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Tool Wear of (Ti,W,Si)N-Coated WC-Ni-Based Cemented Carbide in Cutting Hardened Steel

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***Abstract*—**In this study, WC-Ni-based cemented carbides having different nickel contents were used as the substrate for cutting tool materials. Hardened steel was turned by a (Ti,W,Si)N-coated WC-Ni-based cemented carbide tool, and the tool wear was experimentally investigated. The following results were obtained: (1) In the (Ti,W,Si)N-coated WC-Ni-based cemented carbide, the hardness of the coating film was not much different from the content of the binding material, Ni, and the adhesion strength increased with a decrease in Ni content. (2) There is little difference between the wear progress of the (Ti,W,Si)N-coated WC-7%Ni-based cemented carbide tool and that of the (Ti,W,Si)N-coated WC-6%Co-based cemented carbide tool. (3) The wear progress of the (Ti,W,Si)N-coated WC-Ni-based cemented carbide became slower with a decrease in Ni content.

From the above, it is has become clear that WC-Ni-based cemented carbide can be used as a substrate for cutting tool materials.

***Keywords*—**Rare metals, turning, WC-Ni-based cemented carbide, (Ti,W,Si)N coating film, hardened steel.

I. Introduction

CEMENTED carbides, which are made with sintered WC particles using cobalt (Co), nickel (Ni), etc. powder as the binder material, are sintered alloys [1]. WC-Co-based cemented carbide is widely used when cemented carbide is used as a cutting tool material. On the other hand, WC-Ni-based cemented carbide is hardly used for the cutting of other than non-ferromagnetic materials. This is the reason that WC-Ni-based cemented carbide is hardly used as a cutting tool material. In the case of the same WC particle size, the toughness of WC-Ni-based cemented carbide is higher than that of WC-Co-based cemented carbide. However, the hardness of WC-Ni-based cemented carbide is lower than that of WC-Co-based cemented carbide [2]. Furthermore, in order to increase the hardness of cemented carbide, increasing the WC particle content is an effective method. However, in the case of WC-Ni-based cemented carbide, when the WC content increases and the Ni content decreases, bores readily occur in the cemented carbide and the strength of the cemented carbide thus decreases. This is also the reason for WC-Ni-based cemented carbide not being used as a cutting tool material.

On the other hand, Ni and Co are rare metals. In 2006, the reserve/production ratio (= reserves/world mine production) of Ni and Co was 41 years and 134 years, respectively [3]. However, in 2011, the reserve/production ratio of Ni and Co is 44 years and 77 years, respectively [4]. That is, in the last five years, the reserve/production ratio of Ni has increased slightly 1.1-fold, whereas the reserve/production ratio of Co has sharply decreased by a factor of 0.57. It is considered that much of the total demand for Co is for the lithium-ion secondary battery; consumption of the lithium-ion secondary battery will decrease while consumption of Co will increase in the future. Therefore, it is possible to switch from a Co to a Ni binder of cemented carbide, and the amount of Co, which is a rare metal, can be reduced. In addition, although price fluctuations are seen, the price per unit mass of Ni is about half that of Co.

From the above, it is considered that WC-Ni-based cemented carbide, which is hardly used as a cutting tool material, is an effective cutting tool material in terms of reduction of rare metals. WC-Co-based cemented carbide is coated in hard materials such as TiN, etc. in order to improve its wear resistance when used as a cutting tool material. Therefore, it is considered that the hardness of WC-Ni-based cemented carbide rises and wear resistance is improved by coating the WC-Ni-based cemented carbide with a hard material.

Incidentally, polycrystalline cubic boron nitride compact (cBN) seems to be an effective tool material because it has good heat resistance and wear resistance in cutting hardened steel. However, in milling, a major tool failure of cBN readily occurs by fracture because cBN has poor fracture toughness. In this case, coated cemented carbide tools, which have good fracture toughness and wear resistance, seem to be effective tool materials. TiN and (Ti,Al)N [e.g., 5, 6] are generally used for the coating film. So, there are many studies on the wear resistance of these coating layers. Although there are some studies on the tool wear characteristics of PVD-coated cemented carbide tools in the cutting of hardened steel [7] or sintered steel [8], there are few studies on tool wear in the cutting of hardened sintered steel.

