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Pre-, intermediate, and post-treatment of hard coatings to improve their performance for forming and cutting tools

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ABSTRACT

Three coating systems, including single-layer AlCrSiN coatings, two-layer CrSiBN/CrN coatings, and single-layer TiAlN coatings were deposited using an arc evaporation system. The effects of various pre-, intermediate, and post-treatments on the properties and performance of the coatings were studied. The tribological properties of the AlCrSiN and TiAlN coatings were evaluated using ball-on-disc tests. The wear behavior of the AlCrSiN coatings was affected by coating morphology. The wear volume of the counter surface increased with the surface roughness of the coating. Furthermore, material transfer and build up to the coating surface were higher for the surfaces treated by grinding and shot blasting than those treated by other methods. The erosion and corrosion properties of the CrSiBN/CrN coatings were evaluated in molten aluminum and sulfuric acid, respectively. Intermediate treatment of the CrSiBN/CrN coatings improved their erosion and corrosion resistance by preventing formation of localized erosion and corrosion. Post-treatment of the TiAlN coatings decreased the amount of material transfer and wear volume of the counter surface. Meanwhile, drilling tests of the TiAlN coatings showed that post-treatment of the coatings improved the drilling regularity and stabilized the spindle torque, which helped to improve tool wear and cutting performance. Based on these results, mechanical surface pre-treatment by processes like micro-blasting, polishing, and buffing, along with plasma nitriding can improve the tribological properties and adhesion of coating systems. Likewise, intermediate and post-treatment of coating surfaces improve erosion and corrosion resistance and cutting performance. In conclusion, the studied treatment processes gave coatings with good performance that are possible candidates for forming and cutting tools.

1. Introduction

Hard coatings have been used in many industrial applications including cutting tools, forming tools, and machine components [1–3]. The hardness and chemical inertness of hard coatings improve wear resistance, decrease friction coefficient, and suppress interaction between a coated part and its surrounding environment. Recently, hard coatings have been widely applied to forming and cutting tools because of their ability to extend working lifetime and lower manufacturing costs.

Hard coatings are manufactured by an integrated process where the surface quality of the base metal and coating surface play important roles in deciding the performance of a coating system. In particular, optimization of the base metal, surface treatment, and deposition parameters is essential to obtain a coating system with good adhesion and working lifetime [4]. Generally, mechanical- and plasma-assisted methods are used to treat the surface of forming and cutting tools. Mechanical surface treatments include micro-blasting [5,6], sand blasting [7], shot peening [8], and/or grinding and polishing [9,10]. Plasma-assisted surface treatments include plasma nitriding [11–13], and/or plasma etching [14–16]. Surface polishing and plasma nitriding of forming tools can increase both coating adhesion strength and resistance to wear and galling [13,12,17]. The surface roughness and topography of post-treated coated cutting tools strongly affect machining performance [18,19,6].

There is a demand to further improve the performance and working lifetime of physical vapor deposition (PVD)-coated forming and cutting tools. Therefore, understanding the effect of surface pre-treatment and coating post-treatment processes on coating properties is an important factor to optimize the performance of hard coatings deposited by PVD in industrial settings.

The aim of this study was to evaluate the effect of various surface treatments on the tribological, erosion, corrosion, and adhesion properties of AlCrSiN and CrSiBN/CrN coatings. In addition, it was aimed to study the effect of post-treatment on the cutting performance of

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Table 1
Samples and coatings investigated.

Coating	Application	Substrate material	Substrate size (mm)	Hardness HRC	Surface treatment before coating[a]
AlCrSiN	Cold pressing	JIS SKD11 or AISI D2	$\phi20 \times 5$	60	SP, SB, G, PP, PB, PB + PN
CrSiBN/CrN	Die casting	JIS SDK61 or AISI H13	$\phi10 \times 120$	47	PB
CrN/CrN CrSiBN/CrN	Machine parts	JIS SKD11 or AISI D2	$\phi20 \times 5$	60	PB
TiAlN	Drilling	WC–Co	$\phi20 \times 5$	HRA 90	PB

[a] SP: shot peening, SB: Shot blasting, G: grinding, PP: paper polishing, PB: polishing and buffing, and PN: plasma nitriding.

TiAlN coatings. The tribological properties of AlCrSiN coatings were examined using ball-on-disc testing. Meanwhile, the erosion and corrosion properties of CrSiBN/CrN coatings were investigated in molten aluminum and sulfuric acid, respectively. The tribological properties of TiAlN coatings were evaluated and their cutting performance during drilling of austenitic stainless steel was assessed.

