Effect of MnS on the cutting mechanism of powder metallurgy steel in cutting speeds ranging from 1 m/s to 150 m/s

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Abstract. Orthogonal cutting experiment of powder metallurgy steel was performed in cutting speeds ranging from 1 m/s to 150 m/s. High-speed cutting experiment was carried out with a high-speed impact-cutting tester. This study focuses on the change in the effects of free-cutting of manganese sulfide with cutting speed. The principal force and thrust force were measured. The cross sections of the chip and of the machined surface were observed. Color mapping analysis of the tool-chip contact region on the rake face with EPMA was done. Although the serrated type of chip formed in all experiments, the cutting mechanism was analyzed by employing a shear plane model. This paper discusses how the effect that MnS promotes the ductile fracture and the effect that MnS improves the friction property at the tool-chip interface change as the cutting speed increases.

Introduction

Powder metallurgy (PM) technology is widely used in manufacturing of various mechanical parts, because it has an ability to produce the near-net shape parts that reduces the production costs. PM steel is produced by sintering mainly ferrite powder, carbon powder and copper powder at a high temperature. Hence some pores are included in PM steel. The pore in PM steel promotes high tool wear rate, because the pore degrades the thermal conductivity and the pore induces an impact force to the tool face [1]. Besides, the pores deteriorate the machined surface roughness [2]. In order to improve the machinability of PM steel, some free-cutting additives are generally contained. Manganese sulfide (MnS) is one of popular free-cutting additives [3,4,5]. MnS in the shear zone promotes the ductile fracture during shearing, resulting in the low shear stress at the shear zone. Moreover, MnS helps to form a film that can improve the friction property at the tool-chip interface on the tool face. These two effects of MnS can provide the reduction of the cutting force and the prolongation of tool life. High-speed cutting is one of current trends in industry. The demand of high-speed cutting of PM steel has been also increasing. It, however, has not been known well how the effect of free-cutting of MnS on the cutting mechanism changes as the cutting speed increases.

Thus, this study investigated the change in the effect of free-cutting of MnS on the cutting mechanism of PM steel with cutting speed. The orthogonal cutting tests of PM steel with a cutting speed of 1 m/s to 150 m/s were performed. In this experiment, a shaping machine was used for the case that cutting speed is below 1 m/s. For high-speed cutting with a cutting speed beyond 20 m/s, a high-speed impact-cutting tester was used. The cutting mechanisms of an additive-free PM steel (Fe-0.8%C-2%Cu) and a PM steel with MnS (Fe-0.8%C-2%Cu-0.5%MnS) were compared. The changes in the shape of chip, thickness of the plastic flow layer on the machined surface, surface roughness on the machined surface, cutting forces, shear stress at the shear zone and friction angle at

the tool-chip interface with cutting speed were investigated. A color mapping analysis by means of EPMA was carried out to analyze the constituent elements of a film formed on the rake face at a high-speed cutting. By using the results obtained, this paper discusses how the effect that MnS promotes the ductile fracture and the effect that MnS improves the friction property at the tool-chip interface change as the cutting speed increases.
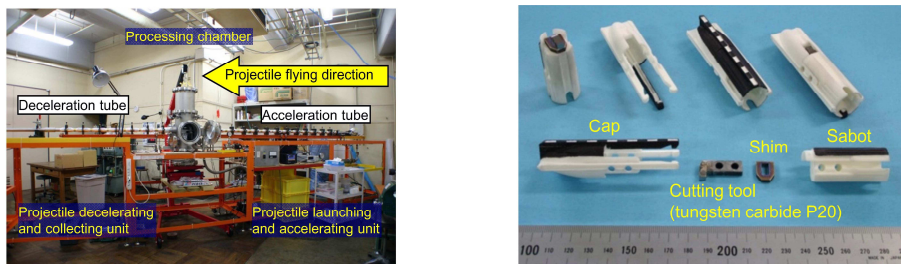
High-Speed Cutting Experiment and Analysis of the Cutting Mechanism

