540 Development of a Multifunctional Fluid for Environmentally Friendly Machining

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Summary

In manufacturing processes, the environmental issues concerning lubrication are not merely cutting fluids. Machine tools generally necessitate a variety of lubricants for its individual sliding and rotating parts, so that the application of environmentally acceptable lubricants to machine tools is of great significance. Further, since some of those lubricants are often contaminated with cutting fluids and disposed without adequate separation treatments, it must certainly be useful to develop a multifunctional fluid which is applicable to both machining and other lubricating parts.

In this study, therefore, a synthetic polyol ester is proposed as a base candidate of such multifunctional fluids. The candidate polyol ester can satisfy the cutting performance and secondary characteristics necessary for MQL lubricants. This ester is combined with a highly effective extreme pressure additive to prepare a potential lubricant as a multifunctional fluid. The developed fluid can demonstrate the excellent performance in MQL machining and the practically sufficient abilities for hydraulic and slideway lubrication.

Keywords: Environmental issues, MQL, Cutting fluids, Polyol ester, Biodegradability, Machine tools

1. Introduction

Programs that attempt to tackle environmental issues, such as the ozone layer destruction, the global warming effect and the environmental pollution, have been adopted throughout the world. In manufacturing processes, one logical step to avoid these problems is dry and near-dry machining where significant progress has recently been made. In particular, minimal quantity lubrication (MQL) machining has been accepted as a successful near-dry application because of its environmentally friendly characteristics, and a large number of studies have already presented that MQL machining can show the satisfactory performance in many practical machining operations⁽¹⁾⁻⁽³⁾.

A very small amount of a cutting lubricant plays an important role to accomplish the successful MQL machining^{(4),(5)}. In this event, the potential MQL lubricants should have not only the high cutting performance, but also the preferable secondary characteristics, such as safety properties, biodegradability, oxidation stability and storage stability⁽⁶⁾.

The other way to solve the environmental issues concerning lubrication in the manufacturing processes may certainly be the application of environmentally acceptable lubricants to machine tools. A variety of lubricants are generally used for the machine tool parts, such as the slideway, spindle and hydraulic systems. Since some of them are often contaminated with cutting fluids and disposed without adequate separation treatments, it must certainly be useful to prepare one environmentally friendly lubricant applicable to both machining and other lubricating parts. The purpose of this paper is therefore to develop a multifunctional fluid having the excellent MQL machining performance, sufficient abilities for machine tool lubrication and high biodegradability as an environmentally friendly lubricant.

2. Experimental

2.1 Test lubricants and additives

Table 1 shows the base stocks of lubricants used in this study. As a cutting lubricant of the MQL system, it should not have any unfavorable influence on environment. It may therefore be required to have high biodegradability, leading to some synthetic polyol esters and vegetable oils as a candidate⁽⁷⁾.

Table 1 Physical properties of base stocks

	Viscosity 40°C mm ² /s	Total Acid Number mgKOH/g	Pour Point °C	Biodegradability	
				CEC	OECD-B
POE-A	19.1	0.02	<-45	100	72
POE-B	31.9	0.60	-20	100	69
VO-C	36.3	0.31	-20	100	No
VO-D	35.6	0.92	-20	100	No

POE-A and POE-B are the biodegradable synthetic polyol esters with linear alkyl chains. They have recently been developed to provide the preferable performance in MQL machining⁽⁶⁾. VO-C is a highly refined vegetable oil and VO-D is an ordinary commercial vegetable oil. These vegetable oils have also been practically used as a conventional MQL lubricant.

In order to accomplish the required individual levels of the lubricating performance for a multifunctional fluid, the application of extreme pressure (EP) additives should probably be considered. Table 2 presents EP additives evaluated in this study. Based on preliminary screening friction tests, three additives, AD-1, -2 and -3, have been chosen from the wide range of various organo-sulfur and organo-phosphorus compounds which are well-known as effective EP additives under the conditions of boundary lubrication. The details of their specific chemical structures are unavailable, unfortunately.

Table 3 shows the physical properties of commercially satisfactory hydraulic fluid HF-E and slideway oil SO-F. Each performance of them is the reference of the required lubricating level for the multifunctional fluid in each corresponding practical evaluation test described below.