Recently, it has become possible to cut hardened steels with (Ti,Al)N-coated WC-Co-based cemented carbide 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 [9]. Titanium/tungsten-based coating film exhibits a superior critical scratch load. Moreover, the titanium / tungsten-based-coated WC-Co-based cemented carbide tool was evaluated through machining of low-carbon steel AISI 5120H, and showed greatly improved performance [9].

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However, the hardness of the (Ti,W)N coating film was lower than that of commercial (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 [10]. This titanium/tungsten/silicon-based coating film exhibits both superior critical scratch load and hardness compared with commercial TiN/(Ti,Al)N coating film. In cutting AISI 5120H, the wear progress of the (Ti,W,Si)N-coated WC-Co-based cemented carbide tool is slower than that of commercial TiN- and (Ti, Al)N-coated WC-Co-based cemented carbide tools [11]. Furthermore, in cutting hardened steel AISI D2, the wear progress of the (Ti,W,Si)N-coated WC-Co-based cemented carbide tool was almost equivalent to that of the commercial (Ti, Al)N-coated WC-Co-based cemented carbide tool [12]. Therefore, titanium/tungsten/silicon coating is an effective tool material because it has good wear resistance. Thus, if it is clarified that there is little difference between the wear progress of the (Ti,W,Si)N-coated WC-Ni-based cemented carbide tool and that of the (Ti,W,Si)N-coated WC-Co-based cemented carbide tool, the WC-Ni-based cemented carbide can be used as a substrate for (Ti,W,Si)N-coated cemented carbide tools. However, the wear progress of (Ti,W,Si)N-coated WC-Ni-based cemented carbide tools in cutting hardened steel is unclear.

In this study, WC-Ni-based cemented carbide with different Ni contents was used as the substrate. The hardened steel was turned by a (Ti,W,Si)N-coated WC-Ni-based cemented carbide tool, and the tool wear was experimentally investigated. The results showed little difference between the wear progress of the (Ti,W,Si)N-coated WC-Ni-based cemented carbide tool and that of the (Ti,W,Si)N-coated WC-Co-based cemented carbide tool; it is clear that WC-Ni-based cemented carbide can be used as a substrate for (Ti,W,Si)N-coated cemented carbide tools.

II. Experimental Procedure

The work material used was hardened steel (AISI D2, 60HRC). The chemical composition of the hardened steel is shown in Table I. The coating material was (Ti,W,Si)N film, and six types of substrates of cemented carbide were used as shown in Table II. Namely, the substrates used were three kinds of WC-Ni-based and three kinds of WC-Co-based cemented carbide.

The configuration of the tool inserts was TNGA160408. An insert was attached onto tool holder MTGNR2525M16. In this case, the tool geometry was (-6, -6, 6, 6, 30, 0, 0.8 mm). The cutting conditions are shown in Table III. Turning tests were carried out on a precision lathe (Type ST5, SHOUN MACHINE TOOL Co., Ltd.) with an added variable-speed drive. The driving power of this lathe is 7.5/11 kW and the maximum rotational speed is 2500 min^{-1}. The tool wear of the six kinds of turning insert was investigated.

