Tool Wear of (Al, Cr, W, Si)-based-coated Cemented Carbide Tools in the Cutting of Hardened Steel

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***Abstract*— In this study, carbonitride and nitride coating films were deposited on a cemented carbide ISO K10 using two different (Al, Cr, W, Si)-targets, namely the (Al53, Cr23, W14, Si10)- and (Al58, Cr24.8, W7.2, Si10)-target. In deposition, N_2 gas or (N_2, CH_4) gas was used as the reaction gas, and the substrate DC bias voltage was -150 or -300V. Then the characteristics of the four types of coating films were investigated. ASTM D2 hardened steel was cut with four types of coated cemented carbide tools. The tool wear of the coated tools was experimentally investigated and the following results were obtained: (1) Compared with the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool and that of the (Al58, Cr24.8, W7.2, Si10)(C, N) coated tool, the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool was slightly slower than that of the (Al58, Cr24.8, W7.2, Si10)(C, N) coated tool. (2) In the case of the (Al58, Cr24.8, W7.2, Si10)N coated tools, comparing the two types of the substrate DC bias voltages, the wear progress at the substrate DC bias voltage of -300 V was slower. (3) In the case of the substrate DC bias voltage of the -300V, comparing the wear progress with the (Al53, Cr23, W14, Si10)N coated tool and the (Al58, Cr24.8, W7.2, Si10)N coated tool, the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool was slower. Therefore, as a target material, the (Al58, Cr24.8, W7.2, Si10)-target has excellent wear resistance.**

***Index Terms*—cutting, physical vapor deposition coating method, tool wear, (Al, Cr, W, Si)-target, (Al, Cr, W, Si)-based coating film, hardened steel**

I. INTRODUCTION

Hardened steels have high hardness and hard strength. Therefore, the hardness steels are often used for parts that require wear resistance. In cutting hardened steels with un-coated cemented carbide tools, the tool wear increases. Cubic boron nitride (c-BN) is generally used as the cutting tool material in cutting hardened steels. For this reason, c-BN tools tend to break easily during intermittent cutting such as milling. In this case, coated tools are generally used in which a hard coating film is deposited on a substrate of cemented carbide [1]. For hard coatings, (Cr, Al) coatings have become widely used in addition to Ti, (Ti, Al) coatings [2]. Varghese et al. [3] reported that the AlCrN coating had better wear resistance and machining performance compared to the AlTiN coating in end milling of MDN 250 maraging steel.

Compared to the (Ti, Al)N coating film, the (Al, Cr)N coating film is a more effective tool material for the cutting of sintered steel [4] and hardened sintered steel [5].

Wada et al. reported that the wear resistance of (Al, Cr, W)N coated tools with W added to (Al, Cr)N coated tools was improved in cutting hardened steel [6] or sintered steel [7].

Furthermore, when cutting hardened steel, the wear resistance of the (Al, Cr, W, Si) N coating was improved by adding Si to the (Al, Cr, W) N coating [8]. The same is valid for TiAlN coatings [9].

The wear progress of the (Al,Cr,W,Si)-carbonitride coated tools was measured in cutting ASTM D2 hardened steel. And the wear progress of the (Al58, Cr24.8, W7.2, Si10)(C, N) coated tool is slightly slower than that of the (Al53, Cr23, W14, Si10)(C, N) coated tool [10]. Therefore, the (Al58, Cr24.8, W7.2, Si10) target has better wear resistance than the (Al53, Cr23, W14, Si10) target. When performing physical vapor deposition with an arc ion plating system, the characteristics of the coating film differ depending on the type of reaction gas and the substrate DC bias voltage. Regarding the reaction gas, for example, when using a Ti target, in the case of TiN nitrogen (N_2) is used, methane (CH_4) is added for TiC and a mixture of the two is employed for Ti(C,N) [11]. Guu *et al*. [12] reported the stoichiometries of eight types of coating films produced by changing the mass flow rate of the N_2 and C_2H_2 gases during the coating process.

