Mechanical and tribological properties of composite CrAlTiSiN and TiAlN multilayer coatings And application to metal forming process

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ABSTRACT

Transition metal nitrides, such as TiN, CrN and TiAlN, have been used as protective hard coatings due to their excellent tribological properties. In this study, chromium aluminum titanium silicon nitride (CrAlTiSiN) composite thin films, titanium aluminum nitride/titanium nitride (TiAlN/TiN) multilayer thin films, and titanium aluminum nitride/chromium nitride (TiAlN/CrN) thin films coatings were synthesized by cathodic-arc evaporation (CAE) process. The behavior of wear cracks and the wear depths, of these coatings were studied. The best tribological coating was obtained according to the minimum wear depth. The results indicated that the CrAlTiSiN composite thin films exhibited excellent antiwear performances; therefore, this coating was applied in extrusion forging of Phillips screw punches as compared with commercial TiN coated tools. The results indicated that, although the CrAlTiSiN composite coatings were thinner than TiN, punches coated with the CrAlTiSiN composite thin films were used to manufacture at least 20,000 more screws than punches coated with TiN. Therefore, CrAlTiSiN composite coatings can increase the lifespan of punches substantially, and satisfy the production requirement and provide benefits.

KEYWORDS: Hard coating, Wear, Extrusion forging.

1 INTRODUCTION

A single coating features various functional characteristics because of material characteristic limitations. In addition, with the development of material science, materials that are difficult to process have increased in number, causing the applications of single coating to be inadequate. To address current problems, numerous researchers have investigated multielement alloy and multiphase and multilayer systems, integrating materials with excellent properties to produce new coatings. This approach not only retained the characteristics of original coatings, but also enabled the advantages of individual coatings to be integrated, thereby enhancing the mechanical performance of the coatings. In surface processing, hard coating is crucial because it directly influences the work environment; thus, hard coatings must possess high hardness and strength, resistance to wear, and excellent impact performance. Such properties extend the lifespan of work pieces and improve product quality. To ensure efficiency and precision, coatings featuring high hardness and resistance to wear and impact are demanded in the international market. Jehn (2000), Zeng et al. (1998), and Nordin et al. (1998) indicated hard coatings used in relevant industries include titanium nitride (TiN), titanium aluminum nitride (TiAlN), chromium aluminum nitride (CrAlN), titanium aluminum carbonitride (TiAlCN), TiN/ molybdenum nitride (MoN), and TiN/chromium nitride (CrN) coatings. Shizhi et al. (1992) and Diserens et al. (1998) showed TiN is widely employed because of its high resistance to wear and heat and excellent mechanical strength. Although the hardness of TiN coatings is superior to that of CrN coatings, CrN coatings are the most ideal material for die-forming applications. Moreover, CrN coatings yield low friction coefficient during the wearing process, which facilitates friction reduction during processing. Therefore, this type of coating is superior to TiN coatings in suppressing corrosion. A low friction coefficient and excellent antiadhesion can increase the releasing capacity between dies and processed components. Because CrN coatings demonstrate greater thermal stability and resistance to adhesion than TiN and TiCN coatings do, CrN-coated tools and precision components feature excellent protection effects and processing quality. Nouveau et al. (2001) and Lu and Chen (2001) indicated CrN attaches firmly to work pieces, which enable the work piece to endure the forces generated during processing. In addition, CrN can be used to coat thick layers.

The die used to punch screw head grooves is called a screw punch. The quality of such punch is the primary factor that influences the quality of screw head grooves. The punch that is specifically used to manufacture cross-shaped grooves on screw heads is the Phillips punch, which must be produced through cold forging for precision requirements. Cold forging is the primary plastic forming approach used for manufacturing small and medium-sized forgings; therefore, numerous studies have investigated extrusion forging. Hashmi et al. (1986) used lead and copper to perform extrusion and forging on symmetrical-axis cylinder billets under static and dynamic conditions. In addition, they analyzed the profile of a deformed cone under low-friction conditions using the rigid-plastic theory and obtained a theoretical prediction that was consistent with the experimental results. Maccarini et al. (1990) applied the FEM, using copper and pure aluminum to experimentally investigate the external force of extrusion forging and backward extrusion and the friction generated at the die/billet interface. As a result, they determined the relationship between stroke and load and between the friction coefficient and flange thickness. Rao et al. (1991) employed the FEM and physical modeling of an aluminum alloy to analyze a tapered top die and a flat bottom die during spike forging under various temperature and lubrication conditions. In addition, they identified the flow behavior of billets and observed that lubrication conditions influenced the material flows and forming loads of extrusion. Hu et al. (1994) employed the FEM and experiments to explore the deformation and loads of pure aluminum rectangular billet during extrusion forging and to determine the flow behavior of metal. Their experimental and simulation results revealed satisfactory forming loads and profiles. Wu et al. (2002) adopted the FEM and symmetrical-axis extrusion forging to analyze the influence of die shapes on extrusion forging and the effects of stroke-forging height and die shapes on the distribution of plastic strain. They then compared forming loads and test piece profiles by using experiments involving two sets of dies with different geometric shapes; the results obtained were consistent. Thus, the findings can be extended to the forming planning of complex preforging dies.

