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Experimental investigation on the cutting mechanism of oxygen free copper in cutting speeds ranging from 1 m/s to 210 m/s

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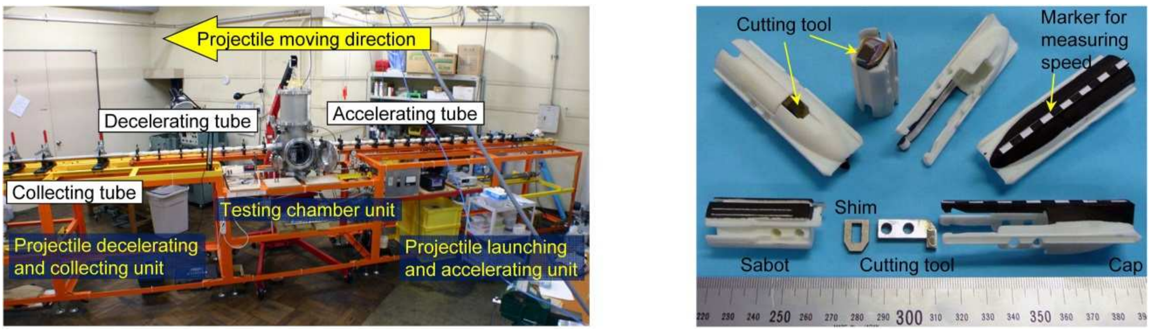
Abstract. The orthogonal cutting tests of oxygen free copper with a cutting speed of from 1 m/s to 210 m/s were performed. The effect of the high-speed cutting on the improvement over the quality of the machined surface, which was evaluated by the thickness of the plastic flow layer and the surface roughness, was examined. By employing the simple shear plane model, the cutting mechanism was analyzed. The results were compared with the results for cutting of aluminum alloy obtained previously. For oxygen free copper, the resultant cutting force does not increase in high-speed cutting. However, the friction angle on the tool-chip interface rises clearly in high-speed cutting. This paper discusses the reason for the increase in the friction angle at the tool-chip interface by investigating the stress and temperature fields on the shear plane and the tool-chip interface.

Introduction

High-speed cutting can provide a high-efficiency production and improve the quality of the machined parts. Hence, in many manufacturing industries, the speed-up of the cutting speed has been promoted in order to manufacture more high-quality mechanical parts efficiently. High-speed cutting process, however, involves some difficulties. Though the rapid tool wear is one of problems that should be solved, the essence is that the unknown cutting phenomena begin to appear in high-speed cutting such as the cutting speed exceeds 100 m/s. Therefore, the cutting mechanism in higher cutting speed should be clarified for optimizing such manufacturing process employing high-speed cutting.

The author has investigated the cutting mechanism in the cutting speed ranging from 1 m/s to 200 m/s. For pure lead, a PM steel and aluminum alloy A2017, the changes in the cutting mechanisms with cutting speed were obtained experimentally [1,2,3]. For these materials, the cutting force drops and then rises as the cutting speed increases. The increase in the cutting force is attributed to the increase in the inertia force that is relevant to the change in the momentum at the shear zone. The inertia force is directly proportional to the density of the workpiece material and to the square of the cutting speed. These results show that the increasing rate of the thrust force tends to be higher than that of the principal force for a workpiece material with high density when the cutting speed is beyond 100 m/s. In other words, these results imply that the apparent friction coefficient at the tool-chip interface elevates in high-speed cutting for a workpiece material possessing a high density. The tribological behavior at the tool-chip interface in high speed cutting relates strongly to this



(a) Panoramic view of the tester (b) Projectile with small built-in cutting tool

Figure 1 High-speed impact cutting tester used in this experiment phenomenon. If the phenomenon is clarified, the strategy against the rapid tool wear will be obtained. However, the complete theory that can explain the characteristic of the tribology under the conditions with high temperature, high normal stress and high strain rate has not been established so far.

