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High Speed Machining of Inconel 718 Focusing on Tool Surface Topography of CBN Tool

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Abstract
Nickel-based superalloys such as Inconel 718 provide several advantages, including a high-temperature strength and high corrosion resistance. Therefore the demand for such materials has rapidly increased, particularly in the aviation and gas turbine applications. On the other hand, they are known as one of the most difficult-to-cut materials due to their mechanical and chemical properties and the tool life is extremely short. Recently, Cubic-Boron-Nitride (CBN) has received a considerable attention as a material for cutting tools and has already established itself in many areas of machining. However, the performance of CBN tools is still insufficient in practical use, especially in the high speed machining of Inconel 718. To overcome this problem, we first conducted orthogonal cutting experiments on Inconel 718 in a wide range of cutting speeds (20 m/min - 300 m/min) in order to clarify the wear mechanisms of the CBN tool in high speed machining. As a result, it was found that the micro tool surface topography, such as grinding marks on the tool rake face, has a significant impact on the progression of the crater wear of the CBN tool when the cutting speed was increased to over 100 m/min. Based on these results, we prepared several cutting tools with different surface topography and evaluated their cutting performances. The experimental results showed that the polished rake face reduced the initial crater wear by approximately 40 % compared to the non-polished tool.

Keywords: Inconel 718, high speed machining, CBN tool, surface topography, wear

1 Introduction

Inconel 718 is one of the important alloys among the nickel and nickel-based alloy, because it has unique properties such as high oxidation and corrosion resistance even at very high temperatures and retains a high mechanical strength under such conditions as well (Choudhury 1998). Therefore the demand for Inconel 718 has rapidly increased as a material for aviation, turbines and nuclear power plant

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applications. However, Inconel 718 is classified as typical "difficult-to-cut materials" due to its physical properties such as lower thermal conductivity, high tendency to work hardening and high affinity for tool materials (Choudhury 1998; Ezugwu 1999; Ezugwu 2003; Dudzinski 2004; Krämer 2012; Zhu 2013). For this reason, when machining Inconel 718 with a conventional cemented tungsten carbide tool, the cutting speed is restricted to 10-50 m/min (Dudzinski 2004; Krämer 2012). To overcome this situation, various materials have been developed for Inconel 718 machining. Ceramic tools are considered to be suitable for high performance cutting of Inconel 718, and they can increase the cutting speed up to 3 to 5 times compared with a cemented carbide tool (Choudhury 1998; Zhu 2013). More recently, whisker-reinforced alumina (WRA) tools were developed and they showed better cutting performance due to their excellent mechanical properties which result from reinforcement of Al_2O_3 matrix by silicon carbide whiskers (Bushlya 2013). However, these cutting tools are mostly limited to semi-finishing and roughing operations due to their spontaneous failure and less predictable tool life (Choudhury 1998; Dudzinski 2004; Bushlya 2013). Therefore, finishing operations are still performed with carbide tools with low cutting speed, leading to the low productivity and high machining cost (Costes 2007).

Recently, Cubic-Boron-Nitride (CBN) has received a great deal of attention as a material for cutting tools. CBN has high thermal conductivity, high hot-hardness and good thermal stability, and it is one of the hardest materials known after diamond (Lin 1995; Huang 2007). CBN cutting tools are already used, especially in the machining of ferrous materials (Huang 2007; Fallböhmer 2000), and are also considered to be a major candidate for Inconel 718 machining. However, the performances of CBN tools are still insufficient in practical use when considering their extremely high fabrication cost, about ten times the price of conventional carbide tools or ceramic tools (Lin 1995), especially in the case of high speed machining of Inconel 718. In addition, the detailed wear behavior of CBN tools in cutting of Inconel 718 is not sufficiently understood yet (Zhu 2013).

This study has been performed in order to extend the tool life of the CBN tool in high speed machining over 100 m/min of Inconel 718. We conducted orthogonal cutting experiments on Inconel 718 with the CBN tool in a wide range of cutting speeds (20 m/min - 300 m/min) in order to identify the wear mechanisms of the CBN tool in each cutting speed. Based on the results, we focused on the influence of the surface topography of the tool rake face on crater wear, and the relationship between the surface roughness of the rake face and the wear resistance was investigated.