2. Experimental details

2.1. Substrate preparation and coating deposition

The substrate materials, substrate dimensions, and surface treatments used before coating are summarized in Table 1. To study the effect of surface pre-treatment on the properties of AlCrSiN coatings, JIS SKD11 or AISI D2 substrates were pre-treated before coating by shot peening, shot blasting, micro-blasting, grinding, polishing with abrasive paper, polishing and buffing (mirror-like finish), or plasma nitriding. The purpose of using various pre-treatments was to produce substrate surfaces with varieties of surface roughness and morphology. Shot peening was performed using steel balls and ceramic beads of 40 μm in diameter. Shot blasting were performed using steel grits of 200 to 300 μm in diameter. Micro-blasting was carried out using a gelatin-based medium (500 to 600 μm in diameter) mixed with fine diamond grits (particle size #3000). Grinding was conducted using a conventional horizontal grinding machine with a diamond grinding wheel. Likewise, abrasive polishing was performed using SiC polishing papers moving gradually from 400 to 1000 grits. Plasma nitriding was performed using a mixture of nitrogen and hydrogen gases. The N_2:H_2 ratio was 1:100 for 100-μm-thick nitriding layer and 1:1 for 20-μm-thick nitriding layer. Plasma nitriding time was adjusted to form a 20-μm diffusion zone (at 450 °C) for AlCrSiN coatings and 100-μm diffusion zone (at 510 °C) for CrSiBN/CrN coatings. After plasma nitriding, substrate surfaces were micro-blasted, polished, and buffed using diamond paste with a particle size of 3 μm followed by ultrasonic cleaning in hydrocarbon oil.

Table 2
Target composition and coating parameters.

Coating	PVD target material (at.%)	Negative bias voltage (V)	Total thickness (μm)
AlCrSiN	$Al_{64}Cr_{33}Si_3$	100	3–4
CrN/CrN	Cr_{100}	120	10–12
CrSiBN/CrN	$Cr_{92}Si_3B_5$ and Cr_{100}	100/120	10–12
TiAlN	$Ti_{50}Al_{50}$	50	3–4

The coatings were prepared using a standard cathodic arc ion plating system with two circular targets for deposition and one target for metal ion cleaning and bombardment. Alloyed targets were used for deposition of AlCrSiN, CrSiBN, and TiAlN coatings, and pure chromium targets were used to prepare CrN. Details of the target materials and coating parameters are summarized in Table 2. Before deposition, the substrates were heated at a base pressure of 2×10^{-2} Pa and cleaned by argon plasma etching followed by titanium ion bombardment. Pure reactive nitrogen gas was used for deposition of the coatings. During deposition, the chamber pressure was maintained at about 4 Pa and substrate temperature was held at 450–480 °C. Deposition was performed at an arc current of 150 A. The total thickness of the coatings was adjusted to 3–4 μm for AlCrSiN and TiAlN coatings, and 10–12 μm for CrSiBN/CrN and CrN/CrN coatings.

Deposition of two-layer CrSiBN/CrN and CrN/CrN coatings was interrupted at an approximate thickness of 5–6 μm to apply intermediate treatments, which were micro-blasting and argon plasma etching. After deposition of 5–6 μm of coating, the chamber was cooled and ventilated, then the coating surfaces were micro-blasted. Argon plasma intermediate etching was performed after deposition of the first coating without ventilating the chamber. All substrates were micro-blasted and polished to remove any surface inclusions. The aim of applying intermediate treatments midway through the deposition was to clean coating surfaces by removing any droplets or inclusions, which was expected to prevent formation of continuous pinholes or pores during subsequent deposition. Prior to the consecutive deposition, the coated substrates were cleaned ultrasonically, positioned in the deposition chamber and then a layer with a thickness of 5–6 μm was deposited as described above. Finally, the coating surfaces were micro-blasted to remove surface droplets. Single-layer CrN and two-layer CrSiBN/CrN coatings of the same thickness were also fabricated by continuous deposition without any intermediate treatment or deposition interruption.

JIS SKD61 or AISI H13 samples (ϕ 10 mm × 120 mm) were used for erosion tests with two-layer CrSiBN/CrN coatings. Intermediate micro-blasting and argon plasma etching were conducted as mentioned above. To improve the erosion resistance and thermal fatigue of the tool steel during direct contact with molten aluminum, a 100-μm-thick plasma nitride layer was formed on one sample. Likewise,

Table 4
Pre-treatment processes and properties of AlCrSiN coatings.

Substrate no.	Pre-treatment	Roughness before coating Ra (μm)	Roughness post-treated Ra (μm)	HRC adhesion strength[a]	Friction coefficient	Scratch test Lc3 (N)
ACSN-1	Shot peening	0.148	0.118	HF1	0.83 ± 0.15	85
ACSN-2	Shot blasting and micro-blasting	0.361	0.309	HF1	0.69 ± 0.05	65
ACSN-3	Grinding	0.397	0.400	HF2	0.55 ± 0.05	71
ACSN-4	Paper polishing	0.021	0.021	HF1	0.66 ± 0.09	85
ACSN-5	Polishing and buffing	0.018	0.020	HF1	0.63 ± 0.18	83
ACSN-6	Plasma nitriding	0.013	0.014	HF1	0.67 ± 0.10	114

[a] Results of Rockwell C indentation test were evaluated based on the VDI 3198 standard [20]. HF1: no delamination, HF2: partial delamination.