The high-speed cutting tests of oxygen free copper in which the material density is higher than that of aluminum alloy was carried out. The cutting speeds investigated were from 1 m/s to 210 m/s. This paper describes the effect of the cutting speed on the quality of the machined surface, firstly. Secondly, the change in the cutting mechanism with the cutting speed is compared with the data for aluminum alloy obtained previously. Finally, this paper discusses the friction property at the tool-chip interface in high-speed cutting by investigating the stress and temperature fields on the shear plane and the tool-chip interface.

Cutting test of oxygen free copper

The cutting tests were conducted under the orthogonal cutting configuration. For low-cutting speed test with a cutting speed of around 1 m/s, a shaping machine was used. For high-speed cutting test with a cutting speed up to 210 m/s, a high-speed impact cutting tester developed was used.

Fig. 1 (a) shows the tester [1,2,3]. The tester is an experimental equipment of an air-gun type. The tester is composed of an accelerating tube, a chamber in which the workpiece is set, a decelerating tube and a collecting tube. Fig. 1(b) shows a projectile. It is assembled with a cap and a sabot in which a small cutting tool is installed. The weight of the projectile is 17.6 g. The projectile is loaded into the end of the acceleration tube, and then accelerated with compressed gas. The small cutting tool being installed in the sabot cuts the workpiece being set in the chamber orthogonally at a high-speed. The cutting speed can be adjusted by the pressure of the compressed gas and the solenoid valve’s opening time. The maximum cutting speed reaches 210 m/s. Chip that is necessary for analyzing the cutting mechanism enters into the cap during cutting so as to be collected after a test. The workpiece material was oxygen free copper (JIS: C1020-1/2H, purity of Cu > 99.96 %). The density is 8941 kg/m3, which is approximately 3.3 times higher than that of aluminum alloy A2017. The crystalline structure of oxygen free copper is FCC, which is the same as the crystalline structure of aluminum alloy. Fig. 2 shows the workpiece. The shape of the workpiece was formed by machining a 1.2 mm thick sheet with wire EDM. The length to be cut is 60 mm. The material of the cutting tool was a tungsten carbide P20 (WC 79%-TiC 8%-Ta(Nb)C 5%-Co 8%). The rake angle and clearance angle of the tool were 0º and 6º, respectively. The depth of cut at the set-up of the experiment was 0.1 mm. In the test, the cutting speed was measured by measuring the speed of the projectile during cutting, and the three components of the cutting force were measured with a piezoelectric dynamometer.

The chip, machined surface, rake and clearance faces of the cutting tool were observed with an optical microscope after the test. The cross-sections of the machined surface and the chip were polished, and then etched with the Grard’s No.1 reagent in order to observe the distortion of the crystalline structure with an optical microscope. The hardness of the cross-section of the machined surface and chip were measured with a micro Vickers hardness tester. The cutting force per the cutting area was calculated using the data of the cutting forces measured and the true depth of cut calculated. The detailed methodology of the analysis is shown in the reference [3]. The observation of the chip morphology revealed that the continuous flow-type of chip was formed regardless of cutting

