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EVALUATION AND COMPARISON OF LUBRICANT PROPERTIES IN MINIMUM QUANTITY LUBRICATION MACHINING

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☐ *Minimum Quantity Lubrication (MQL) machining involves the application of a minute amount of an oil-based lubricant to the machining process in an attempt to replace the conventional flood coolant system. Understanding the correlations between fluid properties and MQL performance can help in selecting lubricants from a variety of choices without going through extensive machining tests. This study compared nine different MQL fluids in terms of their physical properties, wettability, tribological properties (lubricity and extreme pressure (EP) properties), mist characteristics and machinability to determine the correlation of measured properties and MQL drilling and reaming performance. Results show that low fluid viscosity, high mist concentration, large mist droplet diameter and high wettability were best correlated with good machinability. Although it is difficult to draw strong relationships, the optimal machining in a mild cutting condition was found with the low viscosity fluids, which may also have the highest mist concentration, largest drops and best wettability.*

Keywords aluminum machining, lubricity, metalworking fluids, minimum quantity lubrication (MQL), mist, wettability

INTRODUCTION

Flood and through-tool delivering of cutting fluids have been widely used for the machining of automotive engines and transmissions. The use of a large amount of cutting fluid can impact the environment and increase manufacturing costs, and possibly lead to ground contamination, excess energy consumption, the need for wet chip disposal and potential health and safety issues (Stoll et al., 2008; Filipovic and Stephenson, 2006). Although dry machining can completely eliminate the use of cutting fluids,

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there are many other problems that affect machining performance, such as poor lubricity, reduced tool life, thermal damage to workpieces and tool, etc. (Sun et al., 2006; Davim et al., 2007; Heinemann et al., 2006).

Therefore, near-dry, also known as minimum quantity lubrication (MQL), machining was developed as a compromise between high cutting fluid use and dry machining. MQL involves the application of a fine mist of oil instead of a flood of metalworking fluid (MWF). The lubricant flow rate in MQL application is typically less than 50 mL/h, which is a reduction in fluid flow of over 20,000 times compared with conventional flood application. A number of advantages are possible with MQL compared to wet machining, including an improved environment, reduced infrastructure demands in the plants and lower overall costs.

MQL has been studied in many machining processes, such as drilling (Braga et al., 2002), milling (Liao and Lin, 2007), turning (Su et al., 2006; Kamata and Okibawa, 2007), and grinding (Silva et al., 2005; Shen et al., 2008). These studies showed that with the proper selection of MQL system and cutting parameters, it is possible to obtain performance comparable or better than that with flood lubrication. However, there has been relatively little published research on ideal lubricants for MQL. Due to the small volume applied, MQL lubricants need to perform well to take the place of traditional MWFs. MQL lubricants are often straight oils, whereas typical MWFs are waterbased fluids consisting of about 5% oil plus 95% water.

MQL lubricants are also often vegetable-based oils, which have superior lubricity to mineral oils. Suda et al. (2002) evaluated three synthetic polyol esters and one straight vegetable oil with a viscosity range of 19 to 48 cSt. They found the synthetics preferable to the vegetable oil and viscosity was unimportant in tapping tests. Itoigawa et al. (2007) compared a non-polar mineral oil to a polar vegetable oil. They found lower friction with the polar vegetable oil, but the beneficial effects were lost at higher temperatures.

Because there are so many MQL fluids with vastly different properties (each supplier creates their own formula), understanding fluid properties and MQL performance can help in selecting lubricants for MQL machining in the future without going through extensive machining tests. Therefore, the goal of this study is to test commercial MQL fluids in an attempt to determine which property or bench tests are important in predicting the machining performance of those fluids. The evaluation included examining thermal conductivity, wettability, lubricity, extreme pressure (EP) properties, and mist characteristics. These results are then compared to the power consumption, surface roughness, and bore diameters in machining a transmission valve body to determine if those tests can be a predictor of real machining performance.