Fig.1 (a) shows the high-speed impact-cutting tester used in this experiment [6,7,8]. This tester is an air-gun type. In this tester, a light projectile with small built-in cutting tool, as shown in Fig. 1 (b), is accelerated by compressed gas, flying in an acceleration tube at a high-speed. The material of the small cutting tool is a tungsten carbide P20 (79%WC-8%TiC-5%Ta(Nb)C-8%Co). The rake angle and clearance angle are 0º and 6º, respectively. Fig. 1 (c) shows the photographs of the microstructure of the additive-free PM steel and the PM steel with MnS used in this study as the workpiece material. The porosity of the two PM steels was 20 %. The additive amount of MnS is as very little as 0.5 mass %. Though the particles of MnS cannot be found in Fig. 1(c), it is possible to assume that MnS exists in the form of the small sphere. The workpiece that had machined to sheet shape with a wire EDM is placed in the chamber. The length of the workpiece is 60 mm. Hence, the cutting length is 60 mm. The widths of the workpiece, which equal to the widths of cut, are 1.5 mm for the additive-free PM steel and 1.2 mm for the PM steel with MnS. The depth of cut was set to be 0.1 mm before all experiments. Since the flying cutting tool impacts on the workpiece, the true depth of cut could fluctuate during cutting. In order to eliminate the influence of the fluctuation in the true depth of cut on the cutting force, the specific cutting force (cutting force per cutting area) was considered for analyzing the cutting mechanism in this study.

  As it is shown in next section, the serrated chip formed for the two PM steels regardless of cutting speed. However, this study utilizes a cutting model as shown in Fig. 1 (d) to simplify the analysis of the cutting mechanism. The shear angle ϕ was determined by the shape of a segment of the serrated chip as shown in Fig. 1 (d) or Fig. 3. The cutting model shows clearly the relation between the resultant cutting force R and the apparent shear force acting on the shear zone (Fs+Fm), as follows:

$$R\cos(\phi+\beta) = \sqrt{F_P^2 + F_T^2}\,\cos(\phi+\beta) = Fs + Fm \quad \left(\text{where,}\;\; Fs = \frac{bt_1}{\sin\phi}\tau_s,\;\; Fm = \rho V^2\frac{bt_1}{\cos\phi}\right). \quad (1)$$
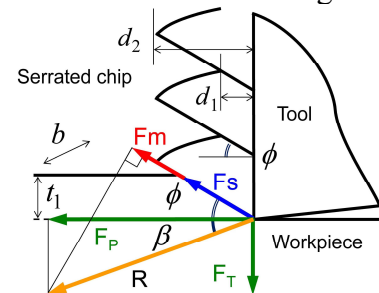
Fs is a force that originates from the shear stress τ_s of the material at the shear zone. Fs is the inertia

(a) high-speed impact cutting tester (b) light projectile with small built-in cutting tool
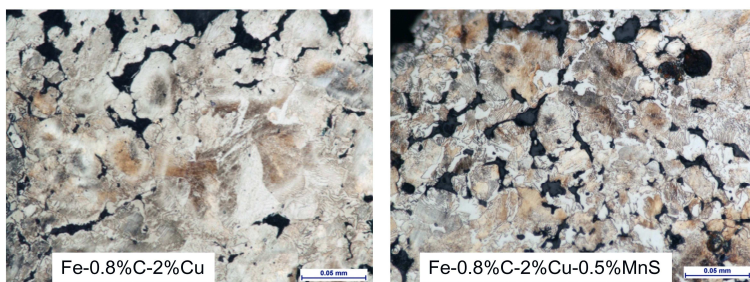
(c) metal structure of PM steels   (d) a cutting model used in this study
Figure 1 Experimental apparatus, workpiece material and cutting model used for analysis

force that derives from the change in the momentum at the shear zone. Thus, the shear stress τ_s is:

$$\tau_s = \sqrt{uF_P^2 + uF_T^2}\ \sin\phi\cos(\phi+\beta) - \rho V^2 \tan\phi. \tag{2}$$

where, uF_P and uF_T are the principal force and thrust force per cutting area, respectively. β ($=\tan^{-1}(uF_T/uF_P)$) is the friction angle. This study discusses the changes in the cutting mechanism and effects of free-cutting of MnS with cutting speed by focusing on the changes in τ_s and β with cutting speed.

