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Tool Wear of Titanium/Tungsten/Silicon/Aluminum-based-coated end Mill Cutters in Millin Hardened Steel

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***Abstract*—**In turning hardened steel, polycrystalline cubic boron nitride (cBN) compacts are widely used, due to their higher hardness and higher thermal conductivity. However, in milling hardened steel, fracture of cBN cutting tools readily occurs because they have poor fracture toughness. Therefore, coated cemented carbide tools, which have good fracture toughness and wear resistance, are generally widely used. In this study, hardened steel (ASTM D2, JIS SKD11, 60HRC) was milled with three physical vapor deposition (PVD)-coated cemented carbide end mill cutters in order to determine effective tool materials for cutting hardened steel at high cutting speeds. The coating films used were (Ti,W)N/(Ti,W,Si)N and (Ti,W)N/(Ti,W,Si,Al)N coating films. (Ti,W,Si,Al)N is a new type of coating film. The inner layer of the (Ti,W)N/(Ti,W,Si)N and (Ti,W)N/(Ti,W,Si,Al)N coating system is (Ti,W)N coating film, and the outer layer is (Ti,W,Si)N and (Ti,W,Si,Al)N coating films, respectively. Furthermore, commercial (Ti,Al)N-based coating film was also used. The following results were obtained: (1) In milling hardened steel at a cutting speed of 3.33 m/s, the tool wear width of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool was smaller than that of the (Ti,W)N/(Ti,W,Si)N-coated tool. And, compared with the commercial (Ti,Al)N, the tool wear width of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool was smaller than that of the (Ti,Al)N-coated tool. (2) The tool wear of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool increased with an increase in cutting speed. (3) The (Ti,W)N/(Ti,W,Si,Al)N-coated cemented carbide was an effective tool material for high-speed cutting below a cutting speed of 3.33 m/s.

***Keywords*—**cutting, physical vapor deposition (PVD) coating system, hardened steel, tool wear

I. Introduction

Hardened steels used for dies or molds are widely cut as a substitute for grinding. Polycrystalline cubic boron nitride (cBN) compact tools are used for cutting hardened steels, due to their higher hardness and higher thermal conductivity. However, in milling, major tool failure of cBN readily occurs by fracture because cBN has poor fracture toughness. Coated cemented carbide is an effective tool material for milling hardened steels because it has good fracture toughness and wear resistance. The physical vapor deposition (PVD) method is a widely used coating technology because of its lower treatment temperature, namely 470 K -870 K [1].

Recently, it has become possible to cut hardened steels with (Ti,Al)N-coated cutting tools. However, as machine parts are often cut at higher cutting speeds for mass production, tool materials must have excellent fracture toughness and wear resistance. A titanium/tungsten-based coating film, namely (Ti,W)N coating film, has been developed [2]. Titanium/tungsten-based coating film exhibits a superior critical scratch load.

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Moreover, the titanium/tungsten-based-coated tool was evaluated through machining of low-carbon steel AISI 5120H, and showed greatly improved performance [2]. However, the hardness of the (Ti,W)N coating film was lower than that of the (Ti,Al)N coating film. So, a (Ti,W,Si)N coating film, which is a titanium/tungsten/silicon-based coating film, has been developed [3].

This titanium/tungsten/silicon-based coating film exhibits both superior critical scratch load and hardness compared with TiN/(Ti,Al)N coating film. In cutting AISI 5120H, the wear progress of the (Ti,W,Si)N-coated cemented carbide tool is slower than that of the TiN- and (Ti, Al)N-coated tools [3]. Therefore, titanium/tungsten/silicon coating is an effective tool material because it has good wear resistance.

Furthermore, new titanium/tungsten/silicon/aluminum-based coating films, namely (Ti,W,Si,Al)N, (Ti,W,Si,Al)C, and (Ti,W,Si,Al)(C,N) coating film, have been developed [4]. However, it is not clear whether these coating films are effective tool materials for milling hardened steel.

In this study, hardened steel was milled with three physical vapor deposition (PVD)-coated cemented carbide end mill cutters in order to clarify effective tool materials for cutting hardened steel at high cutting speeds. The coating films used were (Ti,Al)N, (Ti,W)N/(Ti,W,Si)N, and (Ti,W)N/(Ti,W,Si,Al)N coating film. The tool wear was experimentally investigated.

