EXPERIMENTAL ANALYSIS OF DEPOSITION PROCESS OF LUBRICANT SURFACE BY ELECTRICAL DISCHARGE MACHINING WITH MOLYBDENUM DISULFIDE POWDER SUSPENDED IN WORKING OIL

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1. Introduction

Autonomous machines for space environment have been increasingly required since the construction of International Space Station began in 1998. A problem to be solved is lubrication between sliding parts such as joints. Solid lubricants, such as molybdenum disulfide (MoS2), gold, silver or polytetrafluoroethylene (PTFE) are often used on the sliding parts exposed in the space environment instead of liquid ones because of evaporation and cosmic radiation. Spattering and sintering are usually used to deposit MoS2 layer on a matrix for an exposure test in the space environment [1]. Parts to be modified deform by heat and their size is restricted in spattering process.

On the other hand, electrical discharge machining (EDM) has been used not only for removal process but also for deposit process [2]-[6]. In EDM with silicon powder suspended in working oil, surface roughness has been improved because of the dispersion of discharge [2] so that the friction coefficient has been decreased [7]. In addition, a surface has been modified by the diffusion of silicon [2]. Although a thick layer can be deposited by using a composite electrode [3], the production of a green compact takes much labor. When MoS2 powder is suspended in the working oil, MoS2 layer can be deposited on stainless steel during the finishing EDM process [8]. Many factors affect on the properties of deposited layer. The deposition process must be clear to improve the endurance of the lubricant layer.

In this paper, the deposition process is discussed and the influence of some machining conditions investigated through the friction test.

2. Experimental apparatus

A die-sinking electrical discharge machine (M35KC7G70 by Mitsubishi Electric Works) was used. Another working tank, which measures 280×180×130 mm, with a pump was installed on the table. The working fluid (EDF-K made by Nippon Oil Corp.) was filled over 50 mm from the workpiece surface and circulated with a flow rate of 19 l/min. The distance between the exit of a nozzle and the workpiece center was 10 mm.

The workpiece was washed in acetone for 10 min. with an ultrasonic washer before the evaluation process.

Table 1 shows the conditions in the friction test. In a reciprocating friction tester, a steel ball (JIS SUJ2/ASTM 52100) with a diameter of 7.9 mm was slid on a specimen driven with a crank mechanism. The vertical load can be varied by changing a weight mounted on the ball.

3. Observation of machining phenomena

In order to compare the phenomena in MoS2 mixed EDM with those in Si powder mixed EDM, the discharge dispersion and the gap length between an electrode and a workpiece were measured.

The discharge dispersion was measured by the branched electric current method developed by Kunieda [9]. Fig. 1 shows a schematic view of the electrode unit. The current ratio between each path was calibrated beforehand. The dimensions of the electrode are 110×10×20 mm.

Fig. 2 shows examples of the discharge dispersion under the conditions shown in Table 2. Though the discharge was always concentrated from the beginning of the machining in normal working oil as shown in Fig. (a), the discharge was uniformly dispersed not only at the beginning but also after 60 min. in the working oil mixed with MoS2 powder as
shown in Figs. (b) and (c).

Then the gap length was measured under the conditions shown in Table 3. Fig. 3 shows the relationship between the gap length and powder concentrations. The gap length expanded with an increase of the powder concentration for each powder. Because these phenomena are the same as those in EDM with Si powder, the main factors to make the surface smooth should be the discharge dispersion and the expansion of the gap length.

4. Lubrication performance

Then the reciprocating friction test in air was carried out. The lubricant layer was deposited on stainless steel under the conditions shown in Table 3 and a powder concentration of 20 kg/m$^3$. Fig. 4 shows examples of the reciprocating friction test. The friction coefficient was steeply increased after it exceeded over 0.3. Therefore, the lubrication duration was defined as the number of the reciprocating motion at which the friction coefficient exceeds 0.3.

Fig. 5 shows the dispersion of the lubrication duration along the flow of the working fluid. A low friction coefficient was sustained at the areas near the front edge and at the center of the deposit for long lubrication duration. The biased concentration in a gap between the electrode and the workpiece caused

![Fig. 1 Experimental setup of branched electric current method](image)

![Fig. 2 Examples of discharge position](image)

![Fig. 3 Relationship between gap length and concentration of powders](image)

![Graph of Table 2 Machining conditions for dispersion test](image)

![Graph of Table 3 Electrical conditions for MoS$_2$-mixed oil](image)

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the unstable lubrication duration. No lubrication was observed on a raw or machined surface with normal oil. Fig. 6 shows an analysis result by electron probe micro analysis (EPMA). The concentrations of Mo and S were high at the boundary and lower stream side. However, the concentration of MoS$_2$ was low at C according to the result by the quantitative analysis. MoS$_2$ was decomposed or changed into another compound by the discharge heat.

Because this process is basically removal, deposited MoS$_2$ may be removed. Fig. 7 shows the relationship between the lubrication duration and machining time. The lubrication duration and roughness were saturated over 30 and 60 min, respectively.

5. Dominant properties on deposit

In order to find dominant properties and predict the deposit process, some metals were machined in the mixture of the working fluid and MoS$_2$. Fig. 8 shows the influence of thermal properties. The solid circles and crosses indicate metals on which MoS$_2$ could be and could not be deposited, respectively. ZAS is a zinc alloy for stamping tools made by Mitsui Mining & Smelting Co. Because Sintered WC-Co on which MoS$_2$ could be deposited cannot be separated, WC and Co were independently indicated with the triangles. The product of the thermal conductivity and the melting point dominate the general removal process by EDM. After comparing the properties of the metals and MoS$_2$, it, however, could be deposited on the metals with lower melting point than MoS$_2$.

From the experimental results above, the deposition process was predicted as follows. When the MoS$_2$ concentration in the gap is appropriate, it adheres on the metal melted by the discharge heat. Then MoS$_2$ is caught with the re-solidified metal. Because the properties of the workpiece surface changes with a progress of the deposition, the deposit will be balanced with the removal and the concentration of MoS$_2$ will be saturated.

6. Conclusions
The phenomena during EDM with MoS$_2$ suspended in the working oil were observed. The conclusions can be drawn as follows.

(1) MoS$_2$ could be deposited on metals which melting point is lower than MoS$_2$.
(2) The uneven concentration of MoS$_2$ caused the dispersion of the lubricant duration.
(3) The expansion of the gap length caused the improvement of the roughness.

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