MQL FLUIDS AND EVALUATION METHODS

Nine MQL fluid tested samples, named A to I, were acquired from six suppliers, and their known physical properties are listed in Table 1. There is a large range in the viscosity of the fluids (8.8 to 69 cSt) and in the flash points (182 to 280°C). Fluid E is the same as fluid D except for the addition of a sulfurized EP component.

In this study, fluid B is used as the reference fluid to test against other commercial MQL fluids since it is currently the standard fluid used in MQL machining tests at General Motors. The evaluation metrics are divided into three groups:

i. Physical properties, including density, viscosity, flash point, and thermal conductivity. Since thermal conductivity information was not provided by the supplier, it was measured in this study to complete the physical properties.
ii. Bench testing, including wettability, tribological properties and mist characterization. Wettability was determined by the sessile drop method. Tribological properties included lubricity and EP properties, measured with tapping torque and pin-and-vee block methods, respectively. Mist characterization was the measurement of the mist size and concentration generated by each fluid in the machine enclosure.
iii. Machinability, referring to the ease with which a metal can be machined to an acceptable surface finish. An aluminum transmission valve body was adopted as the workpiece. The power consumption to drill and ream the spool bores using different fluids was recorded, and the bore diameters and surface roughness were measured and compared.

TABLE 1 Tested MQL Lubricants (Sorted by Ascending Order of Viscosity)

Fluid	Density (g/mL)	Viscosity (cSt at 40°C)	Flash point (°C)	Remarks
A	0.87	8.8	200	Biodegraded esters
B	0.93	8.9	214	Renewable acid esters
C	0.90	10	182	Naturally derived synthetic
D	0.93	10	204	Vegetable based
E	0.89	10	204	Vegetable based + EP
F	0.93	28	280	Biodegraded esters
G	0.91	40	231	Naturally occurring fatty oils
H	0.93	52	228	Synthetic ester
I	0.94	69	196	Vegetable based + EP

EXPERIMENTAL SETUP AND RESULTS

Physical Properties – Thermal Conductivity

In MQL machining, the same amount of heat is generated as with traditional machining, but much less fluid is available to carry away the heat. Therefore, the thermal properties of the fluid may be an indicator of their heat removal ability. To consider the effect of temperature on MQL lubricants, thermal conductivity was measured at 25, 50, 75 and 90°C using a thermal property analyzer, KD2 Pro (ThermTest Inc., Houston, Texas). A waterbased fluid, Trimsol (marked as WB in all tests), was also tested at a 5% concentration for comparison with the MQL fluids. Each fluid sample was measured in a thermally isolated box with temperature control to ensure the reliability of results.

Three measurements were conducted in each case and the variation was found to be less than 0.003 W/m-K. Results in Table 2 show that MQL fluids (A-I) have much lower thermal conductivity than water or the waterbased fluid. This implies lower effective heat removal by MQL fluids than conventional waterbased fluids. Poor heat removal could result in thermal damage on the workpiece and tool during the machining. Also, the thermal conductivity of MQL fluids was not affected by temperature in the measurement range of 25 to 90°C, whereas the thermal conductivity of water and waterbased fluid increased with temperature. The range of thermal conductivity was from 0.138 to 0.160 W/m-K, and it tended to increase with the viscosity of fluids.

TABLE 2 Thermal Conductivity (W/m-K) of MQL Fluids at Different Fluid Temperatures

	Fluid temperature			
Fluid	25°C	50°C	75°C	90°C
Water	0.592	0.683	0.726	–
WB*	0.614	0.662	0.671	–
A	0.143	0.145	0.138	0.141
B	0.142	0.142	0.137	0.136
C	0.142	0.142	0.144	0.150
D	0.142	0.142	0.142	0.144
E	0.140	0.137	0.142	0.138
F	0.152	0.149	0.154	0.148
G	0.158	0.155	0.160	0.160
H	0.146	0.143	0.143	0.146
I	0.158	0.154	0.154	0.156

*WB refers to waterbased fluid, 5% Trimsol.