Screws are currently mass produced, which substantially increased the demands for screw punches; therefore, these punches must feature excellent strength and antiweart properties. Generally, screw punches are subjected to thermal and surface processing after formation to increase their strength, toughness, and resistance to wear and impact. Thus, this study focused on the surface processing of Phillips screw punches to enhance their surface quality and antiwear properties.

2 MICROSTRUCTURE AND ADHESION ANALYSES

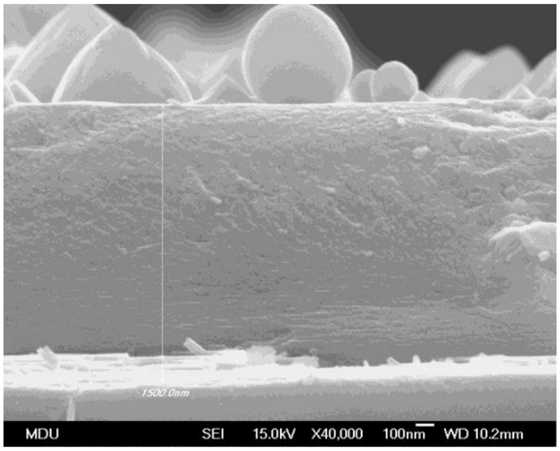
Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings were deposited on polished SKD61 die steels by using a CAE system. Chromium, titanium, CrAl (70 at.% of Cr and 30 at.% of Al), TiSi (80 at.% of Ti and 20 at.% of Si), and TiAl (50 at.% of Ti and 50 at.% of Al) alloy targets were arranged on opposite sides of the chamber to deposit the coatings. The samples were mounted on a rotational substrate holder for the deposition of composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings. The temperature of the sample during the deposition was controlled at about 200-230 ℃, which was measured by a thermocouple located near the sample.

Base pressure prior to deposition was lower than 1×10−3 Pa and substrate bias voltage of −100 V and N2 pressure of 2.7 Pa were used. Next, the samples were mounted on the rotational substrate holder for the deposition of the composite-layered CrTiSiN coatings. The rotational speed of the substrate holder was controlled at 5 rpm. A CrN was used as the bottom interlayer to improve the adhesion strength, and then CrAlTiSiN films were deposited. The total cathode current of both cathodes was 160 A ($I_{[CrAl]}+I_{[TiSi]}=160$ A). Ar and reactive gas (N2) were introduced through a dispensing channel around the target to enhance the reaction of the plasma. Table 1 shows the deposition parameters of the composite CrAlTiSiN coatings. Similarly, the deposition parameters of the multilayered TiAlN/TiN and TiAlN/CrN coatings are also listed in Table 1.

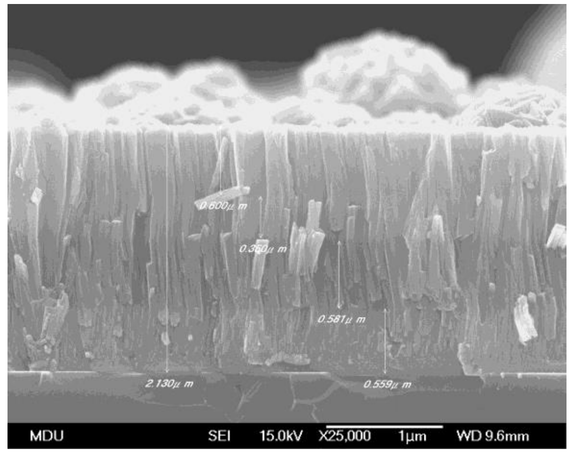
Table 1. Deposition parameters of the composite CrAlTiSiN and TiAlN multilayer coatings.

