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Cutting characteristics of PVD-coated tools deposited by filtered arc deposition (FAD) method

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ABSTRACT

The cutting characteristics of novel physical vapor deposition (PVD)-coated tools deposited using filtered arc deposition (FAD) method are investigated. The TiCN-coated films are extremely smooth without any droplets. They exhibit superior hardness and adherence and a favorable cutting performance for the high-speed milling of a prehardened stainless steel. The availability of a newly proposed VN film is also examined. Owing to the good lubrication and tribological properties of the VN coating film, the lower cutting force, flank wear with, and cutting temperature than those of the TiN-coated tool are obtained in milling of the prehardened steel.

1. Introduction

In the aerospace and power-generating industries, difficult-to-machine materials, such as titanium and nickel-base alloys, are widely used. Therefore, a highly efficient machining process is required. Because of their characteristics, such as low thermal conductivity, high work hardening, and high affinity to cutting tools, the tool life is very short, as the cutting force and tool temperature become very high. Therefore, it is common to use appropriate coating tools on which various types of hard materials are deposited.

Typical hard coating films for cutting difficult-to-machine materials include physical vapor deposition (PVD)-coated TiCN, TiAlN, and/or AlCrN films [1,2]. These films are deposited using either arc ion plating (AIP) method or hollow cathode discharge (HCD) process. In the AIP method, the evaporated and ionized target materials obtained using vacuum arc discharge are deposited on the substrate. Thus, a good adhesion strength can be obtained. However, the AIP method has a disadvantage in that droplets are formed in the cathodic arc jets, thereby deteriorating coating film properties such as smoothness and machined surface roughness. In contrast, in the HCD method, the ionized target metal obtained using electron beam irradiation helps in achieving a smooth coating film surface without any droplets [3]. However, this method has a disadvantage in that the obtained adhesion strength is relatively low. In another study, extremely smooth coated tools have been developed using an unbalanced magnetron sputtering (UBMS) method [4]. However, they are practically inapplicable to high-load machining.

In this study, two new types of coated films are formed using filtered arc deposition (FAD) method [5,6], and are applied to the high-speed milling of a prehardened stainless steel. In the FAD method, the filtered arc source makes it possible to capture the droplets as neutral particles on the baffles, as shown in Fig. 1, whereas the plasma flow is deflected toward the substrate. The coated tools are designed to reduce the cutting force and cutting temperature owing to the smooth surface and low friction coefficient. In this paper, the physical properties of TiCN-coated films deposited using the FAD method under various coating conditions are reported. The coated films were examined in terms

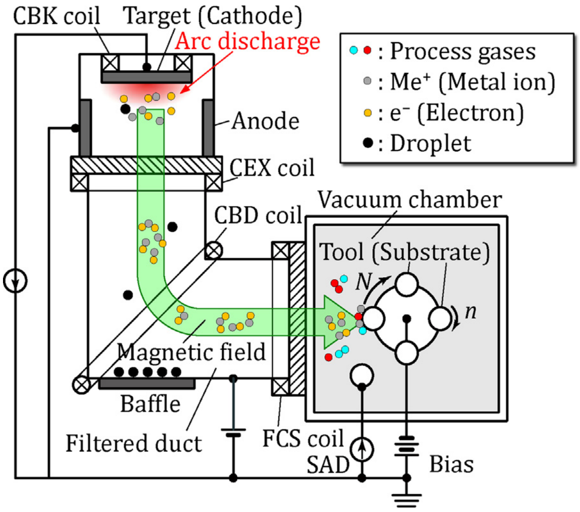

Fig. 1. FAD (filtered arc deposition) coating device.

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of the cutting performance for the high-speed dry milling of a prehardened steel. The cutting performances of the films were then compared to those of the AIP-coated and HCD-coated films.

Furthermore, a VN-coated end mill is developed and is applied to the high-speed milling of a prehardened steel. This film has a low friction coefficient at temperatures above 500 °C [7,8].

2. Filtered arc deposition (FAD) coating method

Fig. 1 shows the schematic of the FAD coating system. In the FAD method, arc discharge occurs between a target (cathode) and an anode, and the target metal is evaporated and ionized. A set of scanning magnetic coils (CEX, CBD, and FCS, as shown in Fig. 1) allows the ion plasma jet to be swept in the vertical direction in order to impinge on the substrate in the vacuum chamber. When N_2 and CH_4 gases are introduced in the chamber, the ionized metal vapor reacts with nitrogen and/or carbon to form a metal–carbide–nitride film on the negatively biased substrate. Because of the high ionization ratio (30–80%) of the evaporated materials, the deposited film exhibits a high density and a good adhesion strength [5]. On the other hand, the unevaporated droplets as neutral particles move straight and are captured by the baffles, as shown in Fig. 1. Thus, an extremely smooth coating film surface can be obtained. To compare the characteristics of the coating film with those of the commercially available one, the well-known TiCN-coated films are formed on the tungsten carbide substrate.

