Tool Wear of (Al,Cr,W)/(Al,Cr,W,Si)-Based-Coated Cemented Carbide Tools in Cutting of Hardened Steel

Tadahiro Wada, Akiyoshi Nitta, and Junsuke Fujiwara

***Abstract*—In this study, a carbonitride coating film was deposited on a cemented carbide ISO K10 using three different Al-Cr-W-Si targets. The coating film structure consists of mono-layer film and multi-layer films. The hardened steel ASTM D2 was cut with five types of coated cemented carbide tools. The tool wear of the coated tools was experimentally investigated. The following results were obtained: (1) Comparing the wear progress of the (Al53,Cr23,W14,Si10)(C,N)- and (Al58,Cr25,W7,Si10)(C,N)-coated tool, the wear progress of the (Al58,Cr25,W7,Si10)(C,N)-coated tool is slightly slower than that of the (Al53,Cr23,W14,Si10)(C,N)-coated tool. (2) Comparing the wear progress of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)- and the (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coated tool, the wear progress of the (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coated tool is slightly slower than that of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)-coated tool.**

***Index Terms*—Cutting, physical vapor deposition coating method, tool wear, (Al,Cr,W)(C,N)-coating film, (Al,Cr,W,Si)(C,N)-coating film, hardened steel.**

I. Introduction

The hardened steel AISI D2 has high hardness, strength and wear resistance. In cutting hardened steel AISI D2, the tool wear increases. Polycrystalline Cubic Boron Nitride (PCBN) is generally used as the cutting tool material in cutting hardened steel. Linhu Tang et al. investigated the wear performance and mechanisms of the PCBN tool in dry hard turning of AISI D2 hardened steel at various hardness levels (40-60 $\pm$1 HRC) [1].

However, in milling, a major tool failure of c-BN readily occurs by fracture because c-BN has poor fracture toughness. Coated cemented carbide tools, which have good fracture toughness and wear resistance, seem to be effective cutting tool materials. TiN, Ti(C,N) and (Ti,Al)N are generally used for the coating film [2].

Cr-Al-N is expected to play a very important role in the future of Surface Engineering, manufacturing industry and in preventing wear of critical components in a wide range of applications [3].

When investigating the potentials of newly developed (Cr,Al)N coatings compared to uncoated tools, CrxAlyN coatings with different chromium to aluminum contents were deposited onto indexed carbide inserts. In order to find improved coatings for dry machining operations both tribological and wear tests were performed [4].

The machining performance of AlCrN and AlTiN coated cemented carbide inserts were investigated during end milling of MDN 250 maraging steel. As a result, the AlCrN coating had better wear resistance and machining performance compared to the AlTiN coating [5].

The performance of mono-layered AlCrN and multi-layered AlTiN PVD coatings on mixed alumina inserts were investigated in the turning of hardened AISI 52100 steel.

As a result, the AlCrN coating exhibited superior machining behavior at higher cutting speeds indicating the suitability of the coating at elevated machining speeds [6].

Tadahiro Wada et al. reported that an (Al,Cr)N coated cemented carbide is an effective tool material for cutting sintered steel [7] and hardened sintered steel [8].

The incorporation of Si [9], Y [9], W [10], Fe [11], Zr [12] or Ti [13] into (Cr, Al) N was reported. In cutting hardened steel [14] or sintered steel [15], the wear resistance of (Al, Cr, W) N coated tools with W added to (Al, Cr) N coated tools was improved. The wear resistance of (Al, Cr, W)(C,N) coated tools with C added to (Al,Cr,W) N coated tools was improved [14]-[17]. Furthermore, the wear resistance of (Al, Cr, W,Si)N coated tools with Si added to (Al, Cr,W) N coated tools was improved [18].

On the other hand, gradient and multilayered coatings composed of different nitride layers show superior mechanical strength, such as hardness and wear resistance, as compared to mono-layered coatings due to their specific interfaces [19]. For this reason, many studies on multilayer coatings have been conducted [19]-[24].

In addition, many studies dealing with multi-layer (Al,Cr,W)/(Al,Cr,W,Si) coating films handled in this study have been reported [25]-[28]. As a result of comprehensive judgment of the study results of Tadahiro Wada et al., the following two points were clarified. (1) The wear resistance of PVD-coated tools was improved by adding W and Si to (Al, Cr) targets. (2) Multi-layer coating films have better wear resistance than single-layer coating film. However, the effect of components (Al, Cr, W, Si) on tool wear have not been clarified.