Coatings	CrAlTiSiN	TiAlN/TiN	TiAlN/CrN
Deposition parameters	Value	Value	Value
Deposition pressure (Pa)	3×10^{-2}	2.7×10^{-2}	2.7×10^{-2}
Deposition time (min)	60	85	85
Distance between cathode and substrate (mm)	150	145	145
CAE target	Cr, $Ti_{80}Si_{20}$, $Cr_{70}Al_{30}$	Ti, Cr, $Ti_{50}Al_{50}$	Cr, $Ti_{50}Al_{50}$
Cathode current (A)	Cr =70, $Ti_{80}Si_{20}$=90, $Cr_{70}Al_{30}$=70	Ti=60, Cr=60, $Ti_{50}Al_{50}$=60	Cr=60, $Ti_{50}Al_{50}$=60
Bias voltage at ion cleaning stage (V)	-800	-800	-800
Bias voltage at coating stage (V)	-100	-150	-150
Substrate temperature (°C)	200-230	230-250	230-250
Reaction gas	Ar、N_2	Ar、N_2	Ar、N_2
Rotation (rpm)	5	2.5	2.5

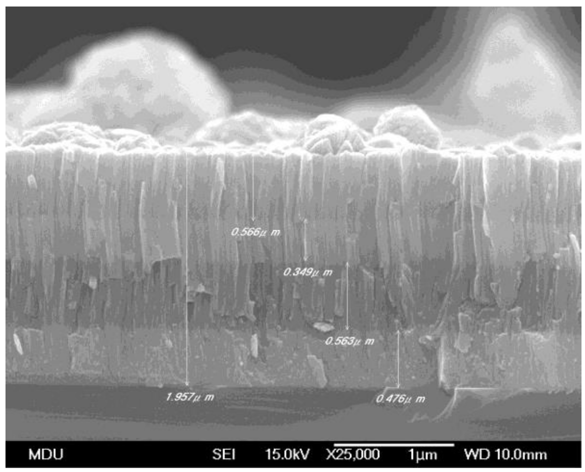
Cross-sectional structures of the deposited Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings were examined in a Joel JSM-7000F high resolution field emission scanning electron microscope (FESEM) equipped with secondary electron imaging (SEI) and backscattered electron imaging (BEI) detectors. The SEM micrograph obtained with backscattered electron detector emphasized the dissimilarity between Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings. Figure 1 shows the Cross-sectional diagrams for Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings. Total thickness of CrAlTiSiN composite, TiAlN/TiN multilayer and TiAlN/CrN multilayer coatings was 1.5 μm, 2.13 μm, and 1.957 μm, respectively. Adhesion of the deposited coatings was assessed using a Rockwell-C indention hardness tester. It uses a standard Rockwell-C ball indenter, causing layered damage adjacent to the indentation boundary. After indentation, a secondary and backscattered SEM was used to evaluate the test. The indentation force (1471 N) is applied to the deposited coatings. Figure 2 shows the typical damage conditions of the deposited CrAlTiSiN composite, TiAlN/TiN multilayer, and TiAlN/CrN multilayer coatings. The failure mode and adhesion strength of the deposited coatings were evaluated using the damaged condition around the indentation crater. By comparison with the VDI 3198 norm, the deposited CrAlTiSiN composite, TiAlN/TiN multilayer, and TiAlN/CrN multilayer coatings possessed HF2, HF2 and HF3 fracture mode, respectively. The CrAlTiSiN composite and TiAlN/TiN multilayer coatings exhibited good film adhesion and TiAlN/CrN multilayer coating presented acceptable film adhesion.