On the other hand, regarding the substrate DC bias voltage, Skordaris *et al*. [13] reported that coatings produced at elevated substrate DC bias voltage possess comparably increased mechanical properties and fatigue endurance. However, their adhesion deteriorates, thus reducing the coated inserts cutting performance especially when a good adhesion during a material removal process as in milling hardened steel is required. Liu *et al*. [14] reported that four groups of (Ti, Al, Zr)N coatings were produced with different bias voltages (50, 100, 150, and 200 V) but the same target current. The results of turning tests indicated that the dominant wear mechanism for the cutting tool prepared at the bias of 50 V was abrasive and

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fatigue wear. The mechanisms were a combination of adhesive wear and abrasive wear when the bias was increased from 100 to 200 V. It is recognized that the quality and performance of PVD coatings on tungsten carbide based cutting tools are strongly affected by the level of residual stress as it may cause the coatings to delaminate from the substrate and affect the tool life [15].

However, there is no study on the investigation of the properties of coating films deposited on cemented carbide ISO K10 by using the (Al58, Cr24.8, W7.2, Si10) target at varying coating conditions (reactant gases and substrate DC bias voltages). In addition, there is no study on examining tool wear in cutting hardened steel with these coated tools.

In this study, two types of different (Al, Cr, W, Si)-target cathode materials were used. Four types of coating films were deposited on a substrate of cemented carbide ISO K10 using these two targets. The ion plating method, one of physical vapor deposition, was used for coating treatment. For the coating treatment, the reaction gases used were N_2 and (N_2, CH_4) gas, and the substrate DC bias voltages used were -150 and -300 V.

ASTM D2 hardened steel was cut with four types of coated tools, and the wear of the tools was investigated.

II. Experimental Procedure

Coating deposition was performed by an arc ion plating system (KOBE STEEL, LTD. AIP-S40). Two types of target (cathode) material were used as shown in Table I.

The component ratios for targets T3 and T4 were determined as follows:

(1) T3 target:

For the target (Al60, Cr25, W15), the ratio of (Al70, Cr30) and W was set to 85:15. For the T3 target, the ratio of (Al60, Cr25, W15) and Si was set to 90:10. Therefore, the composition ratio of the T3 target is (Al53, Cr23, W14, Si10).

(2) T4 target:

For the target (Al64, Cr28, W8), the ratio of (Al70, Cr30) and W was set to 92:8. For the T4 target, the ratio of (Al64, Cr28, W8) and Si was set to 90:10. Therefore, the composition ratio of the T4 target is (Al58, Cr24.8, W7.2, Si10).

The reaction gases used were N_2 gas and CH_4 gas. In this study, the coating films used were T3-N, T4-N and T4-CN, namely (Al53, Cr23, W14, Si10)N, (Al58, Cr24.8, W7.2, Si10)N and (Al58, Cr24.8, W7.2, Si10)(C, N), respectively. The substrate DC bias voltage of -300 V was used to deposit the T3-N, the T4-N and the T4-CN coating films. In addition, the substrate DC bias voltage of -150 V was used to deposit the T4-N coating film. The substrate of the coated tool was cemented carbide ISO K10.

The thickness, micro-hardness (micro-hardness measured by a "PICODENTOR HM500 (FISCHER INSTRUMENTS K.K.)) and scratch strength (critical scratch load measured by a "RST3 Revetest Scratch Tester" (Anton Paar GmbH)) of the coating films formed on the surface of the cemented carbide ISO K10 by the arc ion plating process were measured.

The configurations of the tool inserts were ISO TNGA160408. The insert was attached to a tool holder MTGNR2525M16. In this case, the tool geometry was (-6, -6, 6, 6, 30, 0, 0.8 mm).

The work material used was hardened steel (ASTM D2, 60 HRC). The chemical composition and mechanical properties of the hardened sintered steel are shown in Table II.

The turning tests were conducted on a precision lathe (Type ST5, SHOUN MACHINE TOOL Co., Ltd.) by adding a variable-speed drive. The driving power of this lathe is 7.5/11 kW with a maximum rotational speed of 2500 min^{-1}. Hardened steel was turned under the cutting conditions shown in Table III, and the tool wear was investigated. The maximum value of the flank wear width was measured with a microscope.