II. Experimental Procedures

The work material used was hardened steel (AISI D2, 60HRC). The chemical composition of the hardened steel is shown in Table 1. The tool material of the substrate was cemented carbide, and three types of PVD-coated cemented carbide were used as shown in Table 2. Namely, the coating films used were (Ti,W)N/(Ti,W,Si)N and (Ti,W)N/(Ti,W,Si,Al)N coating film. (Ti,W,Si,Al)N is a new type of coating film. (Ti,W)N/(Ti,W,Si)N and (Ti,W)N/(Ti,W,Si,Al)N comprise a multilayer coating system.

The inner layer of the (Ti,W)N/(Ti,W,Si)N and (Ti,W)N/(Ti,W,Si,Al)N coating system is (Ti,W)N coating film, and the outer layer is (Ti,W,Si)N and (Ti,W,Si,Al)N coating films, respectively. Furthermore, commercial (Ti,Al)N-based coating film was also used as the (Ti,Al)N.

Figure 1 shows a schematic view of milling. Milling tests were conducted on a horizontal machining center (Type A55, Makino Milling Machine Co., Ltd.). The driving power of this machining center is 18.5/22 kW and the maximum rotational speed is 20000 min^{-1}. Hardened steel was milled under the cutting conditions shown in Table 3.

TABLE I
CHEMICAL COMPOSITION OF THE WORKPIECE (AISI D2, 60HRC) (mass %)

C	Cr	Mo	Mn	Si	V
1.47	11.5	0.82	0.37	0.32	0.20

TABLE III
CUTTING CONDITIONS OF THE MILLING TEST

Cutting speed	V=1.67, 2.50, 3.33, 4.17, 5.00 m/s
Feed rate	f=0.05 mm/tooth
Cutting direction	Downcut
Radial depth of cut	Rd=0.1 mm
Axial depth of cut	Ad=10 mm
Cutting tool	Diameter : 10 mm Number of tooth : 6 flutes Helix angle : 45° Flute length : 25 mm
Cutting method	Dry (Air blowing)

TABLE II
TOOL MATERIAL IN TURNING OF AISI D2

Tool type	Tool material
Coated tool	Substrate: K10 Coating layer: (Ti,Al)N, (Ti,W)N/(Ti,W,Si)N, (Ti,W)N/(Ti,W,Si,Al)N

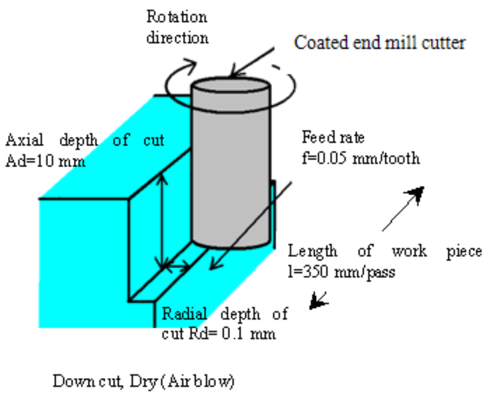


Fig. 1 Schematic view of the milling test

The tool wear of the three kinds of end milling cutter was investigated.

III. RESULTS AND DISCUSSION

The hardened steel was milled with three kinds of coated end mill cutter at a cutting speed of 3.33 m/s. Figure 2 shows the tool wear. In this figure, area "A" shows the rake face in the corner, area "B" shows the flank face in the corner, area "C" shows the rake face at the boundary of the cut depth, and area "D" shows the flank face at the boundary of the cut depth. In the case of the (Ti,W)N/(Ti,W,Si)N-coated end mill cutter, a failure similar to flaking can be seen on the rake face in the cutting corner as shown in Figure (a). However, in the case of the (Ti,W)N/(Ti,W,Si,Al)N- and the (Ti,Al)N-coated end mill cutters shown in Figure (b) and Figure (c), respectively, there is no remarkable failure such as flaking of the rake face in the cutting corner. And the tool wear patterns at cutting speeds of 1.67 m/s and 2.50 m/s, whose figures are not shown here, were similar to the tool wear at a cutting speed of 3.33 m/s as shown in Figure (b). Furthermore, the chips produced in milling were investigated.