2 Experimental details

The experiments were conducted using a CNC lathe (Mori Seiki Corp., Duraturn 2050) with high CBN content tool (CBN content: 93%, Grain size: 2 μm). The experimental setup is illustrated in Fig. 1. Inconel 718 pipe with thickness of 2 mm was used as a workpiece. Table 1 lists the cutting conditions. The orthogonal cutting experiments were carried out with three different cutting speeds (20, 100, 300 m/min) until cutting length reached 25 m. Soluble type cutting fluid (NEOS Co., Ltd., Finecut 2500) was supplied in all experiments.

Table 1: Cutting conditions

Workpiece	Inconel 718	
Tool geometries	Rake angle Flank angle	5° 6°
Cutting speed	20 m/min 100 m/min 300 m/min	
Feed rate	0.1 mm/rev	
Cutting fluid Supply late	Soluble type (JIS A2) 6.1 L/min	

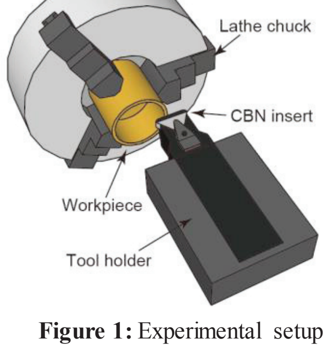


Figure 1: Experimental setup

3 Results and discussion

3.1 Wear mechanism at low cutting speed

Fig. 2 shows 3-D geometries of the rake face of the CBN tool at cutting speed of 20 m/min after cutting for 5, 15 and 25 m, and 2-D profile of the rake face after cutting for 25 m measured by using a two/three-dimensional stylus type profile instrument (Kosaka Lab. Ltd., SE-3500K). As shown in Fig. 2, the workpiece material adhered severely to the tool rake face after cutting for 5 m, and remarkably deep crater wear occurred with progression of the cutting operation. In addition, the 2-D profile shows that the bottom of the crater wear after cutting for 25 m had asperities about the same size as the CBN grains (2 μm). In order to investigate the detailed wear behavior, a cross section of the worn rake face fabricated by using ion milling was observed by scanning electron microscope (SEM: Hitachi Hi-Technologies Corp., TM3000), as shown in Fig. 3. As can be seen from Fig. 4 (a), thick adhesion layer was formed on the tool rake face. In addition, many cracks were observed at the interface between the adhesion layer and the tool substrate (Fig. 4 (b)), indicating that the adhesion layer is unstable and repeats falling and reformation during the cutting process, as well known in general. Moreover, some areas that cracks penetrated into the tool substrate were also observed, as shown in Fig. 4 (c), and this is considered to be a major factor of the progression of the severe crater wear.

From these results, the wear mechanism of the CBN tool at low cutting speed can be considered as illustrated in Fig. 5. First, significant adhesion occurs on the tool rake face in the early stage of cutting (Fig. 5 (a)), then, cracks are generated and advance into tool substrate due to the chip flow (Fig. 5 (b)). Finally, the tool substrate is flaked when the adhesion layer is removed (Fig. 5 (c)). Moreover, Fig. 6 shows the SEM image of the rake face after cutting for 25m, and severe adhesion was observed at the bottom of the crater wear. This result indicates that the crater wear at low cutting speed progresses by the cycle of the adhesions of workpiece material and their removals.

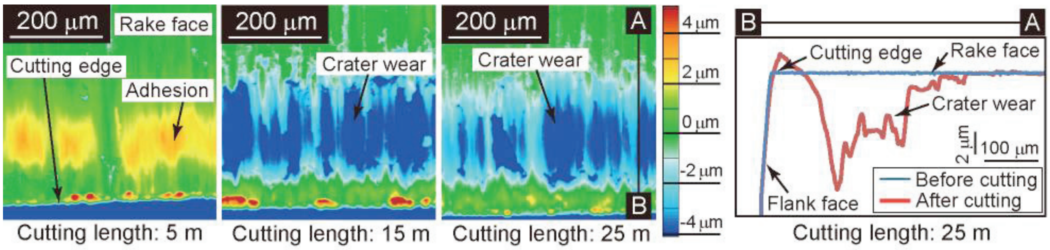


Figure 2: 3-D and 2-D geometries of rake face of CBN tool after cutting for 5, 15, 25 m

