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Investigation of ultra-high speed cutting mechanism by considering tool-chip friction property and inertia force derived from chip formation

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Abstract

The friction angle at the tool-chip interface, which is analysed using the cutting force measured, tends to rise as the cutting speed increases when the cutting speed is in a higher speed range. In order to elucidate a reason of the rising of the analysed friction angle, this study examined the temperature at the tool-chip interface and the chip formation mechanism by performing the orthogonal cutting experiment of a pure lead with a cutting speed of from 1 m/s to 140 m/s using an air-gun type of cutting tester developed. The temperatures at the tool-chip interface directly measured reach the melting point of the pure lead when the cutting speed is beyond 100 m/s. Hence, the true friction between the tool material and the chip material, as the tribological property, must lessen under such a high-speed cutting condition, because a thin molten metal layer will form at the tool-chip interface. Under the ultra-high speed cutting condition where the cutting speed is beyond the plastic wave speed of the workpiece material, the chip formation mechanism changes so that the chip width will widen extremely. Widening of the chip width changes the direction of the inertia force originated from the change in momentum occurring in the shear zone. Considering the change in the direction of the inertia force figured out that the analysed friction angle inevitably rises. The analysed friction angle no longer expresses the true friction property in such high-speed cutting conditions. This study deduces that the thrust force as well as the principal force will keep increasing regardless of the true friction property between the tool and chip materials under the ultra-high speed cutting condition.

High-speed cutting, temperature, friction property at the tool-chip interface, inertia force

1. Introduction

Knowing the variation in the friction property at the tool-chip interface versus cutting speed is crucial to advance high-speed cutting process more. We generally grasp it experimentally in terms of a magnitude of the friction angle β analysed using the relation between the normal force N and the frictional force F acting on the tool face. Many studies concerning the high-speed sliding phenomena has reported that the friction coefficient of the contact bodies decreases as relative sliding speed increases [1]. Applying this knowledge to the high-speed cutting mechanism, we could suppose that the analysed friction angle at the tool-chip interface becomes small as the cutting speed increases. However, the results of the orthogonal high-speed cutting experiment that the author has performed so far using an impact high-speed cutting tester developed, which is an air-gun type of tester, show an opposite tendency.

Figure 1 shows the summarised data of the variation in the analysed friction angle at the tool-chip interface versus cutting speed [2-5]. The friction angle definitely decreases as the cutting speed increases in a relatively low cutting-speed range. However, in a higher cutting-speed range, it turns to rise as the cutting speed increases. Few papers have mentioned the rising of the friction coefficient under high-speed sliding condition [6, 7].

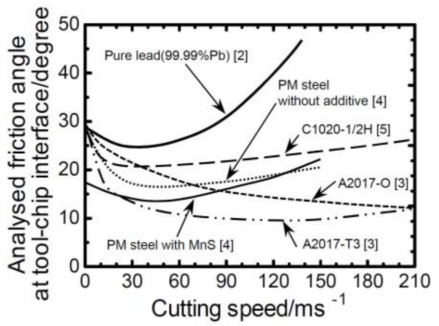


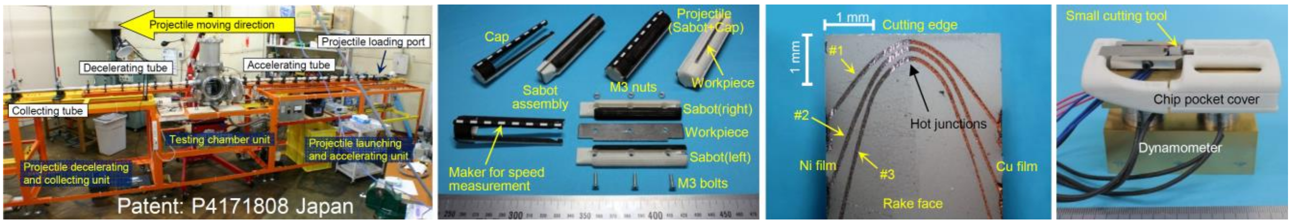
Fig .1 Variation in the analysed friction angle versus cutting speed

This paper investigated a reason of the rising of the analysed friction angle. Since temperature at the interface affects the friction property strongly, the temperatures at the tool-chip interface during cutting were directly measured. Besides, the influence of the change in the chip formation under an ultra-high speed cutting condition where the cutting speed is beyond the plastic wave speed of the workpiece material upon the cutting mechanism was considered. This study selected a pure lead as the workpiece material by considering its slow plastic wave speed (around 70 m/s) and its low melting point (600.6 K). The orthogonal cutting condition examined was; the width of cut b = 2mm, the depth of cut at the set-up t_1 = 0.2 mm, the rake angle $\gamma = 0^{\circ}$, the cutting speed V = 1 m/s to 140 m/s.

2. Investigation of the rising of the analysed friction angle

2.1. Temperatures at the tool-chip interface

The author has established the measurement method of the temperature distribution at the tool-chip interface with Cu/Ni micro thermocouples fabricated on the rake face [8]. This method was applied to the measurement of the temperatures at the tool-chip interface under high-speed cutting conditions.