Bench Tests

Wettability. Wettability is the term used to describe the ability of a fluid to spread out, penetrate and cover the tool and workpiece (Sillman, 1992). The wettability of a fluid is defined as the contact angle between a liquid droplet and a solid surface in thermal equilibrium with each other and the gas phase. The smaller the contact angle, the higher the wettability of the fluid. As illustrated in Figure 1, Young's equation for contact angle θ is:

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cdot \cos\theta, \tag{1}$$

where S, L, and G stand for solid, liquid and gas, respectively, and $\boldsymbol{\gamma}$ is the interfacial tension force vector.

The contact angle was measured by the sessile drop method using a droplet measurement system, DAS 10 developed by KRÜSS (Germany). The droplet is imaged (as in the example shown in Fig. 1) and the computer automatically fits the profile of the droplet and calculates the contact angle. The contact angle was measured on polished aluminum (Al) 6061 and tungsten carbide (WC) surfaces to mimic the aluminum based workmaterial and tool material, respectively. The sample surfaces were cleaned by ethanol and dried between tests.

Three measurements in each case were averaged and are shown in Figure 2. MQL fluids have smaller contact angles than that of water and the waterbased fluid, which means the MQL lubricants can wet the surface more completely, and implies that MQL lubricants have better wettability. The contact angle among all MQL fluids ranged from 8.0° to 20.6° on aluminum and 7.6° to 26.5° on WC. Since the wettability is usually directly related to the surface tension (γ_{LG}) of the fluid, surface tensions were measured by using a Surface Tensiomat (Model 21, Fisher Scientific Inc.). Water and acetone were tested to ensure the accuracy of the measurement. As the results show in Table 3, the measured surface tensions (γ_{LG}) were all

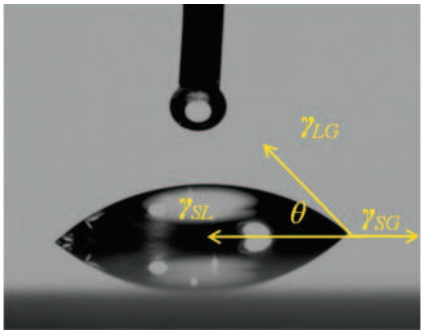

FIGURE 1 Droplet contact mechanism. (Figure available in color online.)

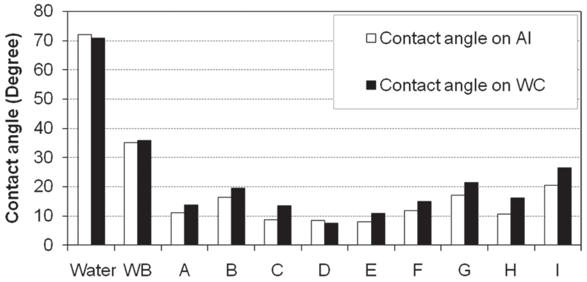

FIGURE 2 Contact angle measurement of selected MQL fluids (a smaller value indicates higher wettability).

similar, so the difference in contact angle between fluids is likely due to their different interfacial tensions (γ_{SL}) with solid surfaces as γ_{SG} was always the same in the Eq. (1). Furthermore, results also show that MQL lubricants generally were more effective at wetting Al than WC, which is also related to γ_{SL} generated by different contact surfaces.

Lubricity. The tapping test is well known as a standard screening method to evaluate the cutting performance of lubricants (Zimmerman et al., 2003). The tapping torque machine (Microtap USA, Rochester Hills, Michigan) was used in this study. The workpiece was a pre-drilled 6061 aluminum plate. The pre-drilled holes were filled with lubricant and then tapped using an M8 tool steel tap rotating at 1200 rpm. The torque data was recorded during the tapping process, as illustrated in Figure 3. The average of the plateau region was used to represent the torque generated in a specific fluid.