TABLE I. Condition of Coating

Target type	Component of target material [at%]	Reaction gas	Substrate DC bias voltage [V]
T3	Al53, Cr23, W14, Si10	N_2	-300
T4	Al58, Cr24.8, W7.2, Si10	N_2, (N_2, CH_4)	-150, -300

Deposition parameters

Temperature of (T4-N) and (T4-CN) coatings: 673 K. Deposition time of (T4-N) and (T4-CN) coatings: 100 ± 5 minute. Chamber pressure of (T4-N) and (T4-CN) coating: 3.5 Pa and 4.0 Pa.

TABLE II. Chemical Composition of the Hardened Steel (ASTM D2, 60 HRC) [mass%]

C	Cr	Mo	Mn	Ni	Si	V
1.48	11.62	0.81	0.42	0.13	0.30	0.20

TABLE III. Cutting Conditions

Cutting speed	Vc=60 m/min
Feed speed	f=0.1 mm/rev
Depth of cut	ap=0.1 mm
Cutting method	Dry

III. Results and Discussion

A. *Characteristics of Coating Films*

With respect to the four types of coating films, SEM micrographs of the coating film (the droplet), the cross section of the coating film and the scratch tracks were observed Fig. 1 shows the case of the T3-N coating film and T4-N coating film. Both the T3-N and the T4-N coating films were deposited at a substrate DC bias voltage of -300V. Figure (i) (left half of Fig. 1) shows the case of the T3-N coating film, and Fig. (ii) (right half of Fig. 1) shows the case of the T4-N coating film. Although not shown in Fig. 1, the characteristics of the other two types of coating films were observed. Table IV shows the characteristics of coating films. Figure (a) shows a micrograph of the coating surface. Figure (i) shows the T3-N coating film. Figure (ii) shows the surface of the T4-N coating film. Droplets adhere to the T3-N and T4-N coating films. Comparing the droplet diameters of the T3-

N and T4-N coating films, the droplet diameter of the T4-N coating film is smaller than that of the T4-N coating film. The particle size of the droplet of the coating film may affect the surface roughness of the finished surface. Therefore, it is considered that the smaller the particle diameter of the droplet, the smaller the surface roughness of the finished surface.

To clarify the formation of the coating on the cemented carbide substrate, a section of the coated cemented carbide was observed under a microscope. Figure (b) shows a cross-sectional micrograph of a cemented carbide coated with T3-N and T4-N.

