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Damage of physical vapor deposition coatings of cutting tools during alloy 718 turning

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ABSTRACT

Ni-based superalloys are typically difficult-to-cut materials. Therefore, the lifespan of cutting tools used to cut these materials is shorter than that of tools used on other materials. This study develops a new coating for cutting tools that has properties required for the turning of Ni-based superalloys. This study examined the cutting performance of TiN-coated cutting tools deposited by arc ion plating according to the damage of the coating and determination of the required properties of the coatings. To evaluate cutting tool damage, many analysis methods were used at each step of damage accumulation. Plastic deformation of the coating was observed at rake and flank face edges by scanning ion microscopy and transmission electron microscopy (TEM). Furthermore, the fracture of the coating near the surface defects (e.g., droplets, voids) was due to the interaction between the work material and surface defects. Moreover, using electron probe microanalysis, scanning auger microscopy, and TEM, the work material was confirmed to adhere to the cutting edge physically or mechanically, not chemically. This means that oxidation and diffusion did not occur in the interface between the adhesive material and coating after cutting. Finally, the effectiveness of different coating types, varying in both composition and deposition method, was verified by evaluating the effect of damage reduction. Using coatings with greater stability at high temperatures and fewer defects can reduce damage of the coated cutting tools, increasing tool lifespan.

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1. Introduction

Ni-based superalloys are typically difficult-to-cut materials. Therefore, the lifespan of cutting tools used for these superalloys is shorter than that of tools used for other materials. When cutting such difficult-to-cut materials, hardmetal possessing high thermal conductivity and high-temperature strength is required as the cutting tool material, and it is necessary to relax cutting conditions [1–4]. For optimal cutting conditions when processing such difficult-to-cut materials, a study that focuses on cutting temperature during machining can be leveraged [5]. Moreover, because of high-speed and high-efficiency machining desirability, a proposed processing method that applies a high-pressure coolant and CNC Lathe with high rigidity has been studied [6]. A phenomenon occurs in the cutting edge during cutting where the strong adhesion of the work material to the edge decreases; this results in the adhesive wear of the cutting edge [7–9]. Furthermore, when these superalloys are cut using uncoated tools, damage results from diffusion wear [10]. Even when using coated hardmetal tools to prevent such damage, the coating peels early during the abovementioned separation of the adhesive material. Therefore, improving the tool lifespan is difficult [11–13]. By performing analysis on the outflow direction of the chips, friction force, and observation of tool damage after cutting, the damage mechanism of the adhesive wear occurring between the tool and workpiece has been reported [14–17]. However, numerical data of existing reports are minimal; thus, whether the initial damage forms in all cases or is a factor of a particular coating is unclear. By identifying contributing factors for understanding the tool damage mechanism, the selection of optimal coating material with required properties for machining alloy 718 and cutting conditions of long-lifespan tools is reasonably achievable. In past studies, improved low friction and high-temperature strength of

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the coating were found to be effective in tool damage reduction during intermittent cutting of alloy 718 [17].

In this study, the damage of physical vapor deposition (PVD) coated cutting tools, especially the damage to the coating used for turning alloy 718, a typical Ni-based superalloy, is observed in detail. First, hardmetal turning inserts were coated with single layer titanium nitride (TiN) coatings. The morphologies of the damage of the cutting edges were observed for the surface and cross section of the inserts. Moreover, the distribution and composition of the adhesive materials on the tool surface are examined, particularly focusing on the damage morphology and interface state between the adhesion products and coating. From detailed observation and analysis of the cross section of the tool cutting edge, the damage factor is discussed. On the basis of these results, a model of the damage mechanism of PVD coating while machining alloy 718 is proposed and verified. Finally, the optimal coating material for damage suppression is proposed.

2. Experimental details

2.1. Cutting conditions

Alloy 718 with aging treatment and 440-HV hardness was used as the work material. The workpiece is cylindrical with 100 mm diameter. The tool is the turning insert CNMG 120408 with a breaker and a rake angle of 13°. Roundness of the cutting edge was about 30 μm. Inserts were set on a tool holder having a seating surface with an approach angle of −5°, front clearance angle of 6°, and side clearance angle of 6°. Therefore, the real rake angle after mounting is about 7°. The tool material is hardmetal (tungsten carbide (WC) – 6 mass% Co–Cr dope) K05 in accordance with JIS standards. The surface was coated using TiN with 3 μm thickness. These coatings were deposited by PVD cathodic arc ion plating (Arc). The coating method, hereafter referred to as TiN-Arc, is a combination of the coat composition and deposition method. CNC Lathe SL-25 (Mori Seiki Co., Ltd.) was used for the cutting test, and the outer diameter was cut. Cutting conditions were as follows: cutting speed Vc = 30 m/min, feed speed $f = 0.2$ mm/rev, cutting depth $d = 0.5$ mm, and wet conditions. Emulsion cutting oil (Blaser SWISLUBE made; Vasco 1000) was used after diluting. The cutting tool damage was observed after four cutting lengths (cutting length $L = 1, 10, 50, 200$ m).