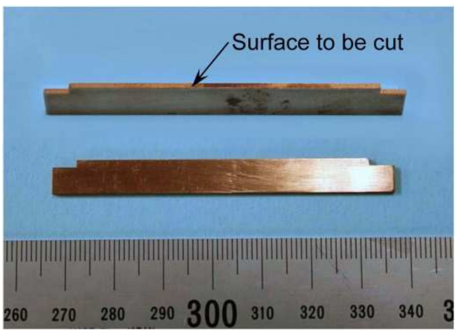


Figure 2 Shape of the workpiece

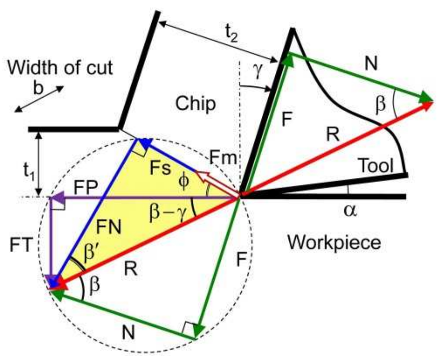


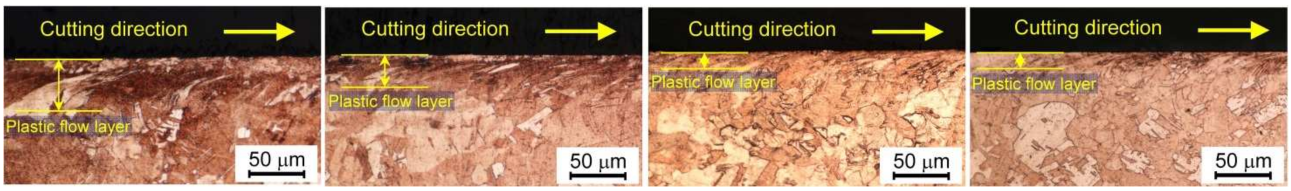
Figure 3 Simple shear plane model

speed. Therefore, the simple shear-plane model that is shown in Fig. 3 was employed to analyze the stress field on the shear plane and tool-chip interface. Average temperatures on the shear plane and on the rake face were calculated by employing a simple temperature analysis [4].

Results and discussions

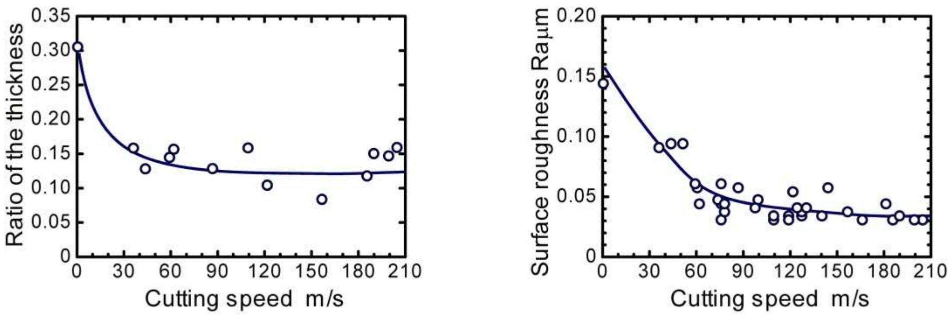
Fig. 4 shows the plastic flow layer just under the machined surface at various cutting speeds. Fig. 5 (a) shows the change in the ratio of the thickness of the plastic flow layer to the true depth of cut with the cutting speed. The thickness of the plastic layer drops when the cutting speed rises from 1 m/s to 30 m/s, and then levels off. The plastic flow layer is never eliminated. It can be seen that the plastic flow layer with a thickness of approximately 15 % of the true depth of cut remains even if the cutting speed reaches 210 m/s. Fig. 5 (b) shows the change in the surface roughness value *Ra* on the machined surface measured along the cutting direction with the cutting speed. The surface roughness value drops rapidly as the cutting speed increases. However, when the cutting speed is beyond 60 m/s, the effect of the high-speed cutting on the improvement over the surface roughness weakens.

Fig. 6 shows the results analyzed by employing the simple shear-plane model. They are the changes in the specific principal force (a), specific thrust force (b), specific resultant force (c), shear angle ϕ that was calculated with the chip thickness (d), friction angle β on the tool-chip interface (e) and friction angle β' on the shear plane (f). For comparison, the results for aluminum alloy A2017-T3 [3] were also shown with a dashed curve. The forces for oxygen free copper are higher than those for aluminum alloy. The resultant force for oxygen free copper drops and then keeps decreasing with the cutting speed, while the resultant force for aluminum alloy falls and then rises. The shear angles for both materials hardly change when the cutting speed exceeds 100 m/s. The shear angle for oxygen free copper is half of that for aluminum alloy. The friction angle β for oxygen free copper is higher than that for aluminum alloy. It rises clearly and monotonously when the cutting speed is beyond 20 m/s. On the other hand, the friction angle β for aluminum alloy tends to increase slightly when the cutting speed is beyond 150 m/s. The increasing rate in the friction angle β for oxygen free copper is higher than that for aluminum alloy. The friction angle β for oxygen free copper elevates by approximately 5º, when the cutting speed rises from 20 m/s to 210 m/s. The friction angle β at the cutting speed of 210 m/s reaches that at the cutting speed of 1 m/s. The friction angle β' on the shear plane for oxygen free copper is higher than that for aluminum alloy regardless of cutting speed. The value of β' for both materials rise and then falls monotonously with the cutting speed. From Fig. 3, this means that the hydrostatic stress on the shear zone grows in high-speed cutting.