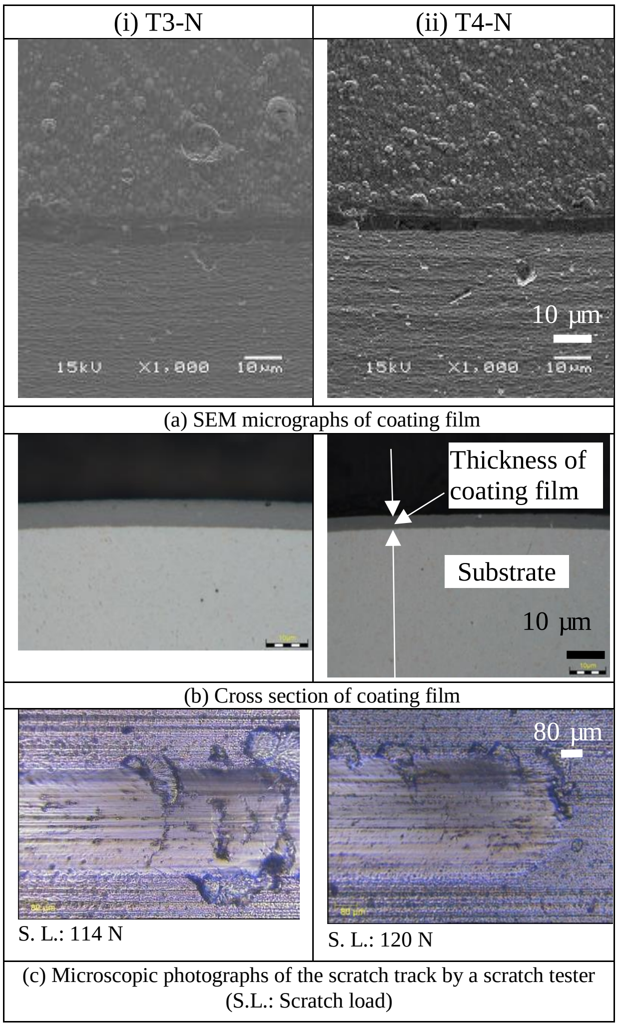


Figure 1. SEM micrographs of the coating film (the droplet), cross section of the coating film and scratch tracks were observed in the case of the T3-N coating film and T4-N coating film at a substrate DC bias voltage of -300 V.

As shown in Fig. (i), a cross-sectional micrograph of the coating shows that the T3-N coating film penetrated the substrate irregularities at the interface between the coating and the substrate. Thereby, the coating film and the substrate are sufficiently close to each other at the interface between the coating film and the substrate, and the thickness of the coating film becomes constant. T3-N coated cemented carbide has a 6.5 µm thick T3-N coating film on the substrate. On the other hand, in the case of the T4-N coated cemented carbide shown in Fig. (ii), the T4-N coating film permeates the unevenness of the substrate at the interface between the T4-N coating film and the substrate. The cross-sectional observation results of the cemented carbide coated with T3-N and T4-N indicate that both the T3-N and the T4-N coating film are in close contact with the substrate material and the thickness of the coating film is constant. The thickness of the T4-N coating film is 3.4 µm.

In order to evaluate the adhesion between the substrate and the T3-N and T4-N coating film, a scratch test, which is typically used to evaluate the adhesion force of thin films, was conducted for two types of coated cemented carbide tools. Figure (c) shows microscopic photographs of the wear track in the scratch test. The critical load of both the T3-N coated cemented carbide shown in Fig. (i) and the T4-N coated cemented carbide shown in Fig. (ii) exceeds 100 N.

Table IV shows the characteristics of the four types of coating films. The T3-N coating film is the thickest at 6.5 µm. The T4-N coating film deposited using the substrate DC bias voltage of -300 V is 3.4 µm, which is the thinnest.

The hardness of the three types of coating films deposited using the T4 target is 2900 $HV_{0.025}$ or more, whereas the hardness of the T3-N film deposited using the T3 target is 2500 $HV_{0.025}$.

The critical scratch load was 100 N or more for each of the coating films, and all the coating films had adhesive strength for use as a coating film for cutting tools.

TABLE IV. CHARACTERISTICS OF COATING FILMS

Tool type	Thickness of film [µm]	Micro-hardness [$HV_{0.025}$]	Critical scratch load* [N]
Type T3-N, -300 V**	6.5	2500	108
Type T4-N, -150 V**	6.3	2950	>130
Type T4-N, -300 V**	3.4	2960	120
Type T4-CN, -300 V**	4.0	2920	125

*: Measured value by scratch test
**: Substrate DC bias voltage

B. *Results of Cutting Test*

Fig. 2 shows the tool wear of the T4-N coated tool at a substrate DC bias voltage of -300 V. In this figure, the cutting distance is 4.7 km. In the case of the Type T4-N coated cemented carbide tool, there is a crater on the rake face, and there is no significant adhesion on both the rake face and the flank face. There is no significant flaking of the coating layer. As a result of examining the tool wear other than the Type T4-N coated tool, whose figures are not shown here, the tool wear of all coated tool types was almost the same as that of the Type T4-N coated tool.

Therefore, the main tool failure for all coated cemented carbide tools was flank wear within the maximum value of the flank wear width of about 0.2 mm.