TABLE I
Chemical Composition and Properties of Hardened Steel (AISI D2, 60HRC) [mass %]

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

TABLE II
Chemical Compositions and Mechanical-Thermal Properties of Cemented Carbide

Substrate for cutting tool material	WC [mass %]	Co [mass %]	Ni [mass %]	Size of WC particle [μm]	Hardness [HRA]	T.R.S. [GPa]	Thermal conductivity [W/(m·K)]
WC-6%Co	92	6	-	1.5	92.0	2.4	97
WC-7%Co	93	7	-	2.0	90.3	3.1	95
WC-8%Co	92	8	-	4.5	89.0	3.0	93
WC-7%Ni	92	-	7	1.5	91.0	3.0	98
WC-9%Ni	90	-	9	1.5	90.0	3.1	95
WC-11%Ni	88	-	11	1.5	89.0	3.5	92

T.R.S.: Transverse rupture strength

TABLE III
Cutting Conditions

Cutting speed	V=0.5 [m/s]
Feed rate	S=0.2 [mm/rev]
Depth of cut	a=0.1 [mm]
Tool geometry	(-6, -6, 6, 6, 30, 0, 0.8mm)
Tool insert	Substrate: WC-Co-based cemented carbide, WC-Ni-based cemented carbide Coating film: (Ti,W,Si)N
Cutting method	Dry

III. Results and Discussion

In order to find the structure of the (Ti,W,Si) N coating layer on the substrate of WC-Ni-based cemented carbide, microphotographic observation was carried out on a cross section of the (Ti,W,Si) N-coated WC-Ni cemented carbide. Fig. 1 shows a micrograph of the cross section of (Ti,W,Si) N-coated WC-7%Ni-based cemented carbide. It is found that the (Ti,W,Si) N coating film enters into irregularities of the substrate at the interface between the coating and the substrate from the cross-sectional micrograph of the coating shown in Fig. 1. Thus, the coating film and the substrate are sufficiently close at the interface between the coating film and the substrate, and the thickness of the coating film is constant. The (Ti,W,Si) N-coated WC-7%Ni-based cemented carbide has a 3.0-μm-thick (Ti,W,Si) N film on a substrate of WC-7%Ni-based cemented carbide.

As a result of the observation of other (Ti,W,Si) N-coated WC-Ni-based and (Ti,W,Si) N-coated WC-Co-based cemented carbide, it can be seen that (Ti,W,Si) N adhered closely to the substrate and that the thickness of the coating film was constant.

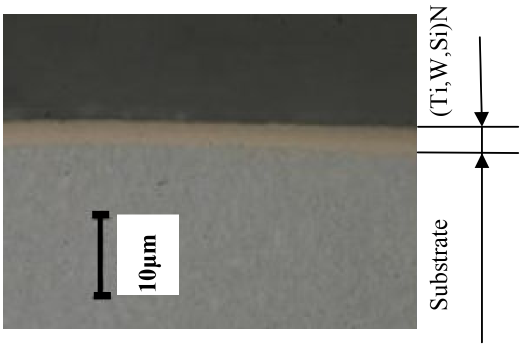


Fig. 1 Micrograph of a cross section of (Ti,W,Si)N-coated WC-7%Ni -based cemented carbide

Table IV shows the properties of coating films of (Ti,W,Si) N-coated WC-Ni-based and (Ti,W,Si) N-coated WC-Co-based cemented carbide. The coating thickness of any of the cemented carbides is constant at 3.0μm. There is little difference in coating hardness, which is substantially 3000 $HV_{0.25N}$, between the substrates. For this reason, there is little difference in either the coating thickness or the coating hardness when (Ti,W,Si) N is coated with a substrate of WC-Ni- or WC-Co-based cemented carbide.

In order to evaluate the adhesion between the substrate and the (Ti,W,Si) N film, a scratch test, which is typically used to evaluate the adhesion force of thin films, was conducted for six kinds of coated cemented carbide tools. Fig. 2 shows microscopic photographs of the wear track in the scratch test. This figure shows the (Ti,W,Si) N-coated WC-9%Ni-based cemented carbide. The pattern of progressive scratch load is whereby cracks on the coating surface form and flaking of the coating layer arises. In Fig. 2 (a), the load that caused the first cracking on the surface is Lc1. In Fig. 2 (b), the load that caused the catastrophic failure is Lc2. In Fig. 2 (c), the film is peeled off over the entire surface of the substrate. In Table IV, the Lc1 of the WC-7%Ni-based cemented carbide is slightly larger than that of the WC-6%Co-based cemented carbide. And the Lc2 of the WC-7%Ni- and the WC-6%Co-based cemented carbide is over 130 N, respectively.

