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Tool Wear of Aluminum / Chromium / Tungsten/ Silicon-Based-Coated Cemented Carbide Tools in Cutting of Hardened Steel

Tadahiro Wada and Hiroyuki Hanyu

Abstract—**In this study, to clarify the effectiveness of aluminum/chromium/tungsten/silicon-based coating films, hardened steel was turned with (Al53, Cr23, W14, Si10)(C, N)-coated cemented carbide tools and the tool wear was experimentally investigated. The following results were obtained: 1) The micro-hardness and the critical scratch load measured value by the scratch tester of the (Al53, Cr23, W14, Si10)(C, N)-coating film was 2990 HV0.25N and over 130 N, respectively. 2) The mean value of the friction coefficient of the (Al53, Cr23, W14, Si10)(C, N)-coating film was 0.41. 3) The wear progress of the (Al53,Cr23, W14, Si10)(C,N)-coated tool was slower than that of the (Ti, Al) N- and the (Al60, Cr25, W15) (C, N)-coated tool. 4) In the case of the feed rate of 0.1 mm/rev, the wear progress of the multilayer coated tool was almost equivalent to that of the monolayer coated tool. However, at a higher feed rate of 0.2 mm/rev, the wear progress of the multilayer coated tool was slower than that of the monolayer coated tool.**

The above results clarify that the new (Al60, Cr25, W15)(C, N)-coating film, has both high hardness and good adhesive strength, and can be used as a tool material in cutting hardened steel.

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

I. INTRODUCTION

An (Al, Cr)N coated tool was evaluated through the machining of sintered steel, and showed greatly improved performance [1]. And, the (Al, Cr)N coated cemented carbide is an effective tool material in cutting hardened sintered steel [2]. However, the results of our study indicate that the critical scratch load, which is the measured value by the scratch test, of the (A l, Cr)N coating film is 77 N and the micro-hardness is 2760 $HV_{0.25N}$. Therefore, in order to improve both the scratch strength and the micro-hardness of the (Al, Cr)N coating film, the cathode material of an aluminum / chromium / tungsten-target was used in adding tungsten (W) to the cathode material of the aluminum / chromium target [3]. Furthermore, the hardened sintered steel was turned with the aluminum / chromium / tungsten-based-coated cemented carbide tools. Compared with commercially available (Al, Cr)N and (Ti, Al)N coated cemented carbide tools, at a low cutting speed of 0.42 m/s, the wear progress of the aluminum/chromium/tungsten-based-coated tool became the slowest [3].

However, the addition of Si to TiN coatings is reported to transform the [111] oriented columnar structure into a dense finely grained structure, and thin films of Ti-Si-N have been deposited by physical vapor deposition to improve the wear resistance of TiN coatings [4]. The hardness of the $Ti_{0.84}Si_{0.15}N_{1.03}$ revealed the highest hardness value, around 47 GPa, which is more than double that of common TiN [5]. The $Ti_{1-x}Si_xN$ system revealed a significant increase in the load values for total failure when compared with that of TiN [6]. However, the (Ti, Al, Si)N forms a two-phase scale as in the (Ti, Al)N, but the oxidation resistance is slightly lower, too [7].

From the viewpoint of film-forming, in Inconel 718 turning, the (Ti, Al)N-multilayer coating showed some performance advantage over the (Ti, Al)N-monolayer at higher speed [8]. Nowadays, most multi-layer coating materials contain a combination of TiN, TiC, Ti(C,N) and Al2O3; to improve the tool life, they are deposited in different sequences [9].

In this study, to improve the tool life in cutting hardened steel, the cathode material of an aluminum/chromium/tungsten/silicon-target was used in adding silicon (Si) to the cathode material of the aluminum/chromium/tungsten-target. Multi-layer coating materials containing a combination of aluminum / chromium / tungsten / silicon-based-coating film and aluminum/chromium/tungsten-based-coating film to improve the tool life were also used. Furthermore, the characteristics of aluminum / chromium / tungsten / silicon-based coating films were investigated.

II. EXPERIMENTAL PROCEDURE

The tool material of the substrate was cemented carbide ISO K10, and four 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 (Ti, Al) N-coating film, which are mono-coating film, and (Al60, Cr25, W15) (C, N)/(Al53, Cr23, W14, Si10) (C, N)-coating film, which is a multi-layer coating film. The (Al53, Cr23, W14, Si10) (C, N)- or (Al60, Cr25, W15) (C, N)/(Al53, Cr23,W14, Si10)(C, N)- is a new type of coating film whereas (Ti, Al)N are conventional and commercially available types. (Al60, Cr25, W15) (C, N)/(Al53, Cr23, W14, 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)-coating system is (Al60, Cr25, W15) (C, N)-coating film, and the outer layer is (Al53, Cr23, W14, Si10) (C, N)-coating film.