Results and Discussions

Fig. 2 shows the photographs of the rake face after cutting at typical cutting speeds. It is seen that a substance that is black in color like soot adheres over the wide area of the rake face as the cutting speed increases for both PM steels. Furthermore, it can be noticed that a welded film was formed on the tool-chip contact area in spite of the very short cutting time. The cutting time is 400 μs when the cutting speed is 150 m/s. Fig. 3 indicates the change in the shape of chip with cutting speed. Fig. 3 (a) and (b) show the photographs of the cross-section of chip at typical cutting speeds. The serrated type of chip formed for both PM steels, regardless of cutting speed. It is worth to note that the pores existing on the surface is not necessarily an origin of the crack for the formation of the serrated chip. Besides, it can be seen that the cutting speed does not affect the shape of the segment of the serrated chip. Fig. 3 (c) shows the change in the ratio d1/d2, which indicates the relation between the peak and valley of a segment of the serrated chip as shown in Fig. 1 (d). Fig. 3 (d) shows the change in the shear angle with cutting speed. These results reveal that MnS diminishes the change in the chip shape with cutting speed. Fig. 4 indicates the changes in the quality of the surface integrities with cutting speed. Fig. 4 (a) shows the appearance of the machined surfaces. Rough surface can be seen for the PM steel with MnS. Fig. 4 (b) shows the cross-section of the machined surface. For the additive-free PM steel, a material adjacent to a pore being on the surface underwent large plastic deformation, plugging the
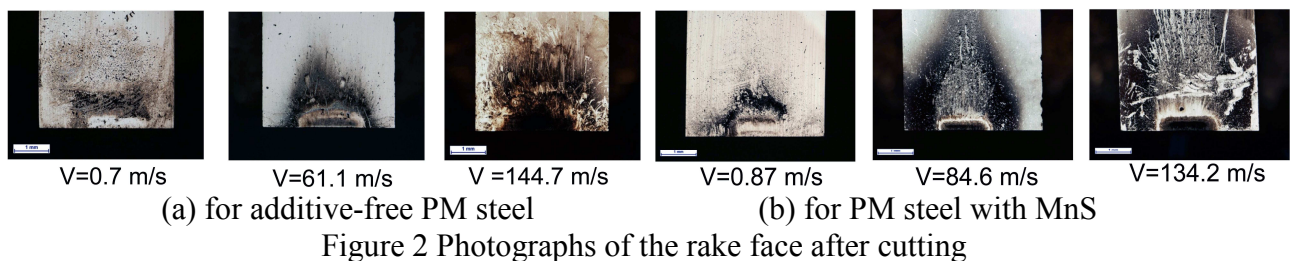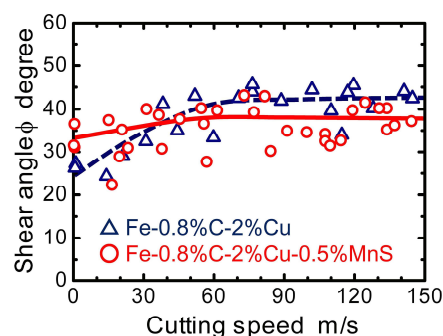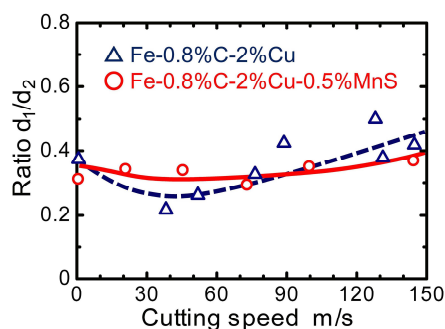

