DEVELOPMENT OF NEWLY CONCEPTUALIZED HIGH WATER-CONTENT LUBRICATION COOLANT

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SUMMARY

Using water-insoluble coolant, which are good in lubrication but easy to mist, always risk in firing and environmental problems. On the other hand, the current water-soluble coolants fail to deliver sufficient lubricative effects to heavy cutting applications. This study has newly proposed and developed a high water-content cutting fluid, based upon a new concept of having a high lubrication capability despite of its water-soluble nature. As compared to the commercialised water-insoluble cutting fluid, the new cutting fluid is free from misting and fully applicable into cutting of various metallic materials, particularly effective in cutting of S45C and SUS304. The study also reveals a fact that a sulfur-type extreme-pressure agent is the key element to enhance the cutting performance at high temperature.

Keywords: high water-content cutting fluid, oil mist-prevention, cutting performance, extreme-pressure agent

1 INTRODUCTION

The high-speed cutting technology is widely applied to meet the needs of high productivity and streamlined automation. As one of the key factors to make the process successful, the cutting fluid has been studied from the viewpoints of safety, washability, cost effectiveness and environment aspects. The water-soluble type is often chosen because it fulfils most of the required criteria [1-2]. In the applications of heavy cutting such as broaching and gear hobbing, the water-insoluble cutting fluids are still preferable for its high lubricity.

The water-insoluble fluids are usually composed of a) mineral oils as the base material, b) fatty acid esters as the primary lubricants, c) extreme-pressure agents (hereunder abbreviated as EP agent) extracted mainly from chlorine compounds, d) a variety of additives like oiliness improvers, rust inhibitors and anti-oxidants and etc.. This kind of oil based cutting fluids is flammable and thus potentially risks in fire hazard. The cutting fluid often forms heavy mists during the operation, which also expose the operators to an unhealthy environment.

On top of that, using carcino-genicity of base oils rises as problematic issue of carcinogen. In EU, for example, base oils containing more than 3 % of PCA are required to give a caution [3]. Furthermore, using a chlorine-type EP agent is refrained in all the countries including Japan, as its waste generates carcinogenic dioxins. Currently, chemical industry is looking for a water-content fluid with chlorine-free EP agents as an alternative [4].

The objective of this study is to develop a new type of aqueous cutting fluid, based upon a new concept of having a high lubricity despite of its water-soluble nature. As the result of the research, a high water-content type of cutting fluid has been designed and developed to meet the requirements of both heavy and light cutting. Reported in this paper is the concept of the development and the test results as compared to the commercialized products at the market

2 DEVELOPMENT

Prior to the development, the first trial was conducted to explore the feasibility of applying water-glycol, field-proven incombustible aqueous fluids into metal cutting process. The composition of water-glycol fluids is shown in Table 1 [5-8], where water, glycol and base polymer are the major components while the mineral oil is totally excluded.

The base polymer is usually the polyethers made by randomly adding ethylene oxide and propylene oxide into a polyvalent alcohol. Its molecular weight is as big as several ten thousands. The structure of these polymers, for example, is shown as formula (1).

\[
\text{HO-}\{(\text{CH}_2\text{CH}_2\text{O})_n(\text{CH}_2\text{CHO})_m\}\text{p-H} \quad (1)
\]

\[
\text{CH}_3 \quad n, m>1, \text{p}>1000
\]

As shown in figure 1, the feasibility study tells that the water-content should be controlled between 35-50 vol%, because the lubricity sharply drops if the water-content goes beyond 50%. The cutting fluids are incombustible and mist free, and thus are safe and have less impact to the working environment. Generally, the base polymers of high molecular weight are able to form a thick film effectively improving lubricity. The concern of using

<table>
<thead>
<tr>
<th>Components</th>
<th>Wt %</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>35-50</td>
<td>cooling effect and incombustibility</td>
</tr>
<tr>
<td>Glycol</td>
<td>25-50</td>
<td>Fluidity enhancement</td>
</tr>
<tr>
<td>Base polymer</td>
<td>10-20</td>
<td>lubricity and viscosity enhancement</td>
</tr>
<tr>
<td>Oiliness improver</td>
<td>3-7</td>
<td></td>
</tr>
<tr>
<td>Rust inhibitor</td>
<td>1-5</td>
<td></td>
</tr>
<tr>
<td>Other additives</td>
<td>0-2</td>
<td>sequestering agent, etc.</td>
</tr>
</tbody>
</table>

