool moving in and out of the cut it can pull away the tool coating and carbide substrate, which is known as attrition wear. The tool which was run with MQL application (Figures 4c and 4d) does not show signs of adhesion. The main mechanism of tool damage appears to be chipping and fracturing of the cutting edge.

Mulyadi [10] also compared dry cutting against MQL in milling of H13 tool steel. See Table 2 which compares dry and MQL milling of H13 steel, where *T* refers to the cutting tool life. There were significant differences in the set-up of the two trials and yet the tool life for the case of MQL is around 60% higher than for dry cutting in both cases tabulated.

3.3. Theoretical considerations

This section discusses some additional issues which are of interest. The swarf generated by the milling process was mainly of a light blue colour. It is possible to use the typical tempering colours of steel as a reference to estimate the cutting temperature. Based on the colour of swarf there was some indication of the dry milling process running hotter than the case where MQL was applied.

Figure 2 shows the MQL milling process underway. The cutting zone heated up to the point of emitting a glowing orange plume, in both dry cutting and MQL cutting conditions. This plume is likely to be high-temperature steel dust being emitted from the cutting zone alongside the larger curls of milled swarf. Such dust in the cooled form can be observed as specks on the cutting tool surface in Figure 4d.

Milling was conducted at 9,947 rpm, or 166 revolutions of the tool per second. This is a sufficient speed for the milling tool flutes to generate an airflow of their own. In spite of the high spindle speed, MQL droplets were able to reach the cutting tool. Fluid could be observed on the tool surface after MQL cutting. The MQL unit supplies oil droplets entrained in a flow of air at ambient temperature. Elfizy [11] milled hardened H13 tool steel, showing that a dry air flow was marginally more effective than MQL in terms of the rate of tool wear measured under these conditions. Thus the air flow plays a greater role than merely delivering the lubricant.

Table 2. Comparison of the impact of MQL on tool life in milling of H13 tool steel, based on two sources.

Data source	H13 material heat treatment and hardness	Tool substrate	Solid or inserted	Surface speed (m/min)	Feed per tooth (mm)	MQL flow rate (ml/hr)	T_{MQL} / T_{Dry}
Mulyadi [10]	Annealed, 13HRC	Carbide	Inserted	350	0.05	30	1.6
This work	Hardened tempered, 53HRC	Carbide	Solid	250	0.05	16	1.6

4. Conclusions and recommendations

The performance of minimum quantity lubrication (MQL) was tested in the solid carbide milling of H13 tool steel in terms of tool wear performance, fluid flow rates and device power consumption. The main findings were as follows.

- The milling tool life was 73 minutes when cutting dry, which was extended to 120 minutes when applying MQL. The application of MQL increased the tool life by 60 percent in this case.
- The MQL fluid delivery system ran with a flow rate of 16 ml/hour, which was less than 0.01 percent of the flowrate for the case of the milling machine's flood and 30 bar through-tool fluid delivery systems.
- When using flood and through-tool coolant delivery, the fluid in the machine sump is re-circulated many times. Taking into account an example sump life and example machine usage rates, a fluid consumption rate of 330 ml per hour of running was calculated. The MQL fluid flowrate was less than 5 percent of this value.
- The power consumed by the MQL fluid delivery system was 8 W. Additionally pressurized air was required, which is likely to consume some further tens of Watts. This is significantly less than the power consumption figures quoted in literature studied, for typical machine tool flood and high-pressure cutting fluid systems.
- Due to the need to balance cutting performance against environmental and health and safety criteria, cutting fluid flow rate is a variable which should be considered and decided for a specific machining case, rather than being accepted unchallenged at a default value.

In terms of possible further work to be done, a desirable extension of this study would be to compile comparative data into a tool which can assist manufacturers to choose the correct cooling method for their machining operations. For currently-available cooling methods, a reduction in the associated carbon emission rate may or may not correspond to a reduction in cost rates or other factors such as operator safety. Hence the ability to evaluate trade-offs would need to be incorporated into the tool. It is highly likely that the relative importance (weighting) of carbon emission rates will increase in the next few decades as nations and organizations converge towards carbon-neutral practices. Further to this, the way to circumvent the trade-off approach and create rapid industrial uptake of low-impact cooling options is to replicate the economic and subtle "other" benefits of a liquid delivered at high flowrate to create the so-called "no-brainer" option. Technologies such as cryogenic and ultrasonic machining may contribute in this direction.

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