V=0.7 m/s	V=61.1 m/s	V =144.7 m/s	V=0.87 m/s	V=84.6 m/s	V=134.2 m/s

(a) for additive-free PM steel   (b) for PM steel with MnS

Figure 2 Photographs of the rake face after cutting

V＝0.7m/s	V=51.9m/s	V=88.7m/s	V=131.1m/s	V＝0.9m/s	V=45.8m/s	V=91.7m/s	V=144.7m/s

(a) for additive-free PM steel   (b) for PM steel with MnS
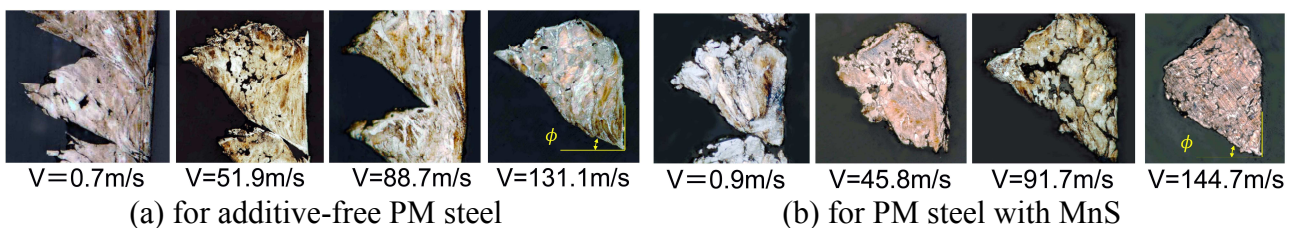
(c) shape of the segment of the serrated chip   (d) shear angle

Figure 3 Change in the shape of chip with cutting speed

pore or squashing the pore. The thickness of the plastic flow layer on the machined surface t_{pf} for the PM steel with MnS is thinner than that for the additive-free PM steel, especially in the slow cutting speed range, as shown in Fig. 4 (c). Fig. 4 (d) shows the change in the surface roughness (Ra) of the machined surface measured along the cutting direction with cutting speed. The value of the roughness for the PM steel with MnS becomes higher than that for the additive-free PM steel in high-speed cutting. Since MnS promotes the ductile fracture in the shearing deformation, the ductility of a material on the machined surface declines by addition of MnS. The reduction of the ductility degrades the effect that a material on the surface plugs up a pore being the surface. This situation appears remarkably in the deterioration of the surface roughness in especially high-speed cutting.

Fig. 5 graphs the cutting forces (uF_P and uF_T) versus cutting speed. When MnS is added, both principal force and thrust force decreases remarkably, especially, in low cutting speed range. When the cutting speed is around 1 m/s, the principal force and thrust force decrease by 50 % and by 75 %, respectively. Increasing the cutting speed decreases both forces. Since the decreasing rates in the forces with cutting speed for the additive-free PM steel is higher than those for the PM steel with MnS, it can be assumed that the effect that MnS decreases the cutting forces tends to diminish as the cutting speed increases. The cutting forces reach minimum in the cutting speeds ranging from 30 m/s to 50 m/s. Further increase of the cutting speed raises the cutting forces due to the increase of the inertia force, as explained in Eq. 1. It is worth to note that the cutting forces for the PM steel with MnS are lower than the cutting forces for the additive-free PM steel in any cutting speeds. Fig. 6 shows the changes in the shear stress τ_s and friction angle β with cutting speed. As described before, MnS promotes the ductile fracture. Thus, the shear stress or shear strength for the PM steel with MnS becomes smaller than that for the additive-free PM steel in any cutting speed, as shown in Fig. 6 (a). MnS decreases the shear stress by about 35 %, when the cutting speed is 1 m/s. The shear stress decreases as the cutting speed increases in the cutting speeds ranging from 1 m/s to 30 m/s. This