Because the difference between fluids is usually small, six holes were tapped for each MQL fluid to improve the analysis. In addition, to ensure that the data were comparable, fluid B was tested before and after each tested sample, as shown in Figure 4. The measured torque of the tested fluid was normalized by the torque of fluid B, which was assigned a relative

TABLE 3 Surface Tension Results of MQL Fluids

Fluid	Surface tension (dyn/cm)
A	29.84
B	29.02
C	32.02
D	30.34
E	28.83
F	30.70
G	32.77
H	31.47
I	30.09

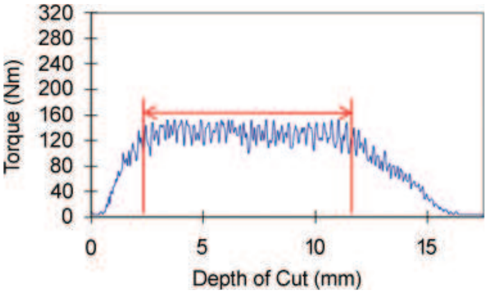

FIGURE 3 An example of measured data in tapping torque test. (Figure available in color online.)

tapping torque of 100. As can be seen in Figure 5, the waterbased fluid has poorer lubricity (higher torque) than MQL lubricants. The error bar stands for one standard deviation from the average. The largest difference in torque among all tested MQL fluids is 12% (Testing fluids A and I). The resolving power, ***S***, is used to evaluate the sensitivity of testing results to distinguish different fluids (Zimmerman et al., 2003),

$$S = \frac{\sigma^2_{between\_fluids}}{\sigma^2_{within\_fluid}}, \tag{2}$$

where $\sigma^2_{between\_fluids}$ provides an estimate of variability across fluids, and $\sigma^2_{within\_fluid}$ estimates the variance of plateau averages for a single fluid. The high resolving power of 33 measured here indicates that the variation between fluids is significantly greater than the variation within a single fluid.

Extreme Pressure Properties. The EP test is used to evaluate the lubricant performance under extreme machining conditions. The Falex pin-and-vee block machine (Fig. 6) was used for the EP test in this study (ASTM D3233). A steel pin was rotated between two steel vee blocks, and an increasing load was applied forcing the vee blocks together. The load was

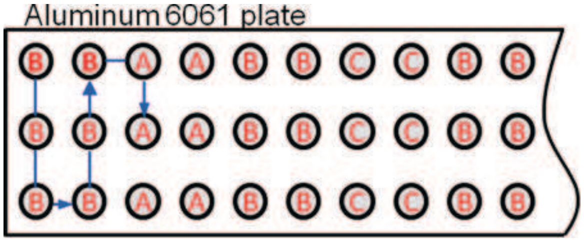

FIGURE 4 Testing procedure of tapping torque evaluation on MQL fluids. (Figure available in color online.)

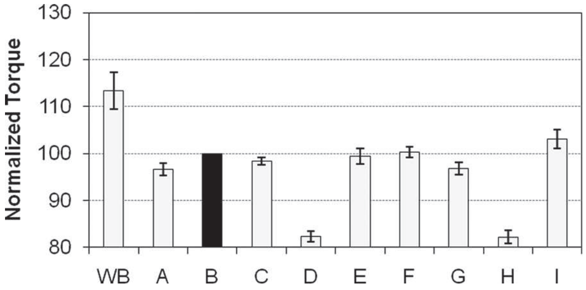

FIGURE 5 Normalized tapping torque efficiency of selected MQL fluids (a higher value indicates poor lubricity).

increased in 1.11 kN (250 lb) increments to a maximum of 17.8 kN (4000 lb). The test ended when the maximum load was reached, when the pin broke, or if the torque started decreasing as the worn pin ceased to make contact with the vee blocks. Generally, fluids with better EP properties can withstand higher loads before the pin breaks. The results of all tested lubricants are shown in Figure 7, presented as maximum loads. The tested MQL lubricants have a wide range of EP properties. The water-based fluid, Trimsol, which contains a chlorinated paraffin as an EP additive, also had relatively good EP properties. Fluid E had better EP properties than fluid D because of its EP additive.