3. TiCN-coated film

3.1. Deposition of coating films

Table 1 lists the coating conditions of the TiCN film. Here, the TiN film is deposited between the substrate (superfine cemented carbide) and the TiCN film in order to improve the adhesion strength. Based on the previous results of the TiN coating, only the CH_4 flow rate is varied, from 5 to 20 cc/min while maintaining a constant bias voltage (−50 V) and N_2 flow rate (20 cc/min), as listed in Table 1. Six types of FAD-coated carbide, AIP-coated, and HCD-coated samples are prepared, as listed in Table 2. The coating time ratio, which is equivalent to the film thickness ratio, of TiN to TiCN is 1/11 for specimens 1–4, whereas it is 1/1 for specimens 5 and 6. The ratio for specimens 5 and 6 is selected based on the commercially available tool, and the carbon content is gradually increased within the TiN/TiCN boundary layer.

Table 1
Coating conditions of TiN/TiCN film.

Coating materials	TiN/TiCN	VN	TiN
Coating method	FAD	AIP	
Coating time t_c [min]	120	60	
Bias voltage e_b [−V]	50	100	
Duct voltage e_d [V]	15	–	–
Coating temperature T [°C]	350	350	
Bombardment time t_b [min]	10	10	
N_2 flow rate f_{rN2} [cc/min]	20	10–60	20
CH_4 flow rate f_{rCH4} [cc/min]	5–30	–	–
Specimen (substrate)	Superfine cemented carbide		

Table 2
Eight types of TiCN-coated-carbide samples.

Process	No.	CH_4 flow rate f_{rCH4} [cc/min]	Arc discharge time ratio TiN/TiCN	Film thickness t_f [μm]
FAD	1	5	1/11	2.09
	2	10	1/11	2.16
	3	15	1/11	2.44
	4	20	1/11	2.81
	5	5	1/1	1.97
	6	10	1/1	1.98
HCD	7	–	–	2.36
AIP	8	–	–	3.08

HCD: hollow cathode discharge, AIP: arc ion plating.

3.2. Mechanical properties of TiCN-coated films

As listed in Table 2, the film thickness increases with the increase in the CH_4 flow rate, whereas it remains at approximately 2 μm, which is the target value, at low CH_4 flow rates (specimen Nos. 1, 2, 5, and 6). It is believed that a non-metallic compound is incorporated into the film because of the chemical reaction between N_2 and CH_4 at higher CH_4 flow rates.

Fig. 2 shows the typical 3D profiles of the coated film surface. The profile of No. 6 is almost same as that of No. 5. As shown in the figure, the AIP-coated film has many lugs and pinholes, because the droplets are emitted from the target metal during the arc discharge process. On the other hand, the FAD-coated and HCD-coated films are extremely smooth with fewer droplets. However, in the FAD method, a small number of particles appear when the CH_4 flow rate is high (Nos. 3 and 4).

Fig. 3 shows the variations in the hardness H_{IT}, residual stress σ_r, and critical scratch load P_c with respect to the CH_4 flow rate. Here the hardness H_{IT} of the thin film is measured by the nanoindentation tester (Fischer Instruments Co., Ltd.: H100) using a Berkovich indenter, and is characterized by the mean contact pressure based on the force–displacement curve in a quasistatic indentation testing. The residual stress σ_r is determined by the Stoney formula, where a TiCN coating was deposited on a stainless sheet and the radius of curvature was measured, before and after coating by the stylus profilometer. The film hardness, which is correlated with the residual stress, decreases with the increase in the CH_4 flow rate, and the adhesion strengths at fr_{CH4} = 15 and 20 cc/min are low. This is because the ratio of the compound, which is chemically unbound to Ti, increases. Compared to the commercially available AIP-coated and HCD-coated films, the adhesion strength is improved at fr_{CH4} = 5 and 10 cc/min, particularly for specimen Nos. 5 and 6.

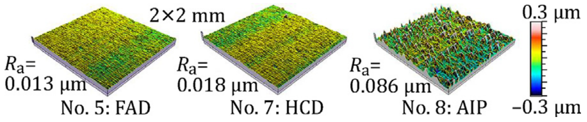

Fig. 2. Typical 3D profiles of TiCN-coated film surface.

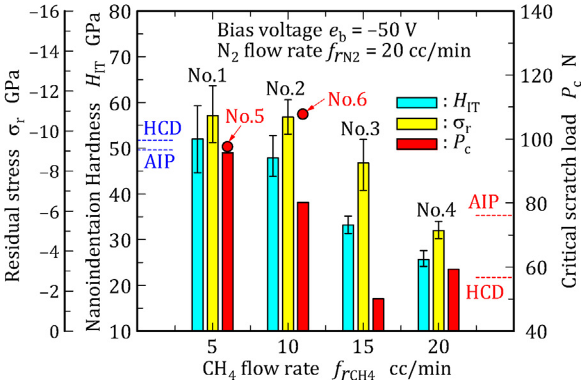

Fig. 3. Variation of nanoindentation hardness, residual stress and critical scratch load of TiCN coating film with CH_4 flow rate.

4. End milling with TiCN-coated tools

4.1. Experimental procedure

Dry side milling tests on a prehardened stainless steel (JIS SUS420J2/ISO X30Cr13) are carried out using TiCN-coated carbide end mills with the help of a vertical machining center (DMG-MORI: NVD1500DCG), as shown in Fig. 4. The FAD-coated and TiCN-coated tools, indicated as Nos. 5 and 6, respectively, as listed in Table 2, are chosen because of their good mechanical properties. In addition, the HCD-coated and AIP-coated tools are used. Table 3 lists the cutting conditions.

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