Interaction between Additives in Metalworking Fluids under Difficult Cutting Conditions

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In order to investigate the interaction between additives in metalworking fluids under difficult cutting conditions, tapping tests were conducted under different metalworking conditions for metalworking fluids consisting of liquid paraffin added with tricresyl phosphate (TCP), polysulfide (PS), and oleic acid (OA). The tapping torque was measured for tapping M6 threads in S45C steel by using workpieces designed with relatively small prepared hole for creating difficult cutting conditions. For evaluating the effect of metalworking fluids, two quantities - mean tapping torque ($N_{\text{mean}}$) and maximum tapping torque ($N_{\text{max}}$) - in the tapping torque signals were introduced. When one of the extreme-pressure (EP) agents, i.e., TCP or PS, is added into the liquid paraffin, both $N_{\text{mean}}$ and $N_{\text{max}}$ decrease considerably. Moreover, when both the EP agents are added, the values of both $N_{\text{mean}}$ and $N_{\text{max}}$ are smaller than those obtained for the same concentration of a single EP agent; this implies the synergy between TCP and PS. OA, when used with the two EP agents, does not always decrease the values of $N_{\text{mean}}$ and $N_{\text{max}}$; there exists an optimal concentration level for TCP, PS, and OA for minimizing the values of $N_{\text{mean}}$ or $N_{\text{max}}$.

**Keywords:** difficult cutting, tapping, metalworking fluid, extreme-pressure agent, oiliness agent, tricresyl phosphate, polysulfide, oleic acid

1. Introduction

Under metal-cutting conditions, there are three types of surfaces - nascent metal surfaces dug up by the cutting edge, friction surfaces between a tool and a chip, and friction surfaces between a tool and a workpiece - requiring lubrication. In order to support lubrication on these surfaces, some additives such as extreme-pressure (EP) agents and oiliness agents are added into metalworking fluids. In particular, EP agents play important roles in difficult cutting operations such as tapping, broaching, and reaming. In addition, the composition of EP agents and oiliness agents governs the lubrication performance of metalworking fluids. Therefore, it is important to know the optimal compositions of additives and the interaction between them for the preparation of metalworking fluids.

In the previous studies, the effect of EP agents such as tricresyl phosphate (TCP)\(^1\)-\(^3\) and polysulfide (PS)\(^4\)-\(^6\) have been reported. In addition, the interactions between additives such as those between TCP and PS\(^7\), TCP and sulfur\(^8\), and TCP and oleic acid (OA)\(^9\), have been studied.

In this study, in order to investigate the interactions between EP agents and those between EP agents and oiliness agents, tapping tests were conducted under different metalworking conditions for metalworking fluids consisting of liquid paraffin added with TCP, PS, and OA. The tapping torque was measured for M6 threads in S45C steel by using workpieces designed with relatively small prepared holes for creating difficult cutting conditions.

2. Experimental

2.1. Apparatus\(^10\)

Figure 1 shows a schematic diagram of the tapping system used to measure the tapping torque. A workpiece is fixed to a workpiece holder on the right-hand side of a torque transducer. A tap is connected to the spindle of a motor by using a tap holder and a flexible coupling; this minimizes not only the misalignment between the tap axis and spindle axis but also the backlash and vibration from the motor. The motor is placed on the slider of a linear motion bearing so that the tap moves forward smoothly in the prepared hole of the workpiece, under the influence of the thrust force generated by tapping.
2.2. Workpiece and tap

The workpiece is cylindrical in shape with a diameter of 14 mm and a length of 40 mm; it is made of S45C steel with a hardness of 50 HRC. It has a central prepared hole with a diameter in the range 4.6–5.0 mm. Prepared hole diameters below 4.92 mm are smaller than that defined in the Japanese Industrial Standards, JIS-B1004. The tap used is a commercial spiral pointed tap for M6 tapping with a pitch of 1.0 mm; it is made of high-speed steel containing a high proportion of vanadium.

2.3. Metalworking fluids

Four types of metalworking fluids were prepared: white oil, fluid A, fluid B, and fluid AB. The constituents are listed in Table 1.

2.4. Procedure

The workpiece and tap were prewashed in hexane and acetone by using a brush and an ultrasonic cleaner. After injecting 0.5 ml of metalworking fluid on to the workpiece and tap, the tap was manually pushed into the prepared hole of the workpiece until the tapping began. The tap rotational speed was 48 rpm. The tapping torque was measured at room temperature, 25ºC.

3. Results and discussion

3.1. Signals of tapping torque

Figure 2 shows the variation in the signals of the tapping torque according to the distance at which the full internal threads are fabricated with white oil. Under all the conditions, the tapping torque increases until the distance becomes 0 mm. Subsequently, the value of the tapping torque becomes asymptotic with some fluctuations. For a small prepared hole diameter, the asymptotic value and the fluctuations appear to increase.

3.2. Effect of prepared hole diameter

For evaluating the signals, the quantities $N_{\text{mean}}$ and $N_{\text{max}}$ are introduced. The former is defined as the mean tapping torque at distances ranging from 2 mm to 6 mm; in other words, it is the tapping torque necessary for ordinary cutting operations. The latter is defined as the maximum tapping torque at distances greater than 6 mm; it is the tapping torque necessary for unusual cutting operations.