Table 1: Composition of water-glycol hydraulic fluids
this kind of base polymer is its instability as undergoing a high shearing stress and/or high temperature. The breakage of the molecular bonds often takes place, resulting in a decrease in lubricity. That is the reason why such base polymers are unfavorable to heavy machining where the temperature goes up to 1,000 °C or more in average and the pressure at the tool tip rises up to several GPa[9].

Figure 2 shows an example, which schematically explain the negative correlation between the lubricity (reverse to the coefficient of friction) and the shear stability (viscosity deterioration) with respect to the molecular weight of the polyethers. It is well balanced when the molecular weight is around several thousands. The above findings lead to a new concept of cutting fluids, which include the shear stable and oil-soluble polyethers with the molecular weight of several thousands, and mineral oils with high lubricity as the base material. The structure of the oil-soluble polyethers is given in formula (2).

\[ \text{RO-}(-\text{CH}_2\text{CHO}-)_m\text{-H} \]  

(2)

An emulsion-type cutting fluid composed mainly of mineral oils was made but found to be unstable and liable due to scumming or phase separation. It also quickly putrefied when mixed with the slide oil. As shown in figure 3, the mineral oils have giant micelles surrounded by emulsified surfactants, with lipophilic groups pointing inward and hydrophilic groups outwards. The fluid is eventually separated into two discontinuous components; water and the oil droplets in size of several microns.[10]

To solubilize the cutting fluids continuously and homogeneously, the mineral oil is used as dispersing medium, instead of an emulsion-type fluid. The mineral oil base itself is able to dissolve the slide oils and stably keep the cutting fluid solublized. As the result, a high water-content cutting fluid has been successfully developed by reversely dissolving water in a mineral oil. In the high water-content cutting fluid, the surfactants wrap up the water droplets to form a micro-micelle of about 0.1 µm in size. Figure 4 illustrates a model of micro-micelles of water solubilized in a base mineral oil. Since the mineral oil components coat water droplets with the hydrophilic groups pointing inward and lipophilic groups outwards, water micelles are uniformly solubilized in the mineral oil. The oil-soluble polyethers together with EP agents comfortably form a thick layer along the metal surface to expectedly enhance the lubricity and extreme-pressure property significantly.

### 3 EXPERIMENTAL CONDITIONS

In order to investigate the performance of the newly developed high water-content cutting fluids, turning tests were done on a NC lathe. Two kinds of cutting fluids with different water-content, 35 % for Fluid B and 40 % for Fluid C, were prepared to see the influence of water-content on the cutting performance and anti-mist aspect.
steel (SUS304), chrome molybdenum steel (SCM440) and gray cast iron (FC300). The cutting tool was a cemented carbide type. The surface roughness of the finished workpiece and the depth of crater wear on the cutting tool were examined by the ZYGO, while the flank wear was measured by the SEM.

4 RESULTS AND DISCUSSION

The changes in the flank wear and crater wear of cutting tool along with the time of cutting S45C were shown in figure 5 (a) and (b). Both tool wears were reduced at the condition of using the high water-content cutting Fluids B and Fluid C, comparing with using the water-insoluble Fluid A. Of the fluids tested, Fluid B was most stable in terms of effects of cooling and EP agent at high temperature.

![Figure 5](image)

(a) Changes in flank wear width

Figure 6 (a) showed the change in the flank wear of the tool when cutting SUS304. Using Fluid B was able to keep the tool wear as small as 110mm for as long as 60 minutes, while the Fluid A and Fluid C gave a sharp increases in the tool wear and resulted in tool lives about 30 minutes. The tool edges after 30 minutes cutting with Fluid A and Fluid B were shown in the SEM photos of figure 6 (b) and (c). A fracture wear was clearly observed at the tip of tool used with Fluid A, while the wear occurred on the tool used with Fluid B was very limited. It is also found at the tools used with Fluid A and Fluid C that the crater wear increased proportionally to the flank wear. That is one of the main factors having the tool fractured.