(a) Whole view of the high-speed impact cutting tester (b) The projectile with built-in the workpiece (c) Rake face of the small cutting tool (d) Small cutting tool set on the dynamometer

Fig .2 Apparatus of the high-speed orthogonal cutting experiment

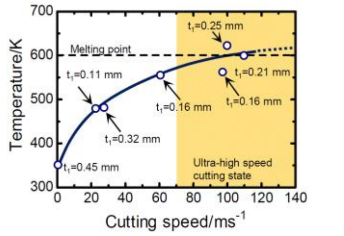


Fig .3 Evolution of the temperature at the tool-chip interface versus cutting speed

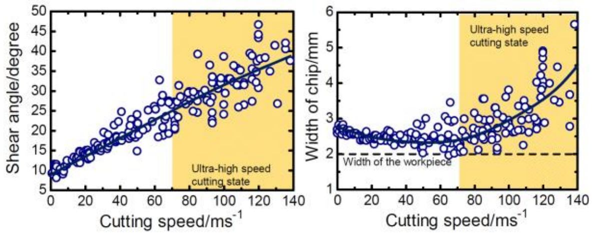


Fig. 4 Variation of the shear angle and the width of chip versus cutting speed

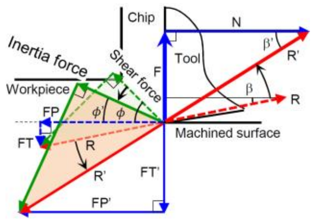


Fig. 5 Cutting model

Figure 2 shows the apparatus of the orthogonal high-speed cutting experiment used in this study. A projectile with built-in a plate shaped workpiece is loaded into an accelerating tube, accelerating to a high speed with compressed gas. On the rake face of a small cutting tool, three pairs of Cu/Ni micro thermocouples were fabricated. The small cutting tool is fixed on a dynamometer that is able to follow up to 15 kHz, setting in a testing chamber. Cutting occurs in the testing chamber. During cutting, the projectile captures the chip, which is indispensable for the analysis of the cutting mechanism. After cutting, the projectile is decelerated with compressed gas in a decelerating tube, stopping in a collecting tube.

Figure 3 shows the evolution of the temperature at the tool-chip interface versus cutting speed obtained. The temperatures reach the melting point of the pure lead when the cutting speed exceeds 100 m/s. Thus, it is reasonable to consider that the true friction between the tool material and the chip material must lessen because a thin molten metal layer will form at the interface when the cutting speed exceeds 100 m/s. However, the analysed friction angle keeps increasing, as shown in Fig. 1. Therefore, it seems that there are some reasons other than the effect of the tribological property at the tool-chip interface.

2.2. Influence of the chip formation mechanism

In the ultra-high speed cutting condition, the high-levels of hydrostatic stresses are developed in the shear zone by the plastic shock waves [9]. Hence, under the ultra-high speed cutting condition, the chip formation mechanism changes so that the chip width will widen in order to release the high hydrostatic stress in the shear zone [2].

Figure 4 shows the variation of the shear angle ϕ and the chip width w_c versus cutting speed. The shear angle ϕ is the calculated one using the relation between the undeformed chip thickness t_1 and the chip thickness t_2. The chip width widens extremely as the cutting speed increases when the cutting speed is beyond 70 m/s. By considering the widening of the chip width, this study reconsidered the direction of the inertia force, which originates from the change in momentum occurring in the shear zone, as follows:

$$\tan\phi' = \frac{\frac{b}{w_c}\sin\phi\cos\gamma}{\cos(\phi-\gamma) - \frac{b}{w_c}\sin\phi\sin\gamma} \equiv \frac{b}{w_c}\tan\phi \quad (\text{for} \quad \gamma = 0)$$

When the widening of the chip can be ignored, the angle of the inertia force ϕ' equals to the shear angle ϕ. When w_c is wider than b, ϕ' becomes smaller than ϕ. The wider w_c becomes, the smaller ϕ' will be. By referring Fig. 4, when the cutting speed is 140 m/s, the shear angle ϕ reaches 40˚ and the chip width w_c becomes wider by approximately 2.3 times than the width of cut b. Therefore, the angle of the inertia force ϕ' becomes smaller by approximately 20˚ than the shear angle ϕ. Since the magnitude of the inertia force is in proportion to the square of the cutting speed, the inertia force is able to become extremely larger than the shear force derived from the elastic-plastic shear deformation in the shear zone when the cutting speed is in higher speed range. Thus, the contribution of the inertia force to the resultant cutting force becomes large under high-speed and ultra-high speed cutting conditions. For this case, as shown in Figure 5, we can realize that the analysed friction angle β, which is obtained by decomposing the resultant force acting on the cutting tool, inevitably rises. The frictional stress at the tool-chip interface never exceeds the maximum yield shear stress of the chip material. Besides, the tool-chip contact region cannot infinitely expand. Therefore, it is worth noting that the analysed friction angle no longer expresses the true friction property between the tool material and the chip material. The force *F* acting of the tool in Fig. 5 is not a force derived from the tool-chip friction but a normal force acting on the cutting edge, which is originated from the inertia force.

3. Summary

The friction angle at the tool-chip interface analysed using the cutting force measured rises in ultra-high speed cutting. The change in the direction of the inertia force due to the widening of the chip width attributes to a principal reason for the rising of the analysed friction angle. In ultra-high speed cutting, the analysed friction angle no longer expresses the true friction property of the tool-chip contact region. The true friction angle at the tool-chip interface must lessen in higher cutting-speed range, because a molten metal layer will form at the interface.

Furthermore, from Fig. 5, we can deduce that the thrust force *FT* as well as the principal force *FP* keeps increasing in ultra-high speed cutting condition, regardless of the tribological property between the tool material and the chip material.

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