As mentioned above, there is little difference in the coating properties of either WC-7%Ni-based or WC-6%Co-based cemented carbide. So, it is considered that (Ti,W,Si) N-coated WC-7%Ni -based cemented carbide is an effective tool material and that hardened steel can be cut by this tool.

TABLE IV
PROPERTIES OF COATING FILMS

Substrate	Hardness of coating film [$HV_{0.25N}$]	Thickness of coating film [μm]	Scratch load [N] Lc1	Scratch load [N] Lc2
WC-6%Co	2970	3.0	84	>130
WC-7%Co	2990	3.0	82	123
WC-8%Co	2990	3.0	62	104
WC-7%Ni	2920	3.0	94	>130
WC-9%Ni	3060	3.0	76	113
WC-11%Ni	2950	3.0	74	105

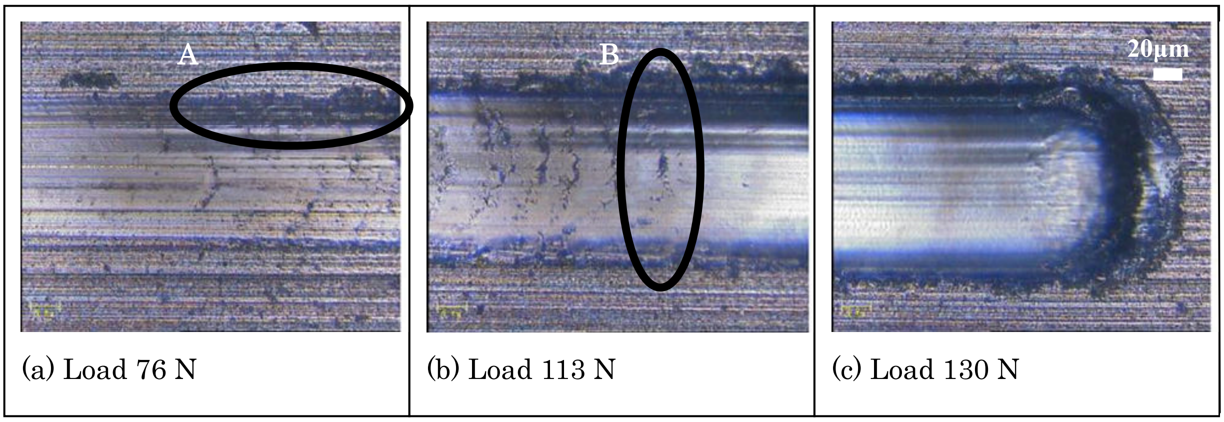
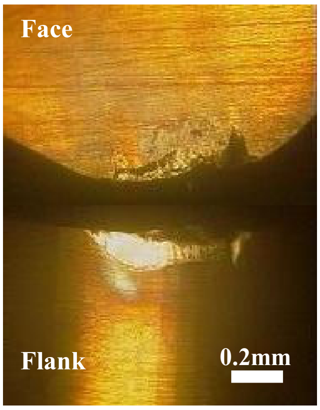
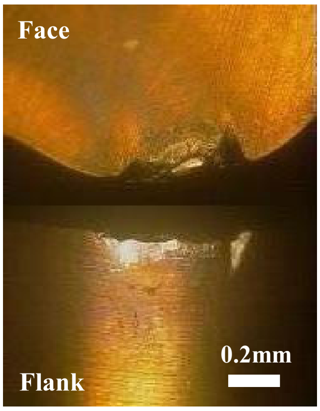


Fig. 2 Microscopic photographs of the scratch track by a scratch tester on (Ti,W,Si)N-coated WC-9%Ni cemented carbide (a) load that caused the first cracking on the surface is Lc1, (b) load that caused the catastrophic failure is Lc2 and (c) film is peeled off over the entire surface of the substrate