2.2 Performance evaluation of base stocks

(a) Oxidation stability

When a MQL system is used, the lubricant may adhere onto the interior and exterior surfaces of the machine tools in the form of a thin oil film⁷⁾. Since such a thin oil film can easily oxidize and form sticky substances, MQL lubricants should be stable against thin film oxidation. In order to simulate this thin film oxidation, 5g of lubricant on an aluminum plate having a surface area of 200 mm² were left in atmosphere at 70°C for 168 hrs. After this heating test, the change in the molecular weight was measured by gel permeation chromatography (GPC) analysis.

(b) Lubrication characteristics

The friction test apparatus is the modified Bowden-Leben type ball-on-plate friction tester, which is thought to be a fundamental and convenient method to understand the lubricity of base stocks themselves because the frictional conditions of this test are considered to be lie in the relatively moderate boundary lubrication region. Table 4 shows the conditions of this test and the coefficient of friction between the ball and the plate is obtained as a measure of the lubricity of test oils.

Table 2 Type of EP additives

	Type	Elemental contents	
		S %	P %
AD-1	Organo-sulfur	9.9	-
AD-2	Organo-phosphorus	-	12.0
AD-3	Organo-phosphorus	-	8.4

Table 3 Physical properties of reference lubricants

	Viscosity 40°C mm ² /s	Total Acid Number mgKOH/g
HF-E	32.6	0.50
SO-F	66.0	0.28

Table 4 Test conditions of ball-on- plate friction test

Load	1kg
Speed	0.5mm/sec
Upper Specimens	1/2inch Steel Ball
Under Specimens	JIS S30C Steel Plate
Temperature	25°C

2.3 Performance evaluation of EP additives

The situation of the boundary lubrication is considerably severe in hydraulic systems and slideways of machine tools, so that some effective EP additives are in general necessary to provide sufficient lubricity there. Under the circumstances, severer friction test should be applied in order to determine the acceptable performance of oils and a four-ball friction test may possibly be appropriate to the occasion rather than the above ball-on-plate friction tester. The method of the four-ball test is based on ASTM D2266. The test load is 396N, the rotation speed is 1800rpm and the test duration is 30 minutes. The wear scar diameter on the ball is measured to evaluate the lubricity of test oils.

2.4 Evaluation of practical performance

(a) Tapping test

The tapping test is well known as a standard screening method to evaluate the cutting performance^{(8),(9)} and, in particular, the tapping energy efficiency is a sensitive and accurate evaluation basis⁽¹⁰⁾. The tapping energy efficiency is calculated by Eq. (1) and the conditions of this tapping test are shown in Table 5.

Table 5 Test conditions of tapping test

Tool	M8 Nut Tap (Diameter: 8mm)
Hole Diameter	6.8mm
Cutting Speed	9.0m/min
Workpiece	JIS S25C Steel JIS AC8A Aluminum Alloy
Reference Oil	Di-iso decyl adipate(DIDA)
MQL	Air 0.3MPa, Oil 25ml/h, Outer

$$\text{Tapping energy efficiency, \%} = \frac{\text{Tapping energy of reference oil}}{\text{Tapping energy of test sample}} \times 100 \quad (1)$$

(b) Wear test using rotary vane pump

Satisfactory lubrication given by hydraulic fluids plays a significant role to guarantee the smooth operation of pumps. The evaluation of the practical lubrication abilities of hydraulic fluids is often indicated by anti-wear characteristics described as HM grade requirements in ASTM D6158-99. Its testing method is specified in ASTM D2882 and its test conditions are shown in Table 6. The evaluation of anti-wear characteristics is carried out by the total wear amount of the vanes and the ring.

Table 6 Test conditions of wear test

Type of Rotary Vane Pump	Vickers 104C
Test Method	ASTM D2882
Pump Speed	1200r/min
Pump Outlet Pressure	13.8MPa
Fluid Temperature	66°C
Test Period	100h

(c) Slideway test

There is no acceptable standard method to evaluate practically the lubricity of slideway oils. In this study, therefore, using the actual slideway of a turning machine, the coefficient of friction and the lost motion are measured to evaluate the slideway lubrication characteristics of test oils. Here, the value of the coefficient of friction is the average during sliding at a given constant feed speed. And the value of the lost motion is a distance of deviation between ordered and operated positions of the machine bed when it has moved as described in Japanese Industrial Standard (JIS) B6330 and at an operating speed of 1.2mm/min. Table 7 shows the test conditions of this slideway test.