Coating deposition was performed by an arc ion plating

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system (KOBE STEEL, LTD. AIP-S40). We measured the thickness, hardness and scratch strength (critical scratch load measured by 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.

The friction coefficient was measured using a pin-on-disk type friction and wear tester (Rhesca Corporation FPR-2100), and the test conditions are shown in Table IV.

TABLE I: TOOL MATERIAL IN TURNING OF HARDENED SINTERED STEEL

Substrate: Cemented carbide ISO K10
Coating layer:
Mono-layer
(Al60, Cr25, W15)(C, N), (Al53, Cr23, W14, Si10)(C, N), (Ti, Al)N
Multi-layer
(Al60, Cr25, W15)(C, N)/(Al53, Cr23, W14, Si10)(C, N)

TABLE II: CHEMICAL COMPOSITION OF THE HARDENED STEEL (AISI D2, 60 HRC) [MASS%]

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

TABLE III: CUTTING CONDITIONS

Cutting speed	V=1.0 m/s
Feed speed	S=0.1, 0.2 mm/rev
Depth of cut	a=0.1 mm
Cutting method	Dry

TABLE IV: TEST CONDITIONS OF THE FRICTION TEST (PIN-ON-DISK TYPE)

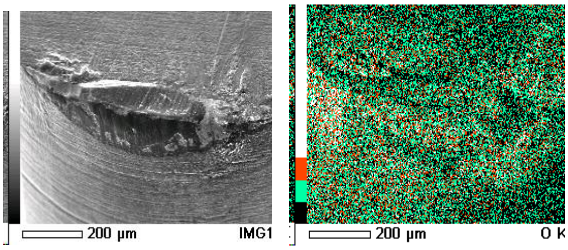
Material of ball	ISO C454 (JIS S45C), (R5.00 mm)
Sliding time	600 s
Sliding speed	100 mm/s
Normal load	490 mN
Temperature	295 K
Humidity	28 %
Atmosphere	Air

III. RESULTS AND DISCUSSION

In turning hardened steel 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 using the three types of coated tools, the wear progress was investigated. Figure 1 shows the SEM observation and the EDS mapping analysis on the worn surface. In Fig. 1, the EDS analysis for the oxygen (O) mapping on the cutting part is shown. Fig. 1(i) and Fig. 1(ii) show the case of the (Al60, Cr25, W15)(C, N)-coated tool at a cutting distance of 2.8 km and the case of the (Al53, Cr23, Si10, W14)(C, N)-coated tool at a cutting distance of 3.3 km, respectively. In the case of the two types of coated cemented carbide tools as shown in Fig. 1(i)(a) and Fig. 1(ii)(a), there is a crater on the rake face, and there is no remarkable adhesion on either the rake face or flank. Moreover, no remarkable flaking of the coating layer is found either. Although this figure in the case of the (Ti, Al) N-coated tool is not shown here, the wear pattern of the (Ti, Al)N-coated tool is the same as the pattern of the two types of coated cemented carbide tool as shown in Fig. 1.

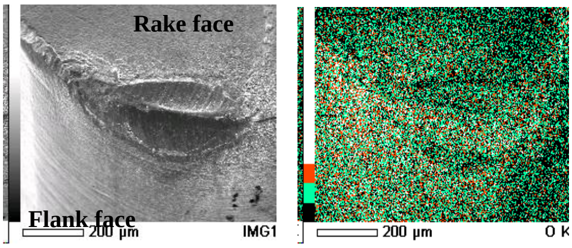
The above results indicate that the main tool failure of the four types of coated tools was the flank wear within the maximum value of the flank wear width of 0.2mm. Therefore, the maximum value of the flank wear width (VBmax) was measured with a microscope.

The wear progress is shown in Fig. 2. The wear progress of the (Al53, Cr23, W14, Si10) (C, N)-coated tool was slower than that of the (Al60, Cr25, W15)(C, N)- or the (Ti, Al)N-coated tool. 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.



(a) SEM image (b) EDS analysis of O mapping

(i) (Al60, Cr25, W15) (C, N), cutting distance 2.8 km



(a) SEM image (b) EDS analysis of O mapping

(ii) (Al53, Cr23, W14, Si10)(C, N), cutting distance 3.3 km

Fig. 1. SEM observation and EDS mapping analysis on the worn surface 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.