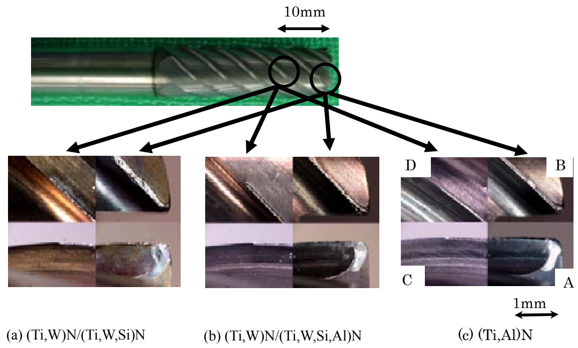


Fig. 2 Tool wear at a cutting speed of 3.33 m/s and a cutting length of 36.4 m

Figure 3 shows the chips obtained from the milling of hardened steel at a cutting speed of 3.33 m/s. In the case of the (Ti,W)N/(Ti,W,Si)N-coated end mill cutter shown in Figure (a), because the color of the chips varies from purple to light blue with the progress of cutting and short segment chips appear, the cutting temperature seems to increase. However, in the case of the (Ti,W)N/(Ti,W,Si,Al)N- and the (Ti,Al)N-coated end mill cutters shown in Figure (b) and (c), respectively, the color of the chips varies from brown to purple with the progress of cutting.

Therefore, in the case of the (Ti,W)N/(Ti,W,Si)N-coated end mill cutter, flaking occurred on the rake face at a higher cutting speed of 3.33 m/s, because the cutting temperature increased. The chips with the (Ti,W)N/(Ti,W,Si,Al)N-coated end mill cutter at cutting speeds of 1.67 m/s and 2.50 m/s, whose figures are not shown here, were similar to the chips at a cutting speed of 3.33 m/s as shown in Figure (b).

Figure 4 shows the tool wear width of the three kinds of coated tool at a cutting speed of 3.33 m/s and a cutting length of 63.4 m. The number of cutting edges of the milling cutter is six. For each cutting edge, the average width of the flank wear-land is the designed "(VB)n" and the maximum width of the flank wear-land is the designed "(VBmax)n." Here, the "n" of the subscript characters shows the number of cutting edges. In Figure 4, "VB" is the average value of each cutting edge and the VBmax is the maximum value of each cutting edge. Both the VB and the VBmax of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool become smaller than those of the (Ti,W)N/(Ti,W,Si)N- and (Ti,Al)N-coated tools.

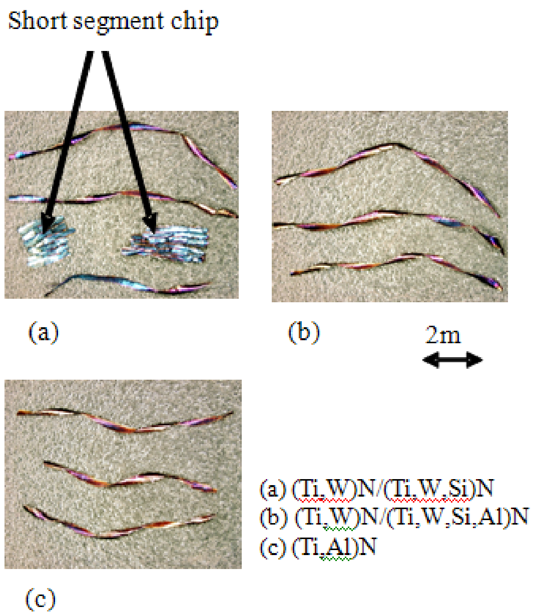


Fig. 3 Chips obtained from the milling of hardened steel at a cutting speed of 3.33 m/s and a cutting length of 36.4 m

The film characteristics were then observed. Table 4 shows the characteristics of the coating films. Both the critical scratch load and the microhardness of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool become larger than those of the (Ti,W)N/(Ti,W,Si)N- and (Ti,Al)N-coated tools. Therefore, it is considered that the tool wear of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool is the smallest because the (Ti,W)N/(Ti,W,Si,Al)N coating film has good wear resistance.