(a) V=1 m/s (b) V=59.7 m/s (c) V=122.3 m/s (d) V=205.3 m/s

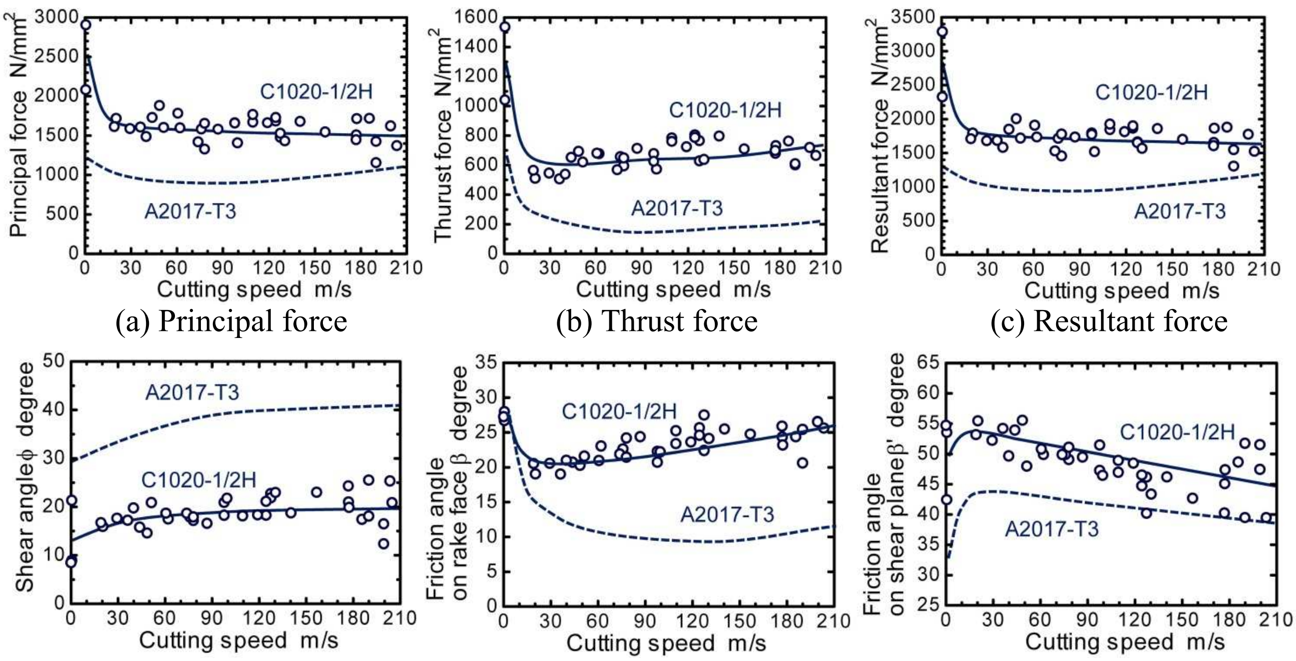
Figure 4 Photographs of the cross section of the workpiece near the machined surface