Mist Characterization. MQL lubricants were applied by mixing air and a small amount of lubricant to generate the oil mist that is applied to the machining process. Therefore, understanding the relationship between lubricant and the generated mist can help to optimize the machining

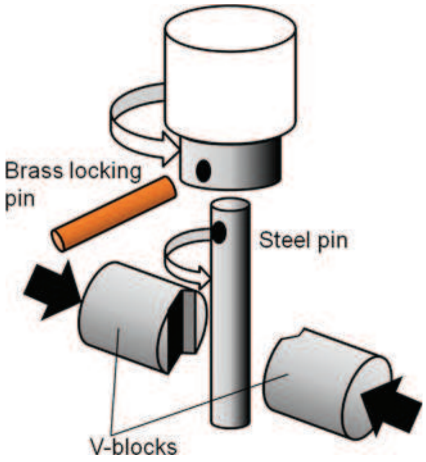

FIGURE 6 Pin-and-vee block test configuration. (Figure available in color online.)

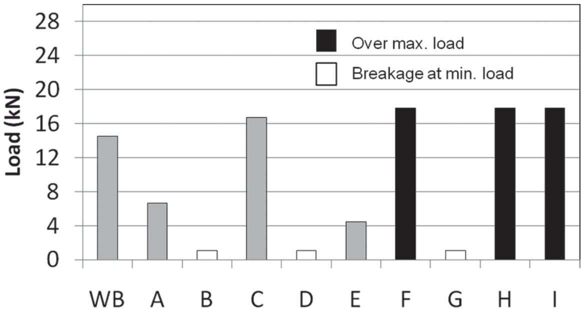

FIGURE 7 Pin-and-vee block EP test results of selected MQL lubricants (a higher value indicates better EP properties).

process. Mist was generated from a dual-channel MQL system (Bielomatik, Inc., Germany) and applied at a flow rate of 40 mL/h through a WC reamer rotating at 6000 rpm into the machine enclosure. Enclosure air was continuously vented through a duct to a mist controller. A portion of the air and mist were then sampled in the ductwork using a Micro-Orifice Uniform Deposit Impactor (MOUDI) from MSP Corp. (Shoreview, Minnesota), to measure the mist particle size and concentration. The schematic of the experimental setup is shown as Figure 8.

Air was sampled through the MOUDI at an air flow rate of 30 L/min for 30 min. The MOUDI consists of 10 impactor stages with cut-sizes from 18 to 0.056 µm to capture corresponding mist sizes. The filter on each stage was weighed out before and after the test to determine the mass of particles in each size range. Based on the processed data, the mass median aerodynamic diameter (MMAD) and the concentration of the oil droplets in the air sample can be calculated. MMAD is the calculated aerodynamic

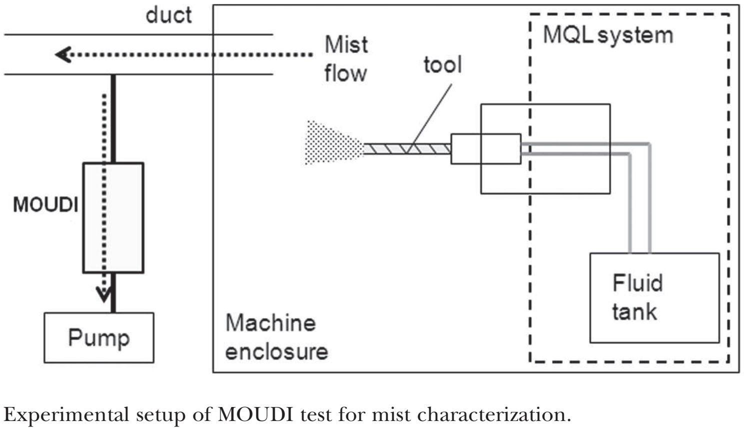

FIGURE 8 Experimental setup of MOUDI test for mist characterization.

diameter, which represents the midpoint of the particle mass, i.e., half the particle mass is on larger particles and half is on smaller particles.