(a) Composite CrAlTiSiN coatings

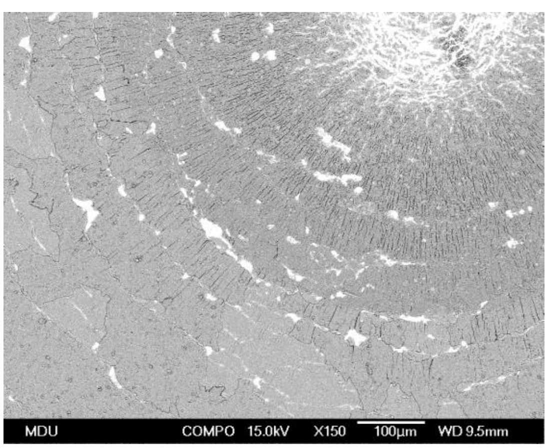


(b) Multilayered TiAlN/TiN coatings

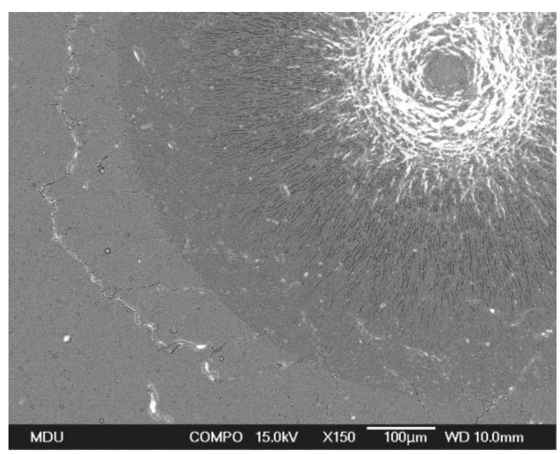


(c) Multilayered TiAlN/CrN coatings

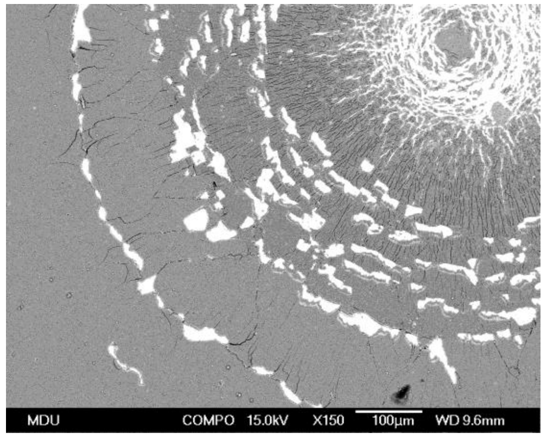
Figure 1. Cross-sectional diagrams for Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings.



(a) Composite CrAlTiSiN coatings (HF2)



(b) Multilayered TiAlN/TiN coatings (HF2)



(c) Multilayered TiAlN/CrN coatings (HF3)

Figure 2. Adhesion diagrams for Composite CrAlTiSiN, multilayered TiAlN/TiN, and multilayered TiAlN/CrN coatings.

3 FRICTION AND WEAR TESTS

Friction and wear tests were carried out on UNMT-1 (Universal Nano and Micro Tribometer, CETR, USA) using reciprocating pin-on-flat mode, surface contact wear mode at room temperature under non-lubricated conditions. The bottom part sample flat is movable and the top pin stay stationary. The friction and wear tests were performed for 15 min at an applied load of 2.5 N. The wear track length was 18 mm. The rotating speed of spindle was 200 rpm. The pins are SKD11 tool steel (HRC 60-62) with diameter of 0.5 mm for each test. The friction force, induced between the pin and the sample, was measured by a force sensor and recorded in a computer automatically. The calculation of friction force divided applied normal force is then to determine the friction coefficient. White light interferometry was used to scan the surface of the test pieces to obtain the sectional areas of the sites of wear, which served as the basis for calculating the wear volumes of each coating under the same condition. For each set of experimental conditions, two tests were repeated and the results given below refer to average values.

The friction and wear between the pin and the coated CrAlTiSiN-, TiAlN/TiN-, and TiAlN/CrN-coated test pieces are evaluated in this study. Figure 3 shows the average friction coefficients between the pin and three CrAlTiSiN-, TiAlN/TiN- and TiAlN/CrN-coated test pieces. The average friction coefficients were 0.67, 0.73, and 0.83 for CrAlTiSiN-, TiAlN/TiN- and TiAlN/CrN-coated pieces, respectively. To evaluate the level of cumulative wear on the CrAlTiSiN-, TiAlN/TiN-, and TiAlN/CrN-coated test pieces caused by abrasion. The surfaces of the test pieces were scanned, and sectional areas of eight locations on the test pieces were measured and averaged. The mean areas were then converted into wear volume. The wear volumes of CrAlTiSiN, TiAlN/TiN, and TiAlN/CrN thin-film coatings were 310,778 μm^3, 271,9488 μm^3, and 421,9463 μm^3, respectively (Fig. 4). The results indicated that the CrAlTiSiN coating yielded a low friction coefficient and minimal wear volume compared with the other two coatings. Thus, the CrAlTiSiN featured the most optimal antiwear property.

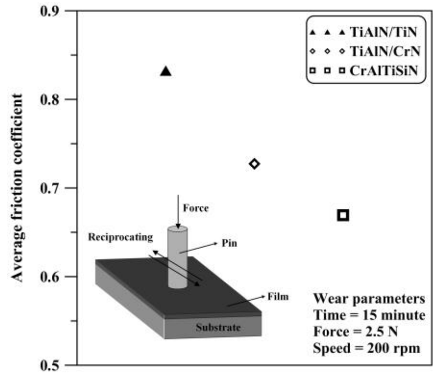


Figure 3. A comparison of the friction coefficients for the three coatings.