The surface finish roughness achieved was three times better as comparing the high water-content cutting Fluids B and Fluid C against the water-insoluble Fluid A.

![Figure 6](image)

(b) SEM photograph of tool wear with Fluid A

(c) SEM photograph of tool wear with Fluid B

Figure 6: Effect on tool wear in cutting of SUS304.

In addition, a considerable mist was generated by the water-insoluble cutting fluid, while almost no mist came out from the high water-content cutting fluids.

The change in tool flank wears in cutting SCM440 was shown in figure 7, in which the effects were little different from one fluid to another. So were the crater wear and the surface roughness.

In cutting of FC300, on the other hand, the tool fracture took place at the first 30 minutes regardless of the type of fluids used. For the materials as brittle as FC300, the lubricity and cooling effect provided by the fluids were insufficient to match the cutting conditions. A sharp increasing in temperature is a reason possibly to break the oil film and cause the severe wear at the cutting edge.
Figure 7: Flank wear width in cutting SCM440

Although both were high water-content, difference in lubricity were clearly observed between Fluid B and Fluid C, especially, in cutting of SUS304. It could be due to the effect of the lubricants and EP agents resulting from different type and amount of the components. As the lubricants, Fluid B totally contained 40.7% of the mineral oils, oil-soluble polyethers and fatty acid ester sulfides, while Fluid C contained totally 39% of the mineral oils and oil-soluble polyethers. It means that Fluid B incorporated the lubricants 1.7% more than Fluid C. Furthermore, Fluid B contained water 5% less than Fluid C, which also made the lubricity better. In another word, having 6.7% more components useful to lubrication was one of the factors contributing to the lubricity of the Fluid B.

As the EP agents, Fluid B totally contained 4.1% of the sulfamide and fatty acid ester sulfide while Fluid C had phosphate and mercaptane in a ratio of 3%. The sulfur type EP agent is the only agent which is particularly effective at high temperature. Using more sulfur type EP agent made Fluid B superior to Fluid C in the cutting process where the cutting temperature rose with the cutting time. Containing phosphor type EP agent which is effective at low temperature only, Fluid C failed to maintain its EP effect as the cutting process proceeded (the temperature became higher).

Nevertheless, no significant difference was found between Fluid B and Fluid C in anti-mist capability. The 5% of difference in water-content affected very little.

On the other hand, the water-insoluble cutting Fluid A contained a lubricant composed mainly of the mineral oil and partly of fatty acid esters, and an EP agent of chlorine-type which was only effective at low temperature. As the result, the EP effect declined and the cooling capability became insufficient as arising in the cutting temperature. The tools were therefore unable to sustain the wear at cutting of ductile materials, such as S45C and SUS304.

From viewpoint of material property, SCM440 is relatively brittle compared to S45C and SUS304, and less affected by the difference in the cutting fluids applied. FC300 is much more brittle so that the cutting area is localized to the edge and its vicinity. The cutting temperature rose sharply because of heat concentration. As the temperature rises high enough to break the lubrication film, the tool worn rapidly and fractured eventually. In cutting of FC300, consequently, it was not able to examine the differences in the type of cutting fluids mentioned above and remained as an unsolved task for future development.

5 CONCLUSIONS

In order to improve the hazardous working environment, a new concept of cutting fluid was proposed and the high water-content cutting fluid was developed. It was practically usable in a substantial circumference turning with a NC auto-lathe. The results achieved in a test compared to the commercialized water-insoluble cutting fluid are summarized below:

(1) The high water-content cutting fluid was developed via solubilizing the micro-micelles of water into a base mineral oil with the aid of surfactants, and showed an excellent anti-misting capability in cutting processes.

(2) The high water-content cutting fluid was fully applicable to metals cutting. With a sulfur type of EP agent, the fluid improved the cutting performance in turning of ductile materials like S45C and SUS304.

6 REFERENCES