Therefore, the characteristics of the coating films were investigated. The results are shown in Table V. Table V shows the characteristics of the coating film. These were compared among the three types of coating films. The thickness of the (Ti, Al)N-, the (Al60, Cr25, W15) (C, N)- or the (Al53, Cr23, W14, Si10) (C, N)-coating films was 3.0 µm, 3.3 µm or 3.7 µm, respectively. However, the micro-hardness of the (Ti, Al)N-, the (Al60, Cr25, W15) (C, N)- or the (Al53, Cr23, W14, Si10) (C, N)-coating film is 2710 HV$_{0.25N}$, 3080 HV$_{0.25N}$, or 2990 HV$_{0.25N}$, respectively. That is, the micro-hardness of the (Al60, Cr25, W15) (C, N)- or the (Al53, Cr23, W14, Si10) (C, N)-coating films of about 3000 $HV_{0.25N}$ is higher than that of the (Al, Cr)N 2760 $HV_{0.25N}$. Moreover, the critical scratch load of the (Al60, Cr25, W15)(C, N)- or the (Al53, Cr23, W14, Si10) (C, N)-coating films over 130 N is higher than that of the (Al, Cr)N-coating film 73N. Therefore, the wear progress of the (Al, Cr)N-coated tool was faster than that of the (Al60, Cr25, W15)(C, N)- or the (Al53, Cr23, W14, Si10) (C, N)-coated tool as shown in Fig. 2.

Although there is nothing remarkable in the characteristics of the two types of coated tools as shown in Table V, the wear progress of the (Al53, Cr23, W14, Si10) (C, N)-coated tool was slower than that of the (Al60, Cr25, W15) (C, N)-coated tool as shown in Fig. 2. The reason for this is discussed below.

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

Coating material	Thickness of film [µm]	Micro-hardness [$HV_{0.25N}$]	Critical scratch load* [N]
(Ti,Al)N	3.0	2710	73
(Al60, Cr25, W15) (C, N) [3]	3.3	3080	>130
(Al53, Cr23, W14, Si10) (C, N)	3.7	2990	>130

*: Measured value by scratch test

The friction coefficient was measured with a pin-on-disk friction and wear tester. Fig. 3 shows the relationship between the sliding time and the friction coefficient under a sliding speed of 100 mm/s and a normal load of 490 m N. The maximum sliding time was 600 s. The friction coefficient of both the (Al60, Cr25, W15) (C, N)- and the (Al53, Cr23, Si10, W14) (C, N)-coating film increased with the increase of the sliding time. After that, the friction coefficient of the (Al53, Cr23, Si10, W14) (C, N)-coating film is smaller than that of the (Al60, Cr25, W15) (C, N)-coating film under the sliding time of 300 s to 600 s. Table VI shows the mean value of the friction coefficient under a sliding time of 100 s to 600 s. The mean value of the friction coefficient of the (Al53, Cr23, Si10, W14) (C, N)-coating film, 0.41, is smaller than that of the (Al60, Cr25, W15) (C, N) coating film, 0.63.

As compared with the oxygen element on the worn surface of the (Al60, Cr25, W15) (C, N)-coated tool shown in Fig. 1 (i)(b) and that of the (Al53, Cr23, W14, Si10) (C, N)-coating tool, which was turned at a long cutting distance, shown in Fig. 1(ii)(b), there is little difference in the oxygen element between the two types of coating films. Therefore, the cutting temperature of the (Al53, Cr23, W14, Si10) (C, N)-coated tool is considered to be lower than that of the (Al60, Cr25, W15) (C, N)-coated tool, and the wear progress of the (Al53, Cr23, W14, Si10) (C, N)-coated tool was slower than that of the (Al60, Cr25, W15) (C, N)-coated tool.

One reason for the lower cutting temperature of the (Al53, Cr23, W14, Si10) (C, N)-coated tool is as follows. The mean value of the friction coefficient is shown in Table VI. The mean value of the friction coefficient of the (Al53, Cr23, W14, Si10) (C, N)-coating film, 0.41, is smaller than that of the (Al60, Cr25, W15) (C, N)-coating film, 0.63. That is, the (Al53, Cr23, W14, Si10) (C, N)-coating film has a lower coefficient of friction as compared with the (Al60, Cr25, W15) (C, N)-coating film. So, in the case of cutting sintered steel by the (Al53, Cr23, W14, Si10) (C, N)-coated tool, the cutting force decreases with the decrease of the friction force between the tool and the work-piece. The lowering of the cutting temperature explains why there is less tool wear of the (Al53, Cr23, W14, Si10) (C, N)-coated tool.