Mist measurement results are listed in Table 4, where σ_g stands for the geometric standard deviation of the MMAD. Mist concentration varied from 8.84 to 11.80 mg/m^3, and mist MMAD varied from 2.90 to 4.07 µm. The MMAD is slightly smaller than usually observed with wet machining, where it is typically 5 to 10 µm (Dasch and Kurgin, 2010). It can also be seen from Table 4 that MQL lubricants with lower viscosity generated relatively higher mist concentration and mist droplets with larger MMAD.

Machining Test. To compare the performance of the lubricants under real machining conditions, two machining processes were tested using the Bielomatik MQL system. In this dual-channel MQL system, air and fluid are transported separately through the spindle and then mix at the entrance to the toolholder creating a mist, which is then sprayed through the tool. To avoid the contamination from different fluids, the system was always purged with the test fluid at a high flow rate for 15 minutes before the test. The oil flow rate was also calibrated to ensure the comparability between tests. Since this system was designed exclusively for an MQL lubricant (an oil-based fluid), no waterbased fluid was used for comparison in the machining test.

The conditions used for each test are shown in Table 5. The two processes included:

- Drilling of three spool bores on a cast 393 aluminum alloy transmission valve body.
- Reaming of same three spool bores on valve body using a PCD reamer.

The bore holes were precast in the valve body so there was relatively little material removal. The parts were machined on an Enshu JE50S CNC machine with a maximum spindle speed of 12,000 RPM. The tools for the testing were from Komet®, Inc. (Schaumburg, IL). The rough drill is a two-fluted carbide step drill, highly polished to enhance lubricity. The reamers have

TABLE 4 Mist Concentration and MMAD of MQL Lubricants

	Concentration (mg/m^3)	MMAD (µm)	σ_g
A	10.41	3.93	2.63
B	11.09	3.85	2.39
C	11.62	4.00	2.46
D	11.80	4.07	2.64
E	10.63	4.02	2.49
F	10.07	3.85	2.59
G	9.08	3.63	2.88
H	9.07	3.43	2.81
I	8.84	2.90	2.60

TABLE 5 Machining Test Settings

Operation	Sizes of step drill/reamer (mm)	Speed (rpm)	Feed (mm/min)	MQL flow (mL/h)
Drilling	9.13/8.09	2419	738	10
Reaming	9.631/8.531	6000	6000	10

eight PCD inserts, four inserts for each diameter. Spindle power measurements were taken for all of the tests. A Montronix Spectra unit was mounted to the spindle, which recorded the DC current readings and translated them into voltage readings. The voltages data were converted to power using a calibrated factor.

Machining Power Consumption. Machining power was recorded when the spool bores in a valve body were first drilled and then reamed. Each spool bore has two diameters at different depths, as shown in Figure 9. Because of the complex structure of a valve body, the spool bore machining generated a complicated power profile, as shown in Figure 10. To compare the power, Fluid B was used as the reference fluid, and the power profile from the test fluid was overlaid on that of the reference fluid. The difference between the two overlaid areas is regarded as the difference in total energy consumption during the machining process. Positive values in Table 6 refer to higher energy needed than for Fluid B, and negative values indicate that the test fluid is more efficient than Fluid B.

Hole Quality. Following the machining tests, the surface finish and diameter of the valve body bores were measured to compare the performance of each fluid. A Taylor Hobson Talysurf (United Kingdom) profilometer was used to measure the surface roughness of the reamed holes in the valve body. A measurement length of 15 mm with 0.8 mm cutoff length was used to calculate the surface roughness, R_a. There were three measurements conducted on each of three reamed holes. Results are shown in Figure 11 where error bars represent one standard deviation from the average of nine measurements in three bores.

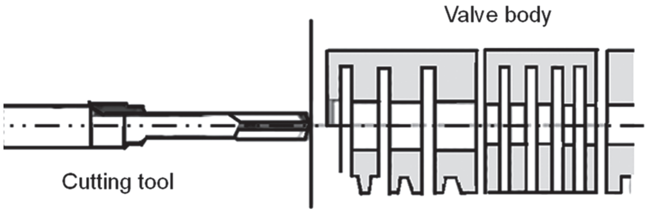

FIGURE 9 Scheme of valve body spool bore machining with step drill/reamer.