(a) Thickness of the plastic flow layer (b) Surface roughness value Ra

Figure 5 Change in the quality of the machined surface with cutting speed

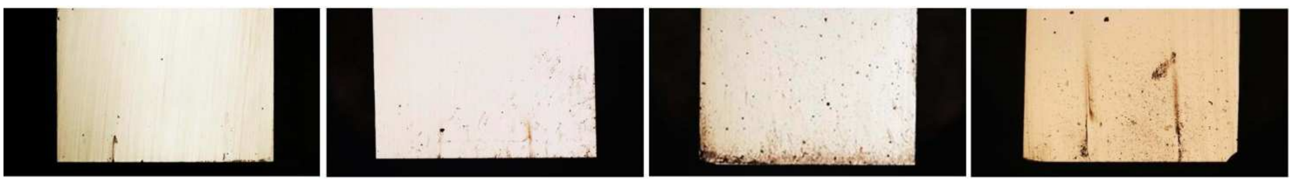
Fig. 7 shows the appearances of the rake face at various cutting speeds. It is worth to note that the significant welded or adhered materials, which can be seen in the cutting of a PM steel [2] and aluminum alloy [3], did not form on the rake face at any cutting speeds. Only both sides of the chip along the chip flow left the signs that the chip slid on the tool face. This mark will develop into the notched wear [5]. The welded or adhered materials on the tool face must influence on the friction angle on the tool-chip interface. The difference in the change in the friction angle β on the tool-chip interface with the cutting speed between oxygen free copper and aluminum alloy may originate from the existence or nonexistence of the welded or adhered materials. Fig. 8 shows the changes in the ratio of the tool-chip contact width to the width of cut, the ratio of the tool-chip contact length to the true depth of cut and the ratio of the tool-chip contact area to the cutting area with the cutting speed. Though the tool-chip contact width is remarkably wide in low-speed cutting, it drops and reaches the width of the workpiece as the cutting speed increases. The tool-chip contact length becomes short, and then elongates in high-speed cutting. As a result, for oxygen free copper, the tool-chip contact area extends with the cutting speed when the cutting speed exceeds 60 m/s, while the area for aluminum alloy keeps decreasing slightly when the cutting speed is beyond 10 m/s. The tool-chip



(a) Principal force (b) Thrust force (c) Resultant force

(d) Shear angle (e) Friction angle on the rake face (f) Friction angle on the shear plane

Figure 6 Changes in the cutting mechanism with the cutting speed



(a) V=1.0 m/s (b) V=76.4 m/s (c) V=144.7 m/s (d) V=190.5 m/s

Figure 7 Photographs of the rake face at various cutting speeds

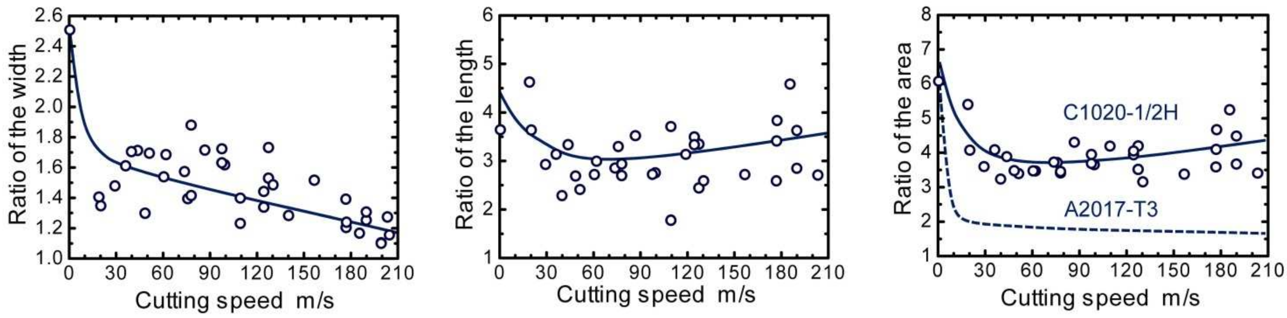


Figure 8 Changes in the tool-chip contact region with the cutting speed

contact area for oxygen free copper is larger than that for aluminum alloy at any cutting speeds. The difference in the tool-chip contact area between oxygen free copper and aluminum alloy will be one of the reasons for the difference in the friction property at the tool-chip interface between them.