As mentioned above, the (Al53, Cr23, W14, Si10) (C, N)-coating film has superior properties as a coating material compared to the (Al64, Cr28, W8) (C, N)-coating film in cutting sintered steel.

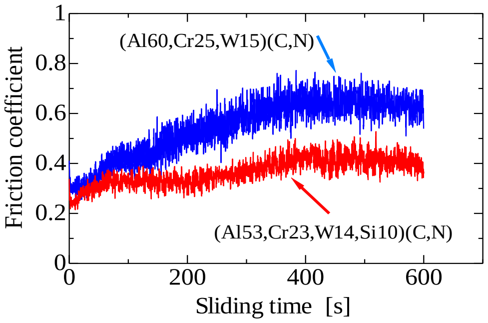


Fig. 3. Relationship between sliding distance and friction coefficient under a sliding time of 0 s to 600s.

TABLE VI: MEAN VALUE OF THE FRICTION COEFFICIENT OF THE COATING FILMS (MEAN VALUE OF FRICTION COEFFICIENT UNDER A SLIDING TIME OF 300 S TO 600 S)

Coating film	Mean value of friction coefficient
(Al60, Cr25, W15)(C, N)	0.63 [3]
(Al53, Cr23, W14, Si10) (C, N)	0.41

Finally, in order to improve the tool life, the wear progress of the multi-layer coating materials containing a combination of aluminum/chromium/tungsten/silicon-based-coating film and aluminum/chromium/tungsten-based-coating film was investigated. Fig.5 shows the wear progress of two types of coated tools at a cutting speed of 1.0 m/s, feed rate of 0.1, 0.2 mm/rev and depth of cut of 0.1 mm. In the case of the feed rate of 0.1 mm/rev, there is nothing remarkable in the wear progress of the two types of coated tool. However, in case of the higher feed rate of 0.2 mm/rev, 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.

As mentioned above, if the cutting force increases with the increase in the feed rate, the tool life can be extended by the use of the multi-layer coated tool.

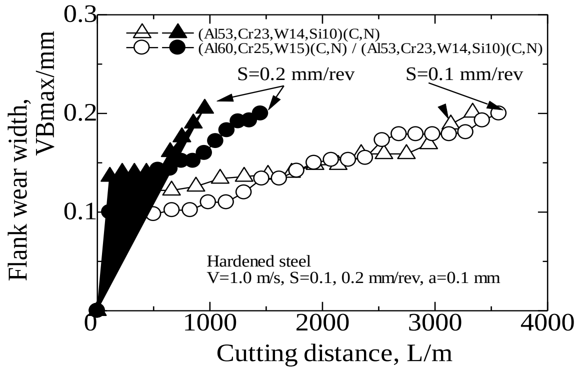


Fig. 4. Wear progress of two types of coated tools at a cutting speed of 1.0 m/s, feed rate of 0.1, 0.2 mm/rev and depth of cut of 0.1 mm.

IV. CONCLUSION

In this study, to clarify the effectiveness of aluminum/chromium/tungsten/silicon-based coating films, we measured the thickness, micro-hardness and critical scratch strength, which was measured by a scratch tester, of aluminum/chromium/tungsten/silicon-based coating films formed on the surface of a substrate, which was a cemented carbide ISO K10 by the arc ion plating process. The hardened steel was turned with the (Al60,Cr25,W15)(C,N)-, the (Al53,Cr23,W14,Si10)(C,N)- and the (Ti,Al)N-coated cemented carbide tools. The tool wear of the coated tools was experimentally investigated.

The following results were obtained:

1) The micro-hardness and the critical scratch load measured value by a scratch tester of the (Al53, Cr23, W14, Si10) (C, N)-coating film was 2990 $HV_{0.25N}$ and over 130 N, respectively.
2) The mean value of the friction coefficient of the (Al53, Cr23, W14, Si10) (C, N)-coating film was 0.41.
3) The wear progress of the (Al53, Cr23, W14, Si10) (C, N)-coated tool was slower than that of the (Ti, Al) N- and the (Al60, Cr25, W15) (C, N)-coated tool.
4) In the case of the feed rate of 0.1 mm/rev, the wear progress of the multilayer coated tool was almost equivalent to that of the monolayer coated tool. However, at a higher feed rate of 0.2 mm/rev, the wear progress of the multilayer coated tool was slower than that of the monolayer coated tool.

The above results clarify that the new type of (Al60, Cr25, W15) (C, N)-coating film has both high hardness and good adhesive strength, and can be used as a tool material in cutting hardened steel.

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