| V=1.0 m/s | V=76.4 m/s | V=144.7 m/s | V=0.9 m/s | V=84.6 m/s | V=144.7 m/s |

additive-free PM steel   PM steel with MnS

(a) appearance of the machined surface

| V=1.0 m/s | V=93.2 m/s | V=128.0 m/s | V=0.9 m/s | V=84.6 m/s | V=144.7 m/s |

additive-free PM steel   PM steel with MnS

(b) cross-section of the machined surface

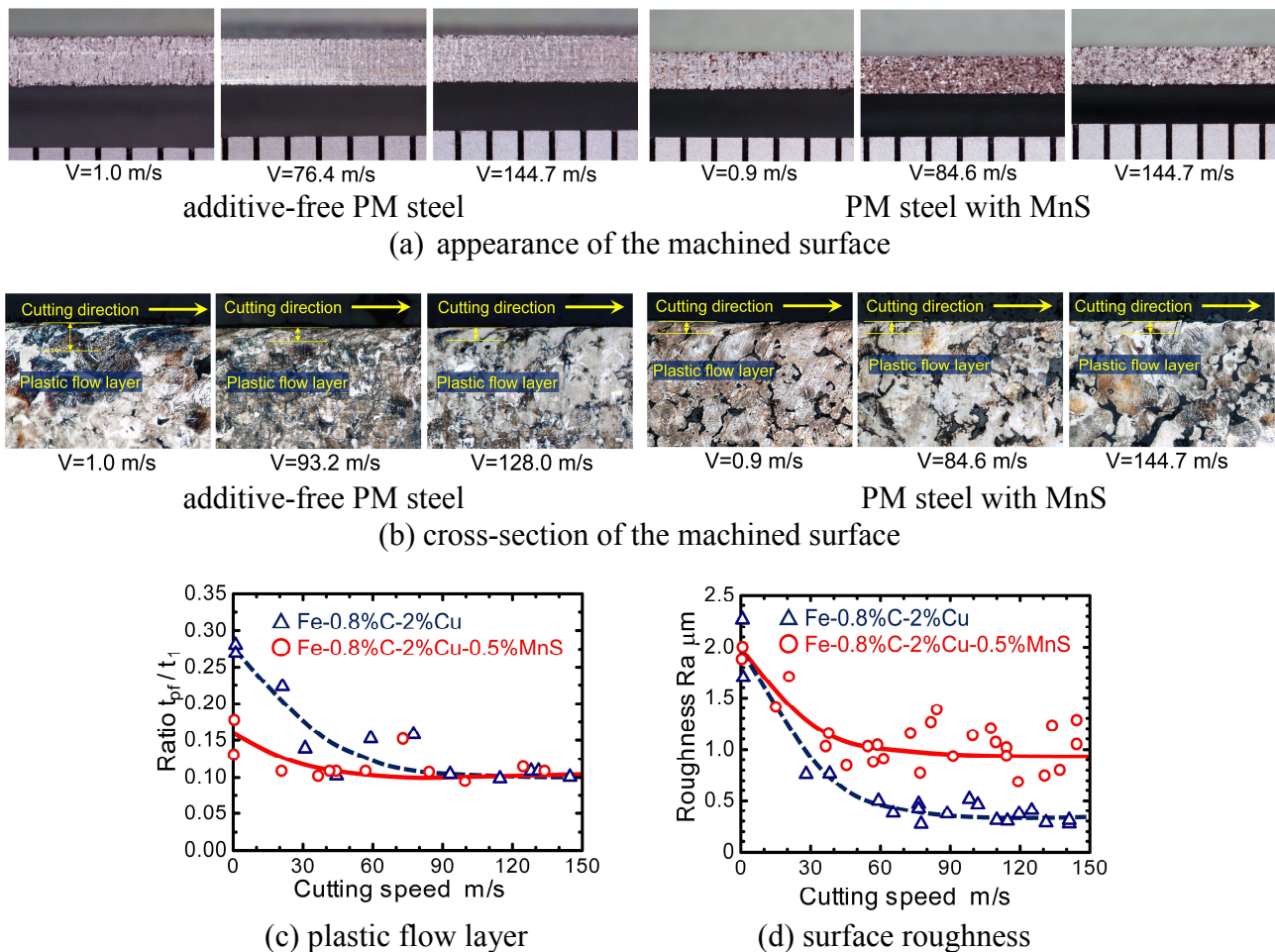(c) plastic flow layer   (d) surface roughness

Figure 4 Change in the quality of the surface integrity with cutting speed

decrease will be mainly due to the thermal softening. Although the decreasing rate tends to be small for both the PM steels when the cutting speed exceeds 40m/s, the shear stress keeps decreasing as the cutting speed increases. A simple estimation of the shear strain rate suggests that the shear strain rate is beyond 10^6 1/s when the cutting speed exceeds 30 m/s for both PM steels and it reaches 10^7 1/s when the cutting speed is 150 m/s. The shear stress for the PM steel with MnS is lower than that for the additive-free PM steel in any cutting speed. Hence, it can be seen that the effect that MnS promotes the ductile fracture never disappear under a severe deformation fields that the shear strain rate exceeds 10^6 1/s.