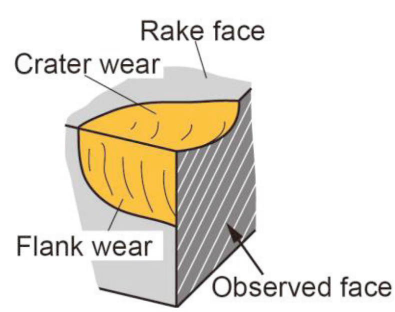


Figure 3: Cross section observation

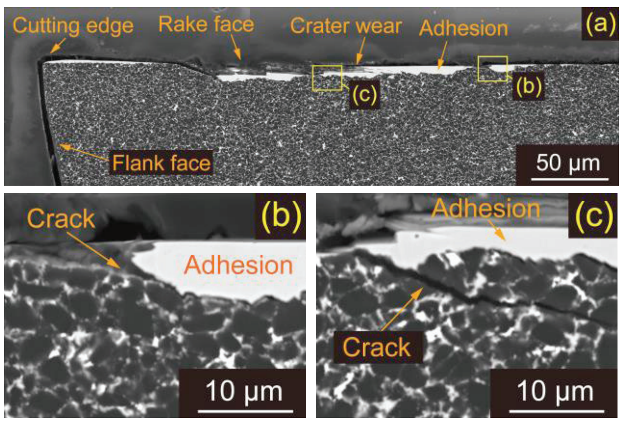


Figure 4: SEM images of CBN tool after low speed machining

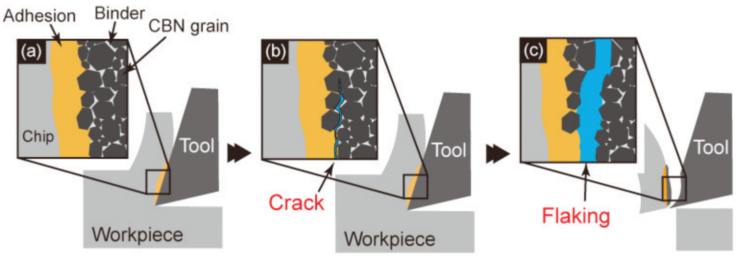


Figure 5: Mechanism of crater wear progress in low speed cutting

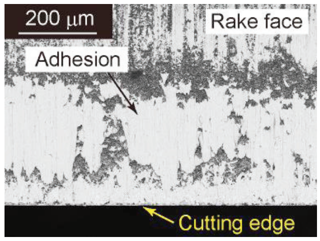
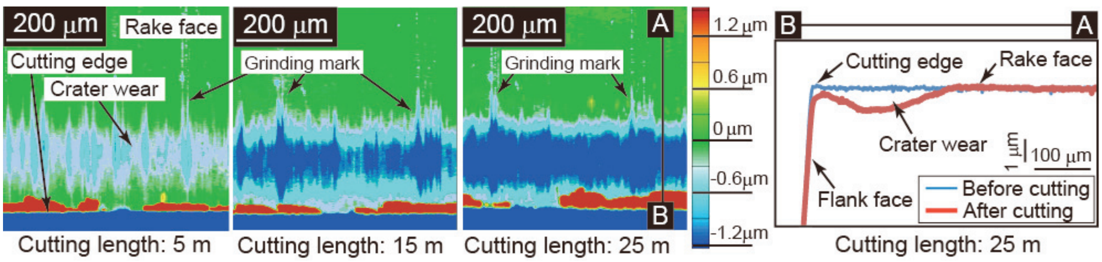