2.2. Observation and analysis of damage

After the turning test, the cutting tool damage was observed by scanning electron microscopy (SEM) and backscattered electron imaging (BEI) of the surface. Electron probe microanalysis/wavelength-dispersive X-ray spectrometry (EPMA/WDS) was used to investigate the distribution and components of adhesive products. Because of the enrichment of oxygen and specific elements at the interface between the adhesion material and coating, component analysis was performed in the depth direction by scanning auger microscopy (SAM). A focused ion beam (FIB) was used to prepare sample cross sections of the damaged portions of the coating, and these cross sections were observed in detail by scanning ion microscopy (SIM). Electron backscatter diffraction (EBSD) was used to analyze the orientation of columnar crystals of the coating. Transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) were performed at high magnification. TEM was used to observe the crystalline morphology of the coating material and evaluate the interface of the adhesion state in the adhesive material. The contrast in the STEM image was influenced by the composition of the material. Table 1 shows the analysis conditions.

Table 1
List of characterization methods used.

Method	Device name	Analytical conditions
SEM	Hitachi, N3500	Acceleration voltage: 15 kV
EPMA/ WDS	JEOL, JXA-8500F	Quantitative analysis Acceleration voltage: 15 kV Probe current: 0.05 μA Beam diameter: 0.5 μm Area analysis Acceleration voltage: 15 kV Probe current: 0.3 μA Beam diameter, rake face: 5 μm flank face: 2 μm
SAM	PHI, SMART200	Acceleration voltage: 10 kV Probe current: 0.01 μA Beam diameter: <0.1 μm Scan area: 20 μm × 20 μm Etching rate: 500 Å/min (SiO_2 conversion)
FIB/SIM	Hitachi, FB2100	Ion beam processing Acceleration voltage: 40 kV Probe current: 1.6, 40 nA SIM observation Acceleration voltage: 40 kV Probe current: 0.02 nA Beam diameter: <5 nm
SEM/EBSD	Hitachi, SU-70 OXFORD, HKL Channel5	Acceleration voltage: 15 kV Step: 0.02 μm, 150 × 300 points
TEM/STEM/ EDS	JEOL, JEM-2010F	Selected-area diffraction (SAD) Nano beam diffraction (NBD) Accelerating voltage: 200 kV Diffraction area: SAD 140 nm NDB <3 nm Energy dispersive X-ray spectrometry (EDS) Accelerating voltage: 200 kV Beam diameter: 1 nm

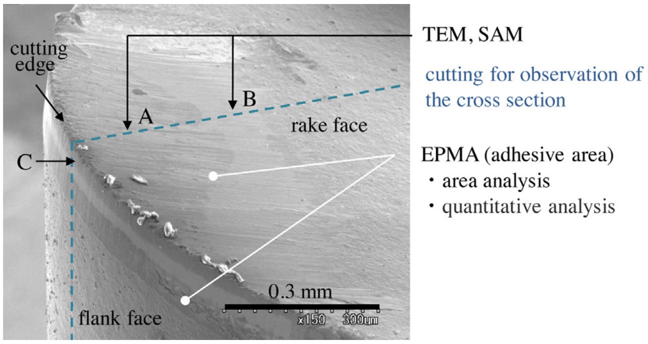

Fig. 1. Analysis point of the cutting tool after turning alloy 718.

Fig. 1 shows the SEM image of the tool edge after machining and the positions where various analyses were performed.

3. Results and discussion

3.1. Observation of lesion surface morphology

Fig. 2 shows the relation between the cutting length and maximum flank wear width. Comparison results of TiN-coated hardmetal tools and uncoated carbide tools show that the maximum flank wear width after cutting 200 m is the same and tool damage patterns are similar. Thus, the coating did not perform the function of protecting the tool and showed no mitigation to the effects of increasing tool wear.

Fig. 3 shows SEM images of the cutting edges after cutting alloy 718 at several cutting lengths. At 1 m cutting length, the

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