In the relatively slow cutting speed range, MnS improves the friction property at the tool-chip interface, as shown in Fig.6 (b). When the cutting speed is below 1 m/s, MnS reduces the friction angle by approximately 40 %. For both PM steels, the friction angle decreases as the cutting speed increases in the cutting speed ranging from 1 m/s to 40 m/s. The decreasing rate of the friction angle for the additive-free PM steel is higher than that for the PM steel with MnS. It is worth to note that the friction angle for both PM steels rises when the cutting speed exceeds 40 m/s. The increasing rate of the friction angle for the PM steel with MnS is higher than that for the additive-free PM steel. When the cutting speed exceeds 120 m/s, the friction angle for the PM steel with MnS becomes higher than that for the additive-free PM steel. For the PM steel with MnS, the friction angle with a cutting speed of 150 m/s becomes higher by about 1.4 times than that with a cutting speed of 1m/s. The phenomenon that the friction angle increases in high-speed cutting can be seen in cutting of pure lead [7] and aluminum alloy A2017-T3 [7]. Although MnS improves the friction property at the tool-chip interface in relatively slow cutting speed, MnS deteriorates the property in higher cutting speed. The deterioration of the friction property at the tool-chip interface must relate to a film formed on the tool face during high-speed cutting.

Fig. 7 shows the chemical compositions of the rake face analyzed by EPMA. It is seen that ferrite adheres on the rake face for the two PM steels, despite very short cutting time. For the PM steel with MnS, manganese and sulfur do not exist uniformly over the tool-chip contact area. They concentrate in the portion where the chip leaves the tool. Besides, a location where manganese exists does not correspond to a location where sulfur exists. It is possible to consider that MnS is decomposed into manganese and sulfur during sliding on the rake face at high speed. The melting point of sulfur is
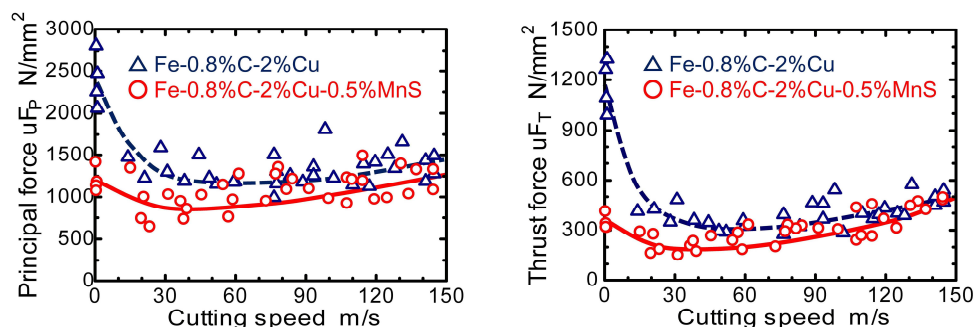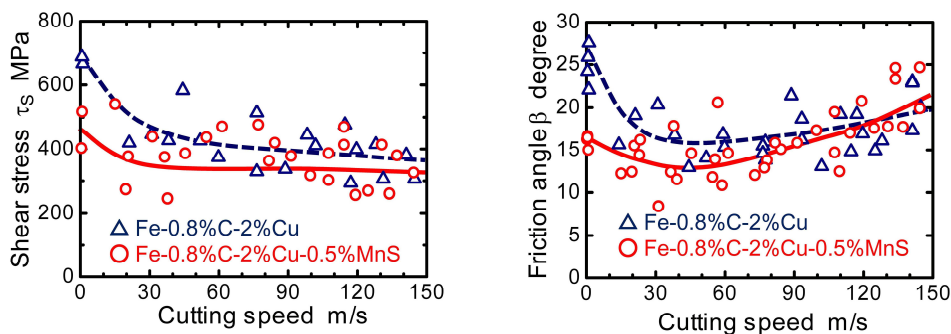