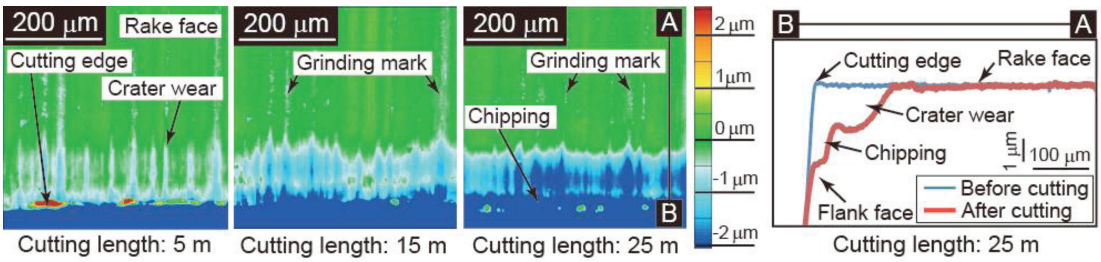
Figure 6: SEM image of rake face after cutting (20 m/min)

3.2 Wear mechanism at high cutting speed

Fig. 7 shows 3-D and 2-D geometries of the tool rake face at cutting speed of 100 and 300 m/min, respectively. Different contour interval is used in each figure, because the wear rates were quite different from one another. As shown in this figure, the crater wear was progressed proportionally to the cutting length at cutting speed of 100 and 300 m/min. In addition, Fig. 8 indicates the SEM images of the cross section at cutting speed of 100 m/min after cutting for 25 m. In contrast to the results at the low cutting speed, adhesion layer was disappeared in high speed machining (Fig. 8 (a)). This is because cutting temperature at tool-chip interface was elevated over recrystallization temperature of workpiece material at high cutting speed. In addition, Fig. 8 (b) shows that the surface of the cutting tool became smooth, indicating that CBN grains themselves were worn. Moreover, in order to quantify the diffused area on the tool rake face, cross section analyses of the tool have been made by EDX (Bruker corp., Quantax 70), as shown in Fig. 9. Line analyses of EDX were conducted and plotted along the dot-lines in the left SEM images. As can be seen in this figure, although no elements from Inconel 718 was detected from the CBN area at the cutting speed of 20 m/min (Fig. 9 (a)), both Ni (base material of Inconel 718) and N (base material of CBN) were detected in the boundary zone between the tool substrate and adhesion,



(a) Cutting speed: 100 m/min



(b) Cutting speed: 300 m/min

Figure 7: 3-D and 2-D geometries of rake face of CBN tool after cutting for 5, 15, 25 m

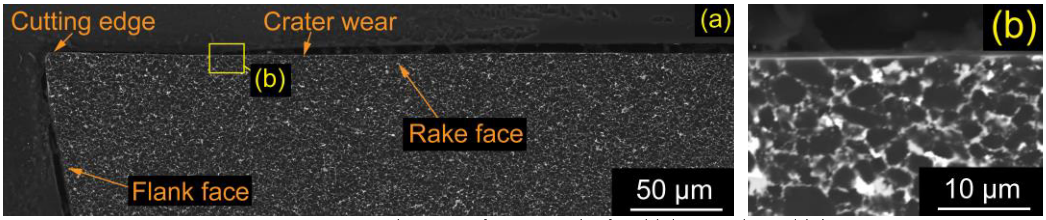
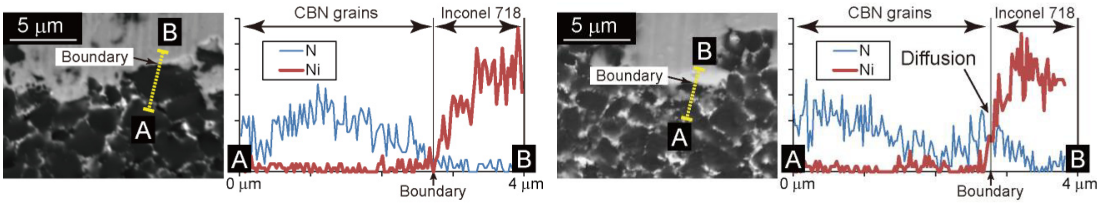