Fig. 3 shows the wear progress of coated tools using nitride or carbonitride of the T4 target at a substrate DC bias voltage of -300 V. Compared with the wear progress of the T4-N and that of the T4-CN [10], the wear progress of the T4-N coated tool is slightly slower than that of the T4-CN coated tool. Therefore, the T4-N film using N_2 gas as a reactive gas exhibits excellent wear resistance in the physical vapor deposition by the arc ion plating system using the target T4. Compared with the properties of the coating as shown in Table IV, the 3.4 µm film of the Type T4-N coated tool is thinner than that of the type T4-CN coated tool. Furthermore, the critical scratch load of the Type T4-N coated tool is lower than that of the type T4-CN coated tool. However, the micro-hardness and critical scratch load of the Type T4-N coated tool are slightly higher than that of the T4-CN coated tool. So, the wear progress of the Type T4-N coated tool is slow.

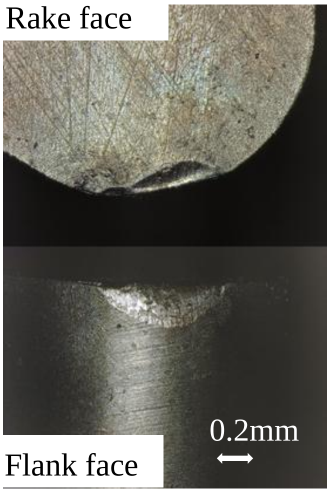


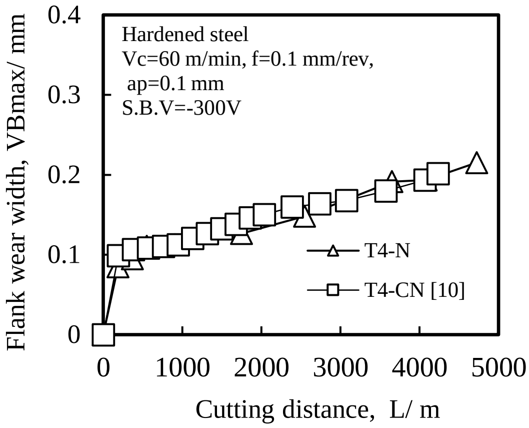
Figure 2. Tool wear of the T4-N coated tool at a substrate DC bias voltage of -300 V and cutting distance of 4.7 km.

As described above, in the case of the T4 target, as a reaction gas nitrogen gas is effective for wear resistance. However, the substrate DC bias voltage affects the properties of the coating film. Therefore, the effect of the substrate DC bias voltage on the characteristics of the coating film is observed.

Fig. 4 shows the effect of the substrate DC bias voltage on the wear progress of the T4-N coated tool. Comparing the two types of substrate DC bias voltages, the wear progress at the substrate DC bias voltage of -300 V is the slowest. Therefore, for T4-N coated tools, a substrate DC bias voltage of -300V is the most effective for wear resistance. Thus, the substrate DC bias voltage of the -300V coating film has excellent wear resistance.

Fig. 3 and Fig. 4 indicate that in order to improve the wear resistance, it is effective to use nitrogen gas as a reaction gas and to use a substrate DC bias voltage of -300V.

For this reason, the wear progress of coated tools using two types of targets was investigated. Fig. 5 shows the wear progress of coated tools using nitrogen as the reaction gas for two types of targets (T3 and T4) at a substrate DC bias voltage of -300 V. Comparing the wear progress of the two types of coated tools, the Type T4-N coated tool has the slowest wear progress. Therefore, the target T4, namely the (Al58, Cr24.8, W7.2, Si10)-target, has excellent wear resistance.



S. B. V.: Substrate DC Bias Voltage

Figure 3. Wear progress of coated tools using nitride or carbonitride of the T4 target at a substrate DC bias voltage of -300 V.