Figure 5 Changes in principal force and thrust force with cutting speed

(a) shear stress at the shear zone (b) friction angle at the tool-chip interface

Figure 6 Changes in shear stress and the friction angle

(a) for additive-free PM steel, cutting speed is 144.7 m/s

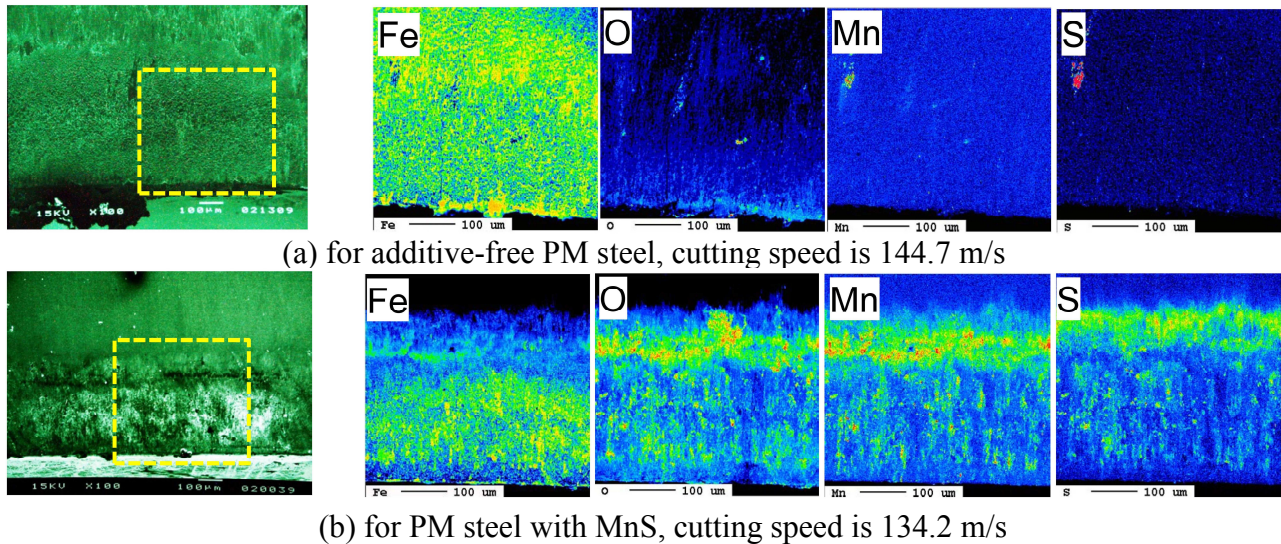(b) for PM steel with MnS, cutting speed is 134.2 m/s

Figure 7 Distribution of ferrite, oxygen, manganese and sulfur on the rake face

relatively as low as 718 K. It can be assumed that the temperatures at the tool-chip interface under high-speed cutting beyond 120 m/s is higher than the melting point of sulfur. Hence, a melting layer at the tool-chip interface may deteriorate the friction property at the tool-chip interface.

Summary

The effect of the free-cutting of MnS on the cutting mechanism of PM steel was investigated experimentally in cutting speeds ranging from 1 m/s to 150 m/s. These following findings were obtained in this experiment. The effect that MnS promotes the ductile fracture at the shear zone reduces the cutting force significantly, when the cutting speed is around 1 m/s. Since the cutting force for the additive-free PM steel drops rapidly as the cutting speed reaches 40 m/s, this effect seems to be relatively weakened in higher cutting-speed range. However, the effect that MnS promotes the ductile fracture never disappear even if the cutting speed reaches up to 150 m/s or even if the shear strain rate exceeds 10^6 1/s. MnS improves remarkably the friction property at the tool-chip interface in relatively slow cutting speed, such as 1 m/s. However, when the cutting speed is beyond 120 m/s, MnS deteriorates the friction property at the tool-chip interface. In such a high-speed cutting condition, MnS being at the tool-chip interface seems to be decomposed into manganese and sulfur. It is possible to consider that the melting layer at the tool-chip interface may cause the deterioration of the friction property at the tool-chip interface.

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