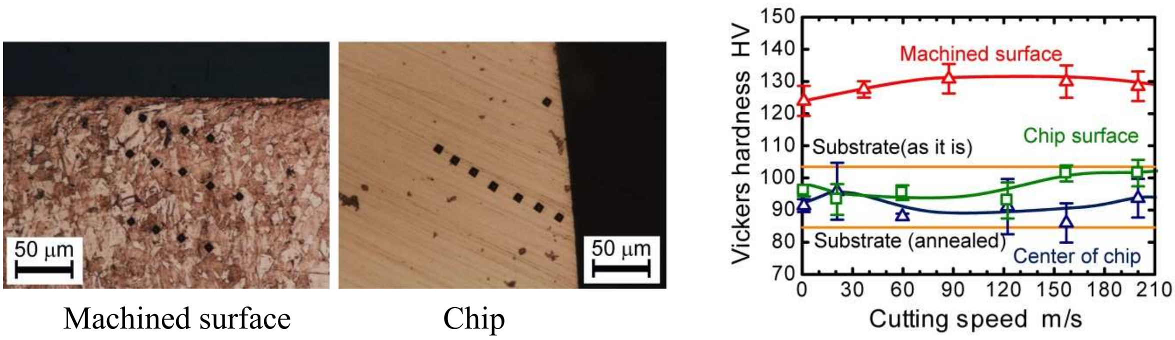
Fig. 9 shows the changes in the Vickers hardness number with cutting speed for the cross section of the workpiece and chip. The photographs show the measured points for the machined surface and the chip. In the graph, the Vickers hardness number for the machined surface was the value measured at an inner position of 10 μm of the machined surface, and for the chip were the values measured at a position of 10 μm inside from the sliding surface and at the center of the chip. The graph reveals that the machined surface suffered hardening clearly. The hardness at the center of the chip is much smaller than the hardness of the substrate. It is close to the hardness of the material annealed. Thus the center of the chip is softened. In contrast, the Vickers hardness number for the chip material near the sliding surface is higher than that for the center of the chip. The hardness of the chip material near the sliding surface reaches the hardness of the material as it is, when the cutting speed is beyond 150 m/s.

As mentioned above, the inertia force rises as the cutting speed increases. Accordingly, the apparent force acting on the shear plane could rise, resulting in the increase in the cutting forces. However, for oxygen free copper, the specific principal force keeps decreasing slightly with the cutting speed, as shown in Fig. 6 (a). This means that the material yield shear stress τ_s is softened thermally. In order to confirm the thermal effect, the temperatures on the shear plane and the tool-chip interface were analyzed with a simple temperature analysis [4].

Fig. 10 (a) shows the result. The average temperature on the shear plane is in the upper range of the recrystallization temperature zone, which lies in from 393 K to 623 K. By employing the simple shear plane model, the material yield shear stress τ_s on the shear plane can be calculated as:

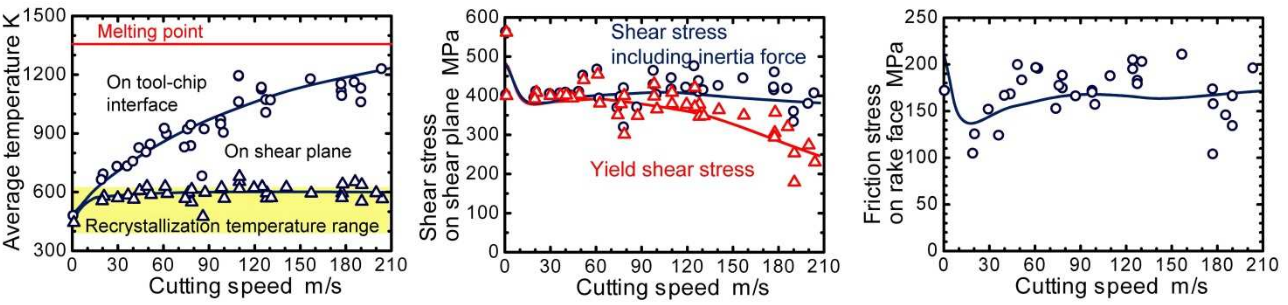
$$\tau_s = \sqrt{uFP^2 + uFT^2}\,\sin\phi\cos(\phi + \beta - \gamma) - \rho V^2 \sin\phi\cos\gamma / \cos(\phi - \gamma) \qquad (1)$$