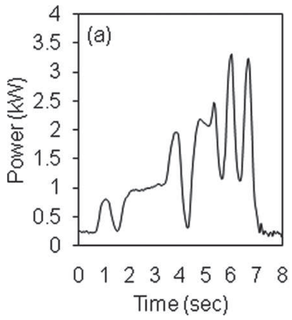

FIGURE 10 An example of power profile with Fluid B in machining of valve body for (a) drilling and (b) reaming of the spool bore.

The diameters of valve body bores were measured using an air column gauge (Intra Corp., Westland, Michigan). The average values of small and large diameters from the three holes on the valve body with different lubricants are listed in Figure 12. Generally, MQL fluids with lower viscosity generated finer surface finishes and more accurate hole dimensions compared

TABLE 6 Comparison of Energy Consumption in Valve Body Machining with MQL Lubricants

Testing Case	Drilling (J)	Reaming (J)
A	90	44
B	**0**	**0**
C	−52	0
D	99	30
E	118	96
F	131	33
G	−1	79
H	111	87
I	226	191

*Bold case is the reference.

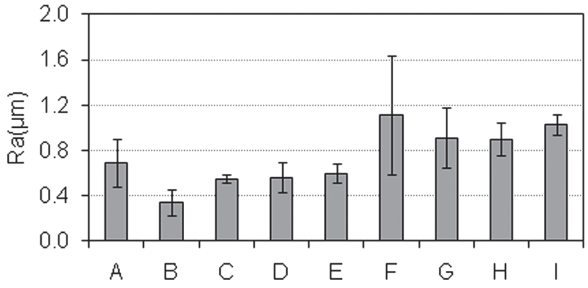

FIGURE 11 Surface roughness of reamed spool bores of valve body.

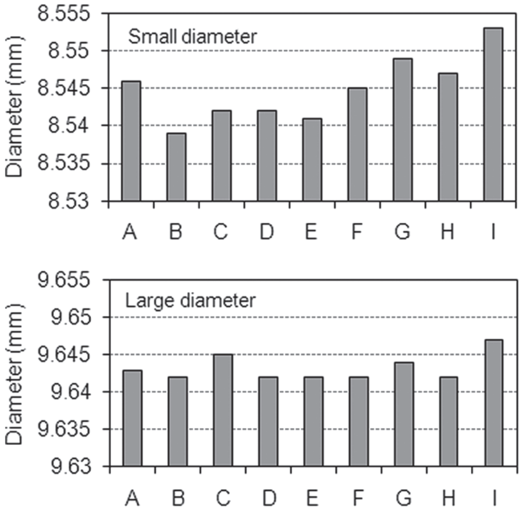

FIGURE 12 Diameters of reamed spool bores of valve body (diameters of tool are 8.531 and 9.631 mm).

with fluids with high viscosity. The reason may be related to their mist characteristics, which will be discussed next. Note fluid A was an exception because it had slightly worse surface finish and diameter accuracy than those of fluids B-D.

CORRELATION ANALYSIS AND DISCUSSION

High machining efficiency is expected from fluids with good lubricity, wettability and thermal properties. To analyze these relationships, the correlations between all tests were calculated based on the three categories discussed, including fluid physical properties, bench test results and machinability. The correlation coefficient (r) was calculated by:

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}}, \tag{3}$$

where X and Y refer to experimental data of the two properties being compared.