The hardened steel was turned with (Ti,W,Si)N-coated tools, which have various substrates, and the tool wear was investigated. Fig. 3 shows the tool wear in the case of a cutting speed of 0.5 m/s, a feed rate of 0.2 mm/rev and a depth of cut of 0.1mm. Figs. 3 (a) and (b) show the case of WC-7%Ni-based and WC-6%Co-based cemented carbide, respectively. In this figure, “L” is the cutting distance. In the case of both the WC-7%Ni-based and the WC-6%Co-based cemented carbide, a tool edge fracture on the cutting edge is found. As a result of the turning test of other (Ti,W,Si)N-coated WC-Ni-based and (Ti,W,Si)N-coated WC-Co-based cemented carbide tool, it emerged that the main tool failure for six kinds of coated cemented carbide tools was flank wear within the maximum value of the flank wear width of about 0.2mm. Therefore, the maximum value of flank wear width (VBmax) was measured with a microscope.



(a)WC-Ni7% (L=3.4 km)



(b)WC-Co6% (L=3.3 km)

Fig. 3 Tool wear

Fig. 4 shows the wear progress in cutting hardened steel with six kinds of PVD-coated tools at a cutting speed of 0.5 m/s, a feed rate of 0.2 mm/rev and a depth of cut of 0.1mm. In the case of both the (Ti,W,Si)N-coated WC-Ni-based and the (Ti,W,Si)N-coated WC-Co-based cemented carbide tools, the wear progress accelerates with an increase of binding material. Compared with the six kinds of coated cemented carbide tools, the wear progress of both the (Ti,W,Si)N-coated WC-7%Ni-based and the (Ti,W,Si)N-coated WC-6%Co-based cemented carbide tool is the slowest. And the wear progress of the (Ti,W,Si)N-coated WC-7%Ni-based tool is almost the same as that of the (Ti,W,Si)N-coated WC-6%Co-based tool, too.

As mentioned above, it is considered that WC-7%Ni-based cemented carbide is an effective substrate material for a cutting tool, the same as WC-6%Co-based cemented carbide.

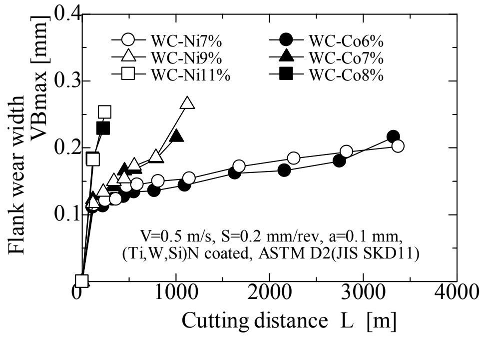


Fig. 4 Wear progress

IV. Conclusions

In this study, in order to clarify whether WC-Ni-based cemented carbide can to be used as an alternative to WC-Co-based cemented carbide, hardened steel was turned by (Ti,W,Si)N-coated WC-Co-based cemented carbide tools. These coated tools had various Ni contents. And the wear progress of the (Ti,W,Si)N-coated WC-Ni-based tools was compared with that of the (Ti,W,Si)N-coated WC-Co-based tools.

The following results were obtained:

1) For the (Ti,W,Si)N-coated WC-Ni-based cemented carbide, the hardness of the coating film was not much different from the content of the binding material, Ni, and the adhesion strength increased with a decrease in Ni content.
2) There is little difference between the wear progress of the (Ti,W,Si)N-coated WC-7%Ni-based cemented carbide tool and that of the (Ti,W,Si)N-coated WC-6%Co-based cemented carbide tool.
3) The wear progress of the (Ti,W,Si)N-coated WC-Ni-based cemented carbide became slower with a decrease in Ni content.

From the above, it was clear that WC-Ni-based cemented carbide can be used as a substrate for cutting tool materials.

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