where, rake angle γ is 0 in this study. Fig. 10 (b) shows the change in the apparent shear stress, which involves the effect of the inertia force, and material yield shear stress on the shear plane with the cutting speed. It can be seen that the material yield shear stress drops clearly. Though the inertia force contributes the increase in the apparent shear stress, the apparent shear stress decreases gradually when the cutting speed is beyond 60 m/s. The shear strain rate at the shear zone estimated is beyond



Machined surface Chip

Figure 9 Changes in the Vickers hardness number at various points with the cutting speed



(a) Temperatures analyzed (b) Shear stress on the shear plane (c) Friction stress on the rake face

Figure 10 Changes in the temperatures, shear stress and friction stress with the cutting speed

10^6 1/s and reaches 10^7 1/s, when the cutting speed is beyond 30 m/s. Hence, it can be seen that, on the shear plane, the thermal softening effect is higher than the strain and strain rate hardening effect. This supports the result that the center of the chip is softened as shown in Fig. 9. On the other hand, the average temperature on the tool-chip interface is far beyond the recrystallization temperature. It elevates as the cutting speed increases. However, in the cutting-speed range investigated, the temperature did not reach the melting point of 1356 K. The mean friction stress on the tool-chip contact region does not decrease in such a high-speed cutting conditions as shown in Fig. 10 (c). Integrating the results of Vickers hardness number of the chip measured near the sliding surface and the temperature analysis leads to a conclusion that the work hardening effect is superior to the thermal softening effect in the vicinity of the sliding surface for the chip material.

Many studies concerning the flow stress of oxygen free copper under high temperature and high strain rate have been performed [6,7,8]. By referring to these findings, for FCC materials, the strain rate sensitivity on the flow stress becomes high when the strain rate exceeds a critical strain rate. For oxygen free copper, the flow stress increases in high temperature such as 1096 K, if the strain and strain rate become high [8]. In the chip, the plastic strain concentrates near the sliding surface. Therefore, for the chip material in the vicinity of the sliding surface, it is possible to consider that the strain and strain hardening effects are superior to the thermal softening effect. The tool-chip contact area increases slightly as mentioned above. Besides, the mean friction stress on the tool-chip contact region does not decrease. Thus, the thrust force increases in high-speed cutting. Since the principal force keeps decreasing slightly, the friction angle on the tool-chip interface rise when the cutting speed is beyond 20 m/s, as shown in Fig. 6 (e). Therefore, the work hardening of the chip material near the sliding surface contributes to the increase in the friction angle in high-speed cutting.

Summary

The cutting mechanism of oxygen free copper was investigated experimentally under the conditions with a cutting speed of from 1 m/s to 210 m/s. The experimental results obtained show the following findings: The quality of the machined surface evaluated by the thickness of the plastic flow layer and the surface roughness improves as the cutting speed increases. However, these improvements by high-speed cutting weaken when the cutting speed is faster than 60 m/s. The principal force drops rapidly when the cutting speed increases from 1 m/s to 20 m/s, and then keeps decreasing slightly with the cutting speed. The thrust force also drops rapidly as the cutting speed increases. However, it rises monotonously when the cutting speed is beyond 20 m/s. The decrease in the principal force is due to the thermal softening on the shear zone. The increase in the thrust force is attributed to the strain and strain rate hardening of the chip material near the sliding surface, even if the temperature on the chip sliding surface is high. Accordingly, the apparent friction angle at the tool-chip interface monotonously rises as the cutting speed increases when the cutting speed is beyond approximately 30 m/s. For oxygen free copper, the primary factor of the increase in the friction angle is not the inertia force but the characteristic of the flow stress under high strain, high strain rate and high temperature.

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