THE LUBRICANT APPLYING EFFECT IN Ti ALLOY Ti-6Al-4V CUTTING

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INSTRUCTIONS
Large amounts of cutting oil are frequently used during cutting to improve lubrication, cooling, and chip disposal. However, the costs incurred when using and disposing of cutting oils, in addition to their negative impact on the environment, has led to increasingly strict work conditions and environmental legislation. One way to reduce the amount of cutting oil is to replace conventional oil supply methods with dry and near-dry cutting procedures. However, a detailed mechanism of near-dry lubrication has yet to be revealed.

Applying materials on the pre-cut surface in ductile metal cuttings can dramatically improve the machinability, due to a reduction in friction between the lamellas of the chip. This effect we define as the lubricant applying effect (called as LAE hereafter) [1]. Kaneeda et al. have already established that this improving machinability phenomenon is quite different from Rebinder effect. LAE have been already recognized in such ductile metals as pure aluminum, pure copper, α-brass and mild steel by Kaneeda et al. [2], [3]. In recent years, LAE have been also recognized in SUS304 cutting by the authors [4]. Kaneeda et al. have also reported the mechanism of LAE. Under optimal conditions LAE can reduce the cutting forces by more than 90%. They determined the percentage of LAE in the lubrication by conducting the oil-submerged cutting [5] and the oil direct injection cutting. These experimental results indicated that the percentage is very high in most cutting conditions. The LAE plays a major role in lubrication in most cutting conditions, therefore, near dry machining could be performed by using the LAE.

The LAE in ductile metal cuttings have been already researched in detail. Ti alloy (Ti-6Al-4V), that is not a ductile metal, is one of the most useful materials for aircraft parts, artificial joints, etc.. In the Ti alloy cutting, it is known that cutting oil can reduce cutting forces by lubrication. Therefore, in this paper we have carried out three types of cutting experiments in order to investigate possibilities of near dry cutting and LAE.

EXPERIMENTAL PROCEDURES
Three types of cutting experiments, that is to say, dry, LAE and oil-submerged (OS) cuttings were conducted on an NC orthogonal precision cutting apparatus as shown in Figure 1. Figure 2 shows the three types of cutting experiment.

<table>
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<th>TABLE 1. Cutting conditions</th>
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<td>Cutting form</td>
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<tr>
<td>Cutting speed V m/min</td>
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<tr>
<td>Depth of cut t₁ μm</td>
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<td>Depth of cut at last pre-cutting tₐ μm</td>
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FIGURE 1. NC orthogonal precision cutting apparatus
In LAE cutting as shown in Figure 2(b), the applied material, corresponding to cutting oil in conventional cutting, was coated on part of the pre-cut surface. The thickness of the applied material was estimated to be less than 1 µm, which led to a lusterless pre-cut surface [1]. Therefore, only minute quantity of the applied material was consumed in the experiments. On the other hand, in the OS, both the workpiece and the nose of the tool were submerged into the cutting oil, which was in an oil bath, as shown in Figure 2(c). Any deviation in supply of the cutting oil could be eliminated. Table 1 shows the cutting conditions. Difficult-to-cut materials, Ti alloy (ASTEM Gr. 5) Ti-6Al-4V was used as the workpiece material. Dimensions of the workpiece material was 80 × 35 × 3 mm. Cemented carbide K10 (WC + Co) was selected as the tool material. The rake angle was a constant 0 deg. Cutting speeds are 5.3, 25.7 and 50.0 m/min. The depth of cut t₁ also ranged from 10 to 100 µm. The depth of cut at the last pre-cutting t₃, being able to control the rate of workpiece hardening in the region to be cut, ranged from 10 to 100 µm [1]. It is one of the most important factors in LAE cutting and controls the cutting forces [2]. Oleic acid was chosen as a cutting oil because of its high performance in LAE cutting of the ductile metal [6]. A quartz force transducer (Kistler Co. type 9251A) was employed to measure the cutting forces. The machined surface roughness was measured by a surface profilometer.
EXPERIMENTAL RESULTS

Figure 3a) shows the tangential cutting forces on the conditions as follows: \( t_L = 10-100 \mu m \), \( t_1 = 10-100 \mu m \) and \( V = 5.3 \) m/min with oleic acid as the applied agent material. The tangential forces in dry cutting conditions were nearly the same values in LAE cutting in all cutting conditions. The tangential forces increased proportionally with an increase of \( t_1 \), then were affected by \( t_L \) to a great extent. This tendency is similar to in ductile material cutting such as pure Al. Figure 3b) shows the tangential forces in the three types of cutting in \( t_L = 10 \mu m \) constant. Other cutting conditions are the same as in Figure 3a). The symbol \( F_C \), \( F_A \), and \( F_S \) means the tangential forces in dry, LAE and OS conditions, respectively. Then marked differences between could be recognised. Similar results were also obtained for the other cutting conditions such as \( t_L = 50 \mu m \) and \( t_L = 100 \mu m \). These results demonstrated that \( F_A \) could be identical \( F_C \), which were only slightly higher than \( F_S \). These results suggest that LAE could not be recognised in the Ti alloy cutting. One reason for this is due to continuous chip formation in the Ti alloy cutting under the conditions investigated, which is described later in detail.

Figure 4 shows micrographs of the machined surface in the three types of cutting. The surface profilemeter measurements presented \( Ra = 0.090 \), 0.093 and 0.089µm, respectively. These results indicated that neither the LAE nor the lubrication produced significant effects on cutting force reduction and surface roughness in Ti alloy cutting.

Figure 5 shows the tangential force, at cutting speed \( V = 5.3, 25.7 \) and \( 50.0 \) m/min in dry and LAE conditions. The figure shows that the cutting forces in dry offered nearly the same value as in LAE conditions under all cutting speeds. This result dedicated no obvious LAE in Ti alloy cutting tested. The cutting forces at \( V = 25.7, 50.0 \) m/min were much smaller than at \( V = 5.3 \) m/min.

Figure 6 shows optical micrographs of the workpiece stopped during the cutting with \( t_L = 50 \mu m \), \( t_1 = 50 \mu m \), \( V = 5.3 \) m/min in the dry condition. The line AB in the Figure 6a) separated the chip and workpiece. The chip above this line has been deformed by severe shearing process. On the other hand the workpiece below the line was entirely undeformed. The chip was a continuous ribbon shape that is extremely homogeneous relative to shear strain and relatively smooth on the rake surface side [7]. The lamella on the free surface side in Figure 6 was similar to in the fan wiper type chip [1]. However, the slip lines started from the tool rake face side and ran parallel each other toward the free surface side.

FIGURE 4. Micrographs of the machined surface and surface roughness
in the chip. The slip lines didn't have concave locus around the free surface, as shown in Figure 6b). This shape of slip line presented not severe friction condition between the lamella. The chip in Figure 6 was obtained in other cutting conditions tested. Therefore, it is concluded that lubrication by the cutting oil wasn't recognized in Ti alloy cutting.

CONCLUSIONS
1) Cutting forces and surface roughness in dry conditions presented almost the same value as in Lubricant applying effect (LAE).
2) LAE wasn't recognized in the conditions as follows: \( t_L=10-100 \, \mu\text{m}, \ t_1=10-100 \, \mu\text{m} \).
3) LAE was not generated at various cutting speeds ranged from 5.3 \text{~} 50.0 \, \text{m/min}.
4) Shapes of chips were identified as the continuous type.

REFERENCES