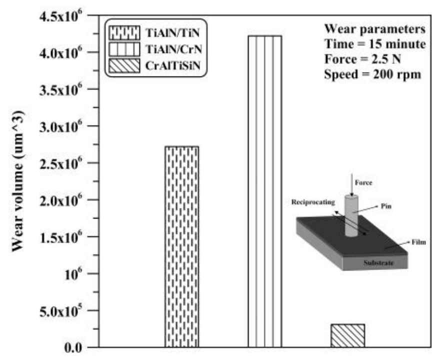
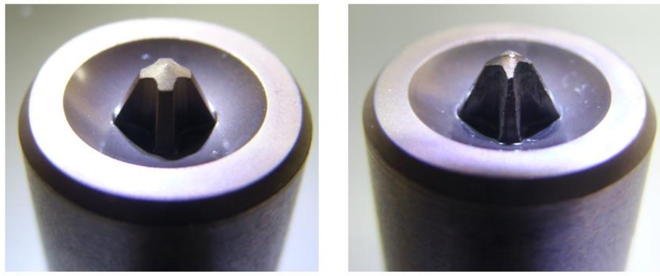


Figure 4. Comparison of the wear volumes for the three coatings.
(Total distance=108000 mm=108 m)

4 EXTRUSION FORGING OF PHILIPS SCREWS

According to the wear test, CrAlTiSiN composite thin-film coating demonstrated excellent antiwear properties; therefore, this coating was applied to Phillips punches (Fig. 5) prior to the extrusion forging of Philips screws. Fig. 6 presents the Phillips punches before and after extrusion forging; signs of wearing were observed on the sides of the punches after extrusion forging. According to ANSI B18.6.3 standards, five random screws were selected to measure the dimension of each part. Table 2 shows the measured dimensions are all comply within the tolerance range. When the wear depth exceeds the screw tolerance, this indicates that the punch has reached the end of its lifespan. Fig. 16 shows that the punches coated with commercial TiN thin films can be used to forge 110,000 screws, whereas the CrAlTiSiN-coated punches developed in this study can forge 130,000 screws. The difference in the number of screws may be attributed to the thickness of thin films: the CrAlTiSiN coating thickness used in this Phillips punches was approximately 0.428 μm, whereas that of commercial TiN thin film is 4–5μm. Table 3 shows the comparison between the number of extrusion forging and the thicknesses of various thin-film coatings.


Figure 5. CrAlTiSiN-coated Phillips punches.



(a) Before (b) After

Figure 6. A comparison of Phillips punches before and after extrusion forging.

Table 2. Measured of screw size after extrusion forging

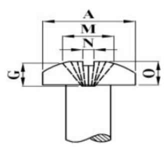
Screw size (mm)	A		O		M		N	G	
	Head diameter		Head height		Dimensions of recess				
					Diameter		Width	Depth	
	Max.	Min.	Max.	Min.	Max.	Min.	Min.	Max.	Min.
	9.474	9.068	3.378	3.099	5.055	4.724	0.787	3.150	2.540
CrAlTiSiN (130,000 screws)	9.257		3.304		4.993		1.105	3.09	
	9.234		3.308		4.999		1.111	3.04	
	9.267		3.330		4.997		1.100	3.06	
	9.252		3.345		4.996		1.114	3.02	
	9.242		3.342		4.987		1.123	3.11	

Figure 7. A comparison of the number of extrusion forgings for Philips screws using various coated punches.

Table 3. A comparison between the number of extrusion forging and the thicknesses of various thin-film coatings.

Thin film	Number of extrusion forging	Thin film thickness (μm)
TiN	110000	4–5
CrAlTiSiN	136000	0.39–0.43

5 CONCLUSION

Currently, the surface processing and coating requirements for dies are crucial to manufacturing industries because these processes can mitigate wear effects, increase product lifetime, and enhance production capacity. Most scholars have focused on coated test pieces and investigated the adhesion property of substrates and thin films under static conditions. Few studies have analyzed coating applications in metal forming. Thus, differences might exist when research results are applied in actual metal forming. In this study, CrAlTiSiN composite thin-film coatings featuring excellent antiwear properties were synthesized and coated onto Phillips punches. The coated punches were used in the extrusion forging of Philips screws. Compared with commercial TiN-coated punches, the CrAlTiSiN-coated punches employed in this study had prolonged lifespan, manufacturing 20,000 more screws. Consequently, increasing the thickness of CrAlTiSiN composite coatings a thickness equal to that of industrial coatings will extend the lifespan of punches and thereby enhance cost-related benefits.

6 ACKNOWLEDGEMENTS

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