As shown in Fig. 3, both $N_{\text{mean}}$ and $N_{\text{max}}$ increase with decrease in the prepared hole diameter. The most severe condition is that in which the prepared hole diameter is 4.6 mm.

3.3. Effect of EP agent

By replacing the white oil with fluid A, B, or AB, $N_{\text{mean}}$ and $N_{\text{max}}$ can be decreased, shown in Fig. 3. In addition, the statistical significant differences between the values of $N_{\text{mean}}$ of fluid A, B, or AB and that of white oil are found by the t-test at the 99% level of confidence, i.e., the $p$-value < 0.01. However, the statistical significant differences between the values of $N_{\text{max}}$ were not found.

For all of the conditions, the values of $N_{\text{mean}}$ and $N_{\text{max}}$ of fluid AB are smaller than those of fluid A or B; this indicates the synergy between the two EP agents, i.e., TCP and PS.

3.4. Effect of EP agent with regard to oiliness agent

Figure 4 shows the effects of the EP agents with regard to an oiliness agent, OA. The values of $N_{\text{mean}}$ and $N_{\text{max}}$ are obtained by using workpieces with a prepared hole diameter of 4.6 mm.

As described above, the $N_{\text{mean}}$ of fluid AB is a smaller than that of fluid A or B when the concentration of OA is 0 wt%. However, when the metalworking fluids with 2.5 wt% or 5.0 wt% of added OA are used, the $N_{\text{mean}}$ of

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<th>Table 1 Metalworking fluids</th>
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<tr>
<td>White oil</td>
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<td>Fluid A</td>
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<td>Fluid B</td>
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<td>Fluid AB</td>
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3.5. Effect of oiliness agent

Based on the experimental results in Fig. 4, the effect of the oiliness agent OA was examined.

As shown in Fig. 4 (a), $N_{\text{mean}}$ has the minimal value by using fluid A when the concentration of OA is 2.5 wt%; the addition of OA is not always effective for decreasing the value of $N_{\text{mean}}$. In addition, the statistical significant differences are found by the $t$-test for the condition of fluid A as shown in Table 2; the statistical difference in $N_{\text{mean}}$ between 0 wt% and 2.5 wt% OA, and that between 2.5 wt% and 5.0 wt% OA are highly significant. This also supports that there exist the optimal concentration levels.

It must be noted that the $N_{\text{max}}$ of fluid AB has the minimal value when the concentration of OA is 2.5 wt%, and that of fluid A also has the minimal value when the concentration of OA is 5.0 wt%, as shown in Fig. 4 (b).

These results indicate that the optimal concentration level for additives for minimizing the value of $N_{\text{mean}}$ is different from that for minimizing the value of $N_{\text{max}}$.

### 3.6. Optimal concentrations of additives

In order to visualize the effects of OA on TCP and PS, from the experimental results in Fig. 4, the contour plots of $N_{\text{mean}}$ and $N_{\text{max}}$ were obtained with the linear interpolation method and shown in Fig. 5; the light part

<table>
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<tr>
<th>Concentration of oleic acid</th>
<th>Fluid A</th>
<th>Fluid AB</th>
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<tr>
<td>0 wt% vs. 2.5 wt%</td>
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<tr>
<td>2.5 wt% vs. 5.0 wt%</td>
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Fig. 5 Contour plots of the mean tapping torque and maximum tapping torque

represents smaller tapping torque, the dark part represents larger tapping torque. The ordinate denotes the concentration of OA, and the abscissa denotes the ratio of TCP and PS. It is obvious that the locations showing the lightest in Figs. 5 (a) and (b) are different. This denotes that there exist two types of the optimal concentration levels and supports that the mechanisms for the generation of $N_{\text{mean}}$ and $N_{\text{max}}$ are different. Possibly, $N_{\text{mean}}$ depends on the friction generated at the sliding interface between the tap and the workpiece. On the other hand, $N_{\text{max}}$ depends on the accidental cause, i.e., the blockage of the chip which causes the seizure between the tap and the workpiece.

It should be effective to estimate the practical concentration levels for the preparation of metalworking fluids by considering these two types of optimal concentration levels. Generally, it is preferable that the concentration levels of additives are kept as low as possible. Therefore, the practical concentration levels, i.e., 2.5-5.0 wt% TCP, 0-2.5 wt% PS, and 2.5 wt% OA under the total concentration of TCP and PS 5.0 wt%, are estimated easily by using Figs. 5 (a) and (b).

4. Conclusions

1. Under difficult cutting conditions, the addition of an EP agent such as tricresyl phosphate (TCP) or polysulfide (PS) into liquid paraffin decreases the mean tapping torque $N_{\text{mean}}$ and the maximum tapping torque $N_{\text{max}}$ considerably.
2. By using TCP and PS simultaneously, the values of both $N_{\text{mean}}$ and $N_{\text{max}}$ decrease as compared to those of a fluid with the same concentrations of a single EP agent; this indicates the synergy between TCP and PS.
3. When an oiliness agent such as oleic acid (OA) is used with the two EP agents, it does not always decrease the values of $N_{\text{mean}}$ and $N_{\text{max}}$; there exists an optimal concentration level for TCP, PS, and OA for minimizing $N_{\text{mean}}$ or $N_{\text{max}}$.

5. References