Table 7 shows the correlations between fluid physical properties and all bench tests. The bold values are properties that are well correlated at a 5% significance level (0.602 for sample size of 9) with each other. As can be seen, low viscosity was correlated with high wettability (low contact angle), high mist concentration and large mist diameter. The high wettability is

TABLE 7 Correlation Coefficients Between Fluid Physical Properties and Bench Tests

	Viscosity	Flash point	Thermal conductivity
Tapping torque	0.011	0.001	0.237
Pin-and-vee block	0.534	0.175	0.314
Contact angle (Al)	**0.647**	0.085	**0.643**
Contact angle (WC)	**0.737**	0.059	**0.658**
Mist concentration	**−0.885**	−0.348	**−0.693**
MMAD	**−0.951**	−0.011	**−0.646**

*Bold values indicate correlations above 5% significance level.

because a low viscosity fluid will easily spread out on the surface. The phenomenon that low viscosity fluids tend to generate large particles is consistent with the even larger particle size found with waterbased fluids (lower viscosity than that of MQL fluids) (Dasch and Kurgin, 2010). The high mist concentration may result from the large particle size in the mist sample. Thermal conductivity was also found to be related to wettability and mist level even though they are theoretically unrelated. These correlations may be more related to viscosity since there is a strong correlation of 0.747 between thermal conductivity and viscosity.

Table 8 shows the correlations between all bench tests and machining tests. The results show that large mist diameters (MMAD) are correlated with lower energy consumption, finer surface finish and more accurate diameters, and high mist concentration can also improve surface finish and diameter accuracy. Because MQL machining is accomplished through the mist sprayed from the cutting tool, it is reasonable that high mist concentrations with large mist size can create a relatively wetter environment in the cutting zone. Consequently, a better surface finish and more accurate diameter can be produced. Additionally, high wettability (small contact angle) was correlated with diameter accuracy, which can also be explained by the ability to wet the cutting region. The weak or non-correlations of other tests may be real or simply difficult to measure in short and mild machining tests. As in the EP test, the fluid with better EP properties did

TABLE 8 Correlation Coefficients Between Bench Tests and Machining Tests

	Tapping torque	Pin-and-vee block	Contact angle (Al)	Contact angle (WC)	Mist concentration	MMAD
Drill energy	0.002	0.356	0.213	0.182	−0.476	−0.557
Ream energy	0.166	0.295	0.514	0.569	**−0.757**	**−0.827**
Surface finish	0.100	0.598	0.348	0.423	**−0.784**	**−0.609**
Small diameter	0.141	0.434	**0.623**	**0.688**	**−0.852**	**−0.848**
Big diameter	0.517	0.359	**0.612**	**0.686**	−0.375	**−0.645**

*Bold values indicate correlations above 5% significance level.

TABLE 9 Correlation Coefficients Between Physical Properties and Machining Tests

	Viscosity	Flash point	Thermal conductivity
Drill energy	0.551	−0.001	0.426
Reaming energy	**0.807**	−0.148	**0.655**
Surface finish	**0.765**	0.592	**0.788**
Small diameter	**0.877**	0.074	**0.835**
Big diameter	0.538	−0.409	**0.645**

*Bold values indicate correlations above 5% significance level.

not reflect an advantage in valve body machining since the process was likely not in the boundary lubrication condition.

To link the physical properties to machining performance from Tables 7 and 8, as calculated in Table 9, we can conclude that low viscosity leads to high mist concentration with large particle size, which can improve the machinability as shown by energy consumption, and improved surface finish and diameter accuracy. Additionally, lubricants with lower viscosity showed better wettability, which can improve the diameter accuracy.

CONCLUSIONS

This study involved the evaluation of nine commercial MQL fluids and a common MWF based on their thermal conductivity, wettability, lubricity, EP properties, mist generation and machinability to determine the importance of fluid properties. Conventional MWFs are typically waterbased whereas MQL lubricants are usually straight oils. As shown in this study, this difference translates into poorer heat removal properties for the MQL lubricants compared to waterbased fluids, but improved wettability and lubricity. Among the MQL lubricants, machining results showed that low fluid viscosity, high mist concentration, large mist droplet diameter and high wettability were best correlated with good machinability. The lack of correlation with EP properties may relate to the mild machining conditions used in this study, which most likely were not within the boundary lubrication regime. Although it is difficult to draw relationships based on these experimental results, the optimal machining under these mild machining conditions was found with the low viscosity fluids, which corresponded to high mist concentration, large droplet size and good wettability.

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