Figure 8: SEM images of CBN tool after high speed machining



(a) Cutting speed: 20 m/min (b) Cutting speed: 100 m/min

Figure 9: Line analyses of EDX

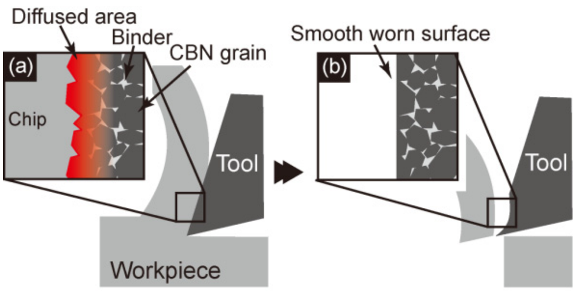


Figure 10: Mechanism of crater wear progress in high speed machining

and the elements from workpiece material seem to diffuse into the CBN grains and vice versa, under the high speed machining condition (Fig. 9 (b)). These results clearly indicate that the wear mechanisms of CBN tool completely changed depending on the cutting speed, and the diffusion due to the high cutting temperature is dominant factor for promoting the crater wear at higher cutting speeds, as illustrated in Fig. 10.

At cutting speed of 300 m/min (Fig. 7 (b)), the crater wear was progressed in the same way at 100 m/min, although the wear rate was higher. In addition, cutting edge chipping was observed at this cutting speed, and this is because the higher cutting temperature made the cutting edge weak and led the chipping, while it is easy to prevent the chippings by chamfering the cutting edge.

3.3 Influence of micro tool surface topography on crater wear

As described above, it is considered that the problem of high speed machining of Inconel 718 with the CBN tool is the thermal wear led by the high cutting temperature and the diffusion of workpiece material rather than the mechanical wear. Now, as indicated by arrows in Fig. 7, at cutting speed of over 100 m/min, it was observed that significant crater wear occurred locally at grinding marks that were generated when the tools were fabricated. Then, the worn rake face after cutting for 25 m at 100 m/min was observed in detail by SEM (Fig. 11), and the result indicates that workpiece material adhered strongly inside the grinding marks. From these results, it is supposed that the micro asperities on the tool rake face, such as grinding marks, promoted the adhesion of Inconel 718, and the adhesion subsequently accelerated the diffusion between the workpiece material and the CBN tool. As a result, significant crater wear occurred locally in the region of grinding marks on the tool rake face.

Based on the hypothesis as described in the previous chapter, additional experiments were carried out with two CBN tools which have different surface roughness of the rake face, in order to investigate the influence of micro surface topography of tool rake face on the wear resistance. The composition of these CBN tools was same as the CBN tool (Normal tool) which was used in the previous experiments. A CBN tool (Ground tool) finished with a #800 grinding wheel has a smoother rake face compared to Normal tool, and the other CBN tool (Polished tool) was polished to a mirror surface without the grinding marks. Table 2 lists the surface roughness of the each CBN tool rake face (Ra: arithmetical mean deviation, Rz: ten-point average roughness). The experiments were carried out only at cutting speed of 100 m/min. The other cutting conditions were the same as those of listed in Table 1.

Fig. 12 shows the changes of the rake faces of Ground tool and Polished tool. In contrast to the result of Normal tool (Fig. 7 (a)), the significant local wear was not observed on the rake face of Ground tool and Polished tool, and their rake faces suppressed the crater wear compared to Normal tool. Moreover, Fig. 13 shows the changes in the maximum depth of crater wear with cutting length, and Fig.14 shows the relationship between the surface roughness (Rz) of the tool rake face and the amount of the crater wear after cutting for 25 m. In these figure, the maximum depth of the crater wear means the biggest difference between the surface topography of virgin tool rake face and that of worn rake face.