Table 7 Test conditions of slideway test

Slideway	Cast iron/Cast iron
Feed Speed	1.2, 60, 400mm/min
Feed Distance	15mm(1.2mm/min) 30mm(40mm/min) 300mm(400mm/min)
Contact Pressure	200kPa

3. Results and discussion

3.1 Performance necessary for base stocks

(a) Oxidation stability

Figure 1 shows the results of the oxidation stability test. The results are presented as increase rates of the molecular weight after the test compared with that before the test. If the molecular weight increases by more than 10%, in general, one feels stickiness when touching. As a matter of fact, the oil films of VO-C and VO-D have become very sticky after the test. In contrast, POE-A and POE-B indicate no significant change in the molecular weight, demonstrating the preferable anti-oxidation characteristics as a MQL lubricant.

Figure 1 Results of oxidation test with thin film

(b) Lubrication characteristics

Figure 2 shows the coefficient of friction obtained by the ball-on-plate friction tester. In this test, the polyol esters provide the somewhat lower coefficient of friction than that given by the vegetable oils. Further, the comparison between POE-A and POE-B suggests a fact that POE-B possesses the superior lubricating capability as a base stock to PO-A. This fact is probably connected with a difference of the total acid number between them.

As a result, from the standpoint of maintaining clean working environment and better lubricity, POE-B should be the optimal base stock for multifunctional fluids.

Figure 2 Results of lubrication test with ball-on-plate

3.2 Improvement of lubrication ability by EP additives

Figure 3 shows the wear scar diameter measured after the four-ball wear test. In this figure, the results obtained by commercial hydraulic fluid HF-E and slideway oil SO-F are also included for comparison. If POE-B contains no EP additive, its lubricity is inferior to those of the commercial lubricating oils.

However, as expected, since EP additives chosen here can improve the anti-wear characteristics under the severe conditions of boundary lubrication, POE-B combined with each of these EP additives can provide the almost equivalent lubrication abilities to commercial ones. In particular, AD-3 is of great interest because it can work as an effective EP additive with an exceptionally small amount of dosage. Since such a low content is normally eliminated from the estimation of environmental impact brought by a bulk substance, this finding may presumably be important in environmentally friendly formulation of lubricating oils.

From the above results, the combination of POE-B and AD-3 is expected to be one possible answer to the multifunctional fluid and its practical performance should individually be examined. This combination is hereafter designated as 'MF' for convenience' sake.

Figure 3 Results of four-ball wear test (a%=several%)

3.3 Evaluation of individual practical performance

(a) Cutting performance

Figure 4 shows the results of the tapping test in the case of MQL cutting with several lubricants, that is MF, POE-A, POE-B and VO-D. For comparison, this figure also shows the results in the case of conventional flood supply of a water-soluble coolant (JIS K2241 type A1). Since the performance of MQL cutting with MF is almost equal to that of conventional cutting, a very small amount of this lubricant is found to be highly effective. This is particularly true in machining of JIS S25C steel and thus MF is determined as a preferable lubricant for MQL machining.

Figure 4 Results of tapping test

(b) Anti-wear performance as a hydraulic fluid

Figure 5 shows the results of the total wear amount of the vanes and the ring in the rotary vane pump. Its accepted level by ASTE is less than 50mg and, of course as seen here, HF-E which is widely used as a commercial hydraulic fluid indicates the satisfactory anti-wear performance. Then MF can further reduce the wear amount, quite smaller than that of HF-E, meaning the EP additive included in MF has the excellent anti-wear ability in practical use.

Figure 5 Results of rotary vane pump Test (ASTMD2882)

(c) Friction and motion characteristics on slideway

Figures 6 (a) and (b) show the results of the slideway test: the coefficient of friction and the lost motion, respectively. These results suggest that MF has the preferable performance compared with commercial slideway oil SO-F in this actual slideway test. In addition, it should be noted that, although the viscosity of MF is in the range of VG32, MF can provide the better friction and motion characteristics than SO-F whose viscosity is in the range of VG68, probably because EP additive AD-3 may work effectively.

(a) Coefficient of friction

(b) Lost motion

Figure 6 Results of slideway test

4. Conclusions

In order to develop a multifunctional fluid, a biodegradable synthetic polyol ester is chosen as a candidate of base stocks and this polyol ester is combined with a organo-phosphorus compound which is a highly effective extreme pressure additive with an exceptionally small amount of dosage. The developed multifunctional fluid can demonstrate the excellent performance in MQL machining and the practically sufficient abilities for hydraulic and slideway lubrication. As a result, this multifunctional fluid is expected to be a potential lubricant applicable to both machining and other lubricating parts in practical use.

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