In this study, two types of aluminum/chromium/tungsten/silicon target cathode materials with varying constituents were used to improve the wear resistance of coated cutting tools in cutting hardened

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steel. For comparison, a cathode material of one type of aluminum/chromium/tungsten target was also used. In addition, multi-layer coating materials were used, including combinations of aluminum/chromium/tungsten/silicon based coating films and aluminum/chromium/tungsten based coating films. Using these three types of targets, the hardened steel was cut with a cutting tool in which cemented carbide K10 substrate metal was PVD coated and the tool wear was examined.

II. Experimental Procedure

The tool material of the substrate was cemented carbide ISO K10, and five types of PVD coated cemented carbide were used as shown in Table I. Namely, the coating films used were (Al60,Cr25,W15)(C,N)-, (Al53,Cr23,W14,Si10)(C,N)- and (Al58,Cr25,W7,Si10)(C,N)-coating film, which are mono-coating film. And (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)- and (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coating film were used as the coating films. (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)- or (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coating film comprises a multi-layer coating system. The inner layer of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)- or (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coating system is (Al60,Cr25,W15)(C,N)- or (Al53,Cr23,W14,Si10)(C,N)-coating film, and the outer layer is (Al53,Cr23,W14,Si10)(C,N)- or (Al58,Cr25,W7,Si10)(C,N)-coating film.

TABLE I: Tool Material

Tool type	Coating film
Type D	(Al60,Cr25,W15)(C,N)
Type G	(Al53,Cr23,W14,Si10)(C,N)
Type O	(Al58,Cr25,W7,Si10)(C,N)
Type D-G	(Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)
Type G-O	(Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)

Substrate: Cemented carbide ISO K10,
Type D, Type G and Type O: Mono-layer coating system,
Type D-G and Type G-O: Multi-layer coating system

Coating deposition was performed by an arc ion plating system (KOBE STEEL, LTD. AIP-S40). The substrate DC bias voltage was -300 V, and the reaction gases used were N2 gas and CH4 gas. We measured the thickness, hardness and scratch strength (critical scratch load measured by a scratch tester) of the coating films formed on the surface of the cemented carbide ISO K10 by the arc ion plating process.

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, 60HRC). 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.

TABLE II: Chemical Composition of The Hardened Steel (AISI D2, 59.0 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	V=1.00 m/s
Feed speed	f=0.1 mm/rev
Depth of cut	ap=0.1 mm
Cutting method	Dry

III. Results and Discussion

The hardened steel was turned with the three types of coated tools, namely Type D, type G and Type D-G at a cutting speed of 1.0 m/s, feed rate of 0.1 mm/rev, depth of cut of 0.1 mm and cutting method of dry cutting. Fig. 1 shows the tool wear. In this figure, “L” is the cutting distance. In the case of the Type D, the Type G or the Type D-G coated cemented carbide tool shown in Fig. 1(a)- (c), there is a crater on the rake face, and there is no significant adhesion on both the rake face and the flank face. Also there is no significant flaking of the coating layer, but there is tool edge fracture on the cutting edge.

As a result of the turning test with the five types of coated carbide tool, 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. Therefore, the maximum value of flank wear width was measured with a microscope.