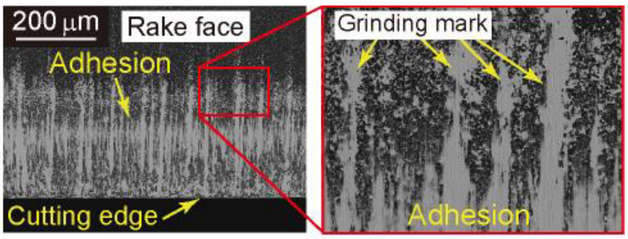
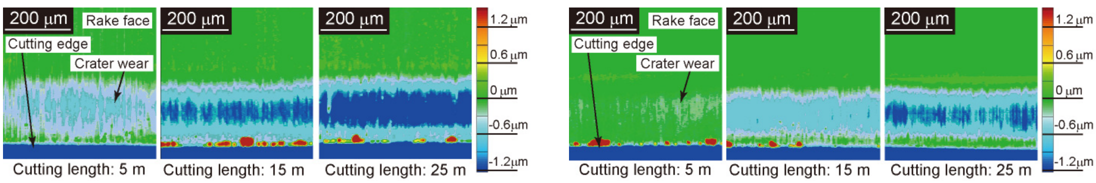


Figure 11: SEM image of rake face around grinding marks after cutting for 25 m at cutting speed of 100 m/min

Table 2: Surface characteristics of prepared CBN tools

	Roughness of rake face	
	nmRa	nmRz
Normal tool	100	578
Ground tool	54	260
Polished tool	~5	22



(a) Ground tool (b) Polished tool

Figure 12: 3-D geometries of rake face of each CBN cutting tool at cutting speed of 100 m/min

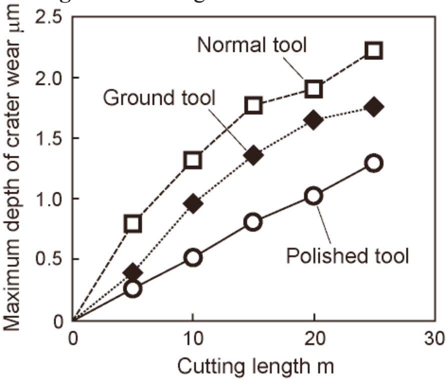


Figure 13: Variation of maximum depth of crater wear with cutting length

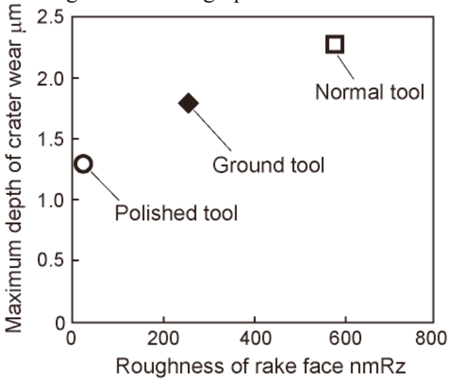


Figure 14: Relationship between roughness of rake face (Rz) and Maximum depth of crater wear

As shown in these figures, it was confirmed that the smoother rake face significantly suppressed the progress of crater wear, indicating that the crater wear resistance has a strong correlation with the surface roughness of tool rake face.

Although it has been recognized that a polished tool surface improves the tribological behavior in metal cutting, the advantages of the smooth surface are mainly explained as resulting from the effects of reducing friction (Yamaguchi 2012) and build up layer formation (Fallqvist 2013). On the other hand, in high speed machining of Inconel 718, the smooth surface on the CBN tool rake face exerts not only above-mentioned effects, but also prevents the local adhesion and the corresponding crater wear. These results suggest that a smoothing of tool surface is especially effective for improving the life of CBN tools in the application of high speed machining of Inconel 718.

4 Conclusions

In this study, high speed machining of Inconel 718 using CBN cutting tools have been studied to clarify the detail wear mechanism and extend the life of cutting tools, with the following findings:

(1) At low cutting speed, the crater wear progresses by the cycle of adhesions of workpiece material and their removals, and severe crater wear occurs by flaking tool substrate when the adhesion is removed.

(2) At cutting speed of over 100 m/min, diffusion due to high cutting temperature is dominant factor for promoting crater wear, and the crater wear progresses proportionally to the cutting length.

(3) In high speed machining of Inconel 718, micro surface topography of CBN tool, such as grinding marks, has a strong correlation with the crater wear resistance. Experimental results clearly showed that a smoothing of tool surface is especially effective for extending the life of CBN tools in high speed machining of Inconel 718.

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