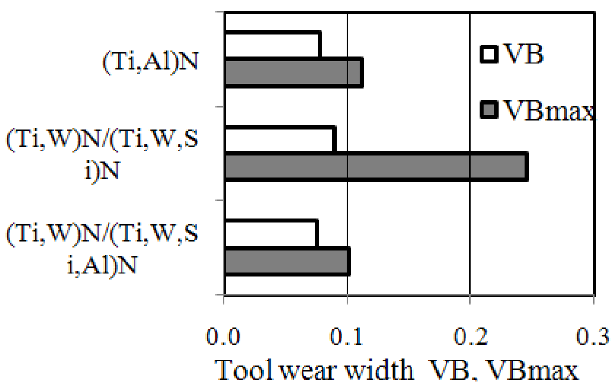


Fig. 4 Tool wear width at a cutting speed of 3.33 m/s and a cutting length of 36.4 m

TABLE IV
CHARACTERISTICS OF THE COATING FILMS

Coating material	Thickness of film (μm)	Critical scratch load* (N)	Microhardness ($HV_{0.25N}$)
(Ti,Al)N	3.0	73	2710
(Ti,W)N /(Ti,W,Si)N	2.5	>100	2800
(Ti,W)N (Ti,W,Si,Al)N	3.5	>100	3200

*: Measured value by scratch test

Fig. 5 shows the influence of the cutting speed on the flank wear width at a cutting length of 63.4 m. Both the VB and the VBmax of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool increase with an increase in cutting speed. Compared with the (Ti,W)N/(Ti,W,Si,Al)N- and the (Ti,W)N/(Ti,W,Si)N-coated tools, both the VB and the VBmax of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool are smaller than those of the (Ti,W)N/(Ti,W,Si)N-coated tool.

Finally, tool wear of the(Ti,W)N/(Ti,W,Si,Al)N-coated tool was observed at higher cutting speeds of 4.17 m/s and 5.00 m/s. Figure 6 shows the tool wear at cutting speeds of 4.17 m/s and 5.00 m/s and a cutting length of 36.4 m. Compared with the tool wear at a cutting speed of 3.33 m/s as shown in Figure 2(b) and the tool wear at cutting speeds of 4.17 and 5.00 m/s, in the case of cutting speeds of 4.17 m/s and 5.00 m/s, a failure similar to flaking is shown on the rake face in the cutting corner as shown in Figure (a) and (b). In this case, the VBmax at cutting speeds of 4.17 m/s and 5.00 m/s was 0.299 mm and 0.305 mm, respectively. Therefore, in milling hardened steel, (Ti,W)N/(Ti,W,Si,Al)N-coated cemented carbide is an effective tool material for high-speed cutting below a cutting speed of 3.33 m/s.

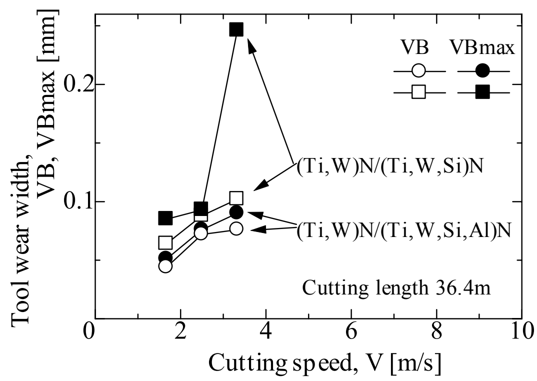
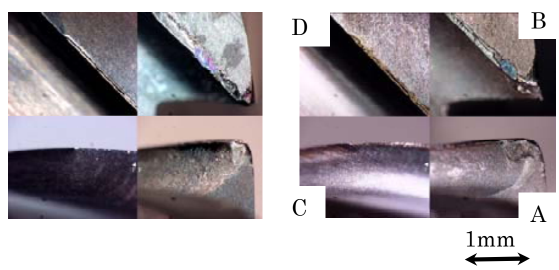


Fig. 5 Relationship between cutting speed and tool wear width at a cutting length of 36.4 m



(a) Cutting speed 4.17 m/s (b) Cutting speed 5.00 m/s
Fig. 6 Tool wear of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool at cutting speeds of 4.17 m/s and 5.00 m/s and a cutting length of 36.4 m

IV. Conclusion

In order to identify an effective tool material for cutting hardened steel (AISI D2, 60HRC), tool wear was experimentally investigated.

The main results obtained are as follows:

- In milling hardened steel at a cutting speed of 3.33 m/s, the tool wear width of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool was smaller than that of the (Ti,W)N/(Ti,W,Si)N-coated tool. And, compared with the commercial (Ti,Al)N, the tool wear width of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool was smaller than that of the (Ti,Al)N-coated tool.
- The tool wear of the (Ti,W)N/(Ti,W,Si,Al)N-coated tool increased with an increase in cutting speed.
- (Ti,W)N/(Ti,W,Si,Al)N-coated cemented carbide was an effective tool material for high-speed cutting below a cutting speed of 3.33 m/s.

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