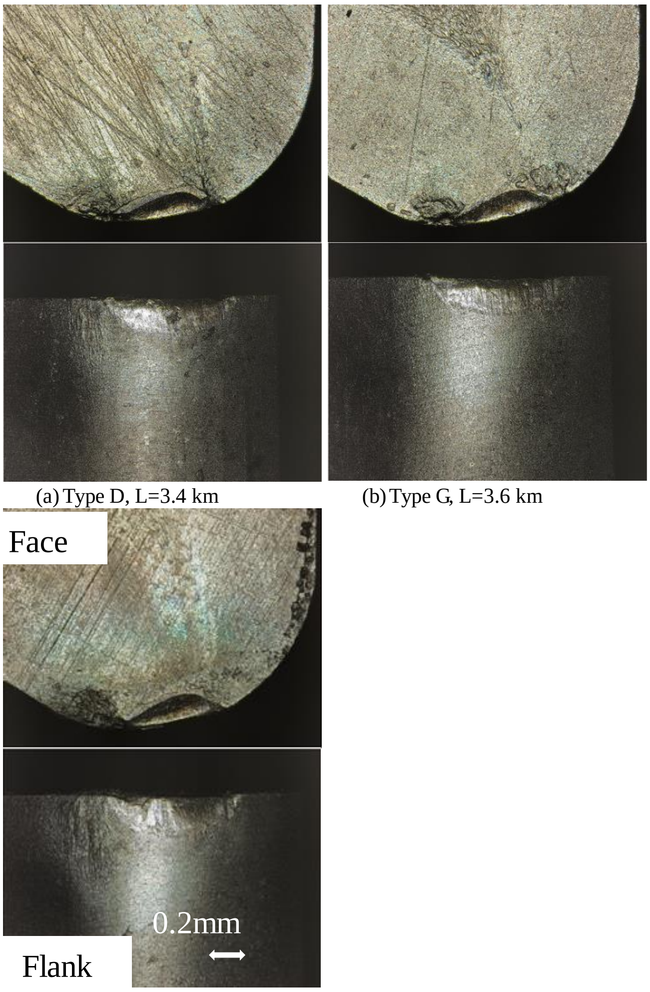
Fig. 2 shows the wear progress. Wada and Hanyu reported that the wear progress of the (Al53,Cr23,W14,Si10)(C,N)-coated tool is slower than that of the (Al60,Cr25,W15)(C,N)-coated tool, and the wear progress of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)-coated tool, which is the multi-layer coated tool, is slower than that of the (Al53,Cr23,W14,Si10)(C,N)-coated tool in the same cutting conditions. The work material AISI D2 used in this experiment is slightly different in the chemical composition and the hardness from the work material AISI D2 used in the previous experiment [18]. For this reason, although the absolute value of the flank wear width as shown in Fig. 1 is different, the same tendency as the previous research result [18] is obtained. That is, the wear progress of the Type G tool, which has the (Al53,Cr23,W14,Si10)(C,N)-coating film, is slower than that of the Type D, which has the (Al60,Cr25,W15)(C,N)-coating film. Furthermore, the wear progress of the Type D-G, which has the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)-coating film (the multi-layer coating film), is slower than that of the

Type G.

This indicates that the aluminum/chromium/tungsten/silicon-based-coating film is formed for the aluminum/chromium/tungsten/silicon-target by adding silicon (Si) to the aluminum/chromium/tungsten-target in order to improve the wear resistance of the aluminum/chromium/tungsten-based-coating film [18].

In general, the component ratios of various elements contained in the coating greatly affect the coating properties. Therefore, the components of the aluminum/chromium/tungsten/silicon-based-coating film were changed to two types, namely the (Al53,Cr23,W14,Si10)(C,N)- and the (Al58,Cr23,W7,Si10)(C,N)-coating film.

Fig. 3 shows the tool wear. In the case of the Type O or the Type G-O coated cemented carbide tool shown in Fig. (a) or Fig. (b), there is a crater on the rake face, no significant adhesion on both the rake face and the flank face, no significant flaking of the coating layer, but there is tool edge fracture on the cutting edge. This tendency is the same among the three types of tools shown in Fig. 1.



(a) Type D, L=3.4 km (b) Type G, L=3.6 km

(c) Type D-G, L=4.1 km

Fig. 1. Tool wear (L:Cutting distance).

Fig. 4 shows the wear progress in turning the hardened steel with the three types of coated tools, namely Type G, type O and Type G-O at a cutting speed of 1.0 m/s, feed rate of 0.1 mm/rev, depth of cut of 0.1 mm and cutting method of dry cutting.

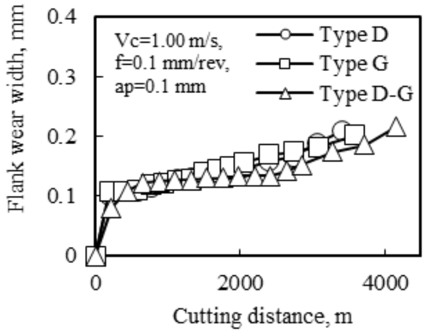
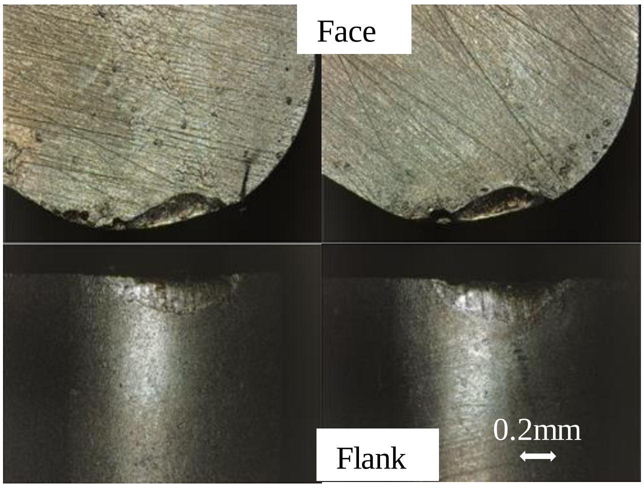