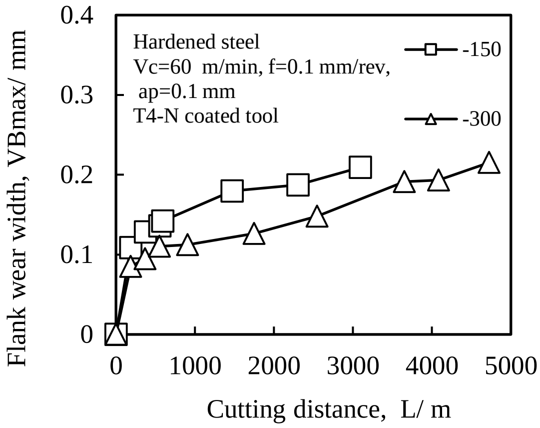
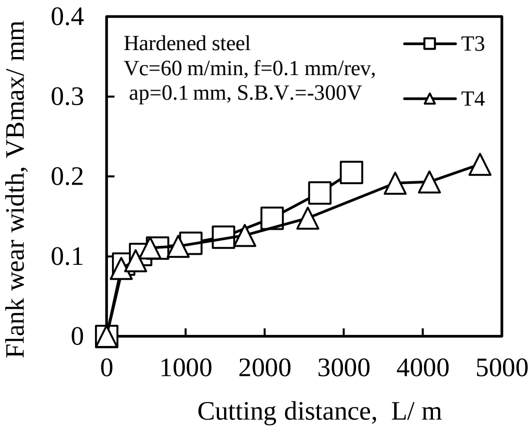


Figure 4. Effect of the substrate DC bias voltage on the wear progress of the T4-N coated tool.



S. B. V.: Substrate DC Bias Voltage

Figure 5. Wear progress of coated tools using nitrogen as the reaction gas for two types of targets (T3 and T4) at a substrate DC bias voltage of -300 V.

From the characteristics of the coating films as shown in Table IV, comparing the thickness of the film of the two types of coated tools, the 3.4 µm film of the Type T4-N coated tool is thinner. However, both the micro-hardness and critical scratch load of the Type T4-N coated tool are higher. So, the wear progress of the Type T4-N coated tool is slower.

IV. Conclusion

In this study, carbonitride and nitride coating films were deposited on a cemented carbide ISO K10 using two different (Al, Cr, W, Si)- targets, namely the (Al53, Cr23, W14, Si10)- and (Al58, Cr24.8, W7.2, Si10)-target.

In deposition, N_2 gas or (N_2, CH_4) gas was used as the reaction gas, and the substrate DC bias voltage was -150 or -300V. Then the characteristics of the four types of coating films were investigated.

ASTM D2 hardened steel was cut with four types of coated cemented carbide tools. The tool wear of the coated tools was experimentally investigated and the following results were obtained:

(1) The (Al53, Cr23, W14, Si10)N coating film deposited using a substrate DC bias voltage of -300 V was the thickest at 6.5 μm. The (Al58, Cr24.8, W7.2, Si10)N coating film deposited using a substrate DC bias voltage of -300 V was 3.4 μm, which was the thinnest.

(2) The hardness of the three types of coating films deposited using the (Al58, Cr24.8, W7.2, Si10)-target was 2900 $HV_{0.025}$ or more, whereas the hardness of the (Al53, Cr23, W14, Si10)N film deposited using the (Al53, Cr23, W14, Si10)-target was 2500 $HV_{0.025}$.

(3) The critical scratch load was 100 N or more for each of the coating films, and all the coating films had adhesive strength for use as a coating film for cutting tools.

(4) Compared with the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool and that of the (Al58, Cr24.8, W7.2, Si10)(C, N) coated tool, the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool was slightly slower than that of the (Al58, Cr24.8, W7.2, Si10)(C, N) coated tool.

(5) In the case of the (Al58, Cr24.8, W7.2, Si10)N coated tools, comparing the two types of substrate DC bias voltages, the wear progress at the substrate DC bias voltage of -300 V was slower.

(6) In the case of the substrate DC bias voltage of the -300V, comparing the wear progress with the (Al53, Cr23, W14, Si10)N coated tool and the (Al58, Cr24.8, W7.2, Si10)N coated tool, the wear progress of the (Al58, Cr24.8, W7.2, Si10)N coated tool was slower.

Therefore, as a target material, the (Al58, Cr24.8, W7.2, Si10)-target has excellent wear resistance.

Conflict of Interest

The author declares no conflict of interest.

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