Fig. 2. Wear progress of three types of coated tools in cutting AISI D2 at a cutting speed of 1.00 m/s, feed rate of 0.1 mm/rev and depth of cut of 0.1 mm.



(a) Type O, L=4.2 km (b) Type G-O, L=5.6 km

Fig. 3. Tool wear (L: Cutting distance).

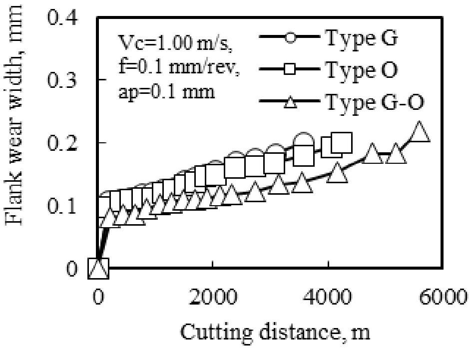


Fig. 4. Wear progress of three types of coated tools in cutting AISI D2 at a cutting speed of 1.00 m/s, feed rate of 0.1 mm/rev and depth of cut of 0.1 mm.

Comparing the wear progress of Type G and Type O, the wear progress of Type O is slightly slower than that of Type G. As shown in Fig. 2 and Fig. 4, the wear progression of the Type G-O coating tool was the slowest. In order to clarify the reason, the characteristics of the coating film were investigated. The results are shown in Table IV. Table IV shows the coating characteristics. These were compared among the five types of coating films. The Type G-O coated tool has a coating film thickness of 1.7 µm, the thinnest of the five coating tools. The Type G-O coated tool has the lowest micro-hardness among the five coating tools. However, the critical scratch load of the Type G-O is not much different from the other types of coated tools.

Therefore, the reason for the slowest wear progression of the Type G-O coated tool cannot be clarified from the coating characteristics of the five tools shown in Table IV.

From the characteristics of the coating, the reason why the Type G-O coated tool is superior in wear resistance cannot be clarified. In order to clarify the reason, the SEM observation and the EDS mapping analysis on the worn surface were performed. These results will be explained in detail in the next report.

TABLE IV: CHARACTERISTICS OF ALUMINUM/CHROMIUM/TUNGSTEN-BASED COATING FILMS

Tool type	Thickness of film [μm]	Micro-hardness [$HV_{0.25N}$]	Critical scratch load* [N]
Type D [17]	3.3	3080	>130
Type G [18]	3.7	2990	>130
Type O	4.0	2920	125
Type D-G [25]	2.5	2630	>130
Type G-O	1.7	2310	>130

IV. CONCLUSION

In this study, a carbonitride coating film was deposited on a cemented carbide ISO K10 using three different Al-Cr-W-Si targets. The coating film structure consisted of mono-layer film and multi-layer films. The hardened steel ASTM D2 was cut with five types of coated cemented carbide tools. The tool wear of the coated tools was experimentally investigated.

The following results were obtained:

(1) Comparing the wear progress of the (Al53,Cr23,W14,Si10)(C,N)- and (Al58,Cr25,W7,Si10)(C,N)-coated tool, the wear progress of the (Al58,Cr25,W7,Si10)(C,N)-coated tool is slightly slower than that of the (Al53,Cr23,W14,Si10)(C,N)-coated tool.

(2) Comparing the wear progress of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)- and the (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coated tool, the wear progress of the (Al53,Cr23,W14,Si10)(C,N)/(Al58,Cr25,W7,Si10)(C,N)-coated tool is slightly slower than that of the (Al60,Cr25,W15)(C,N)/(Al53,Cr23,W14,Si10)(C,N)-coated tool.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Tadahiro Wada does idea proposal, performing experiment, data collecting, data analysis, paper writing, paper finalization and supervising; Akiyoshi Nitta does data collecting; Junsuke Fujiwara does data collecting.

All authors approved the final version.

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