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Bias effects on the tribological behavior of cathodic arc evaporated CrTiAlN coatings on AISI 304 stainless steel

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ABSTRACT

In this study, CrTiAlN coatings were deposited on AISI 304 stainless steel by cathodic arc evaporation under a systematic variation of the substrate bias voltage. The coating morphology and properties including surface roughness, adhesion, hardness/elastic modulus (*H*/*E*) ratio, and friction behavior were analyzed to evaluate the impact of the substrate bias voltage on the coating microstructure and properties. The results suggest that for an optimized value of the substrate bias voltage, i.e. −150 V, the CrTiAlN coatings showed increased Cr content and improved properties, such as higher adhesion strength, hardness, and elastic modulus in comparison to the coatings deposited by other substrate bias voltage. Moreover, the optimum coatings achieved a remarkable reduction in the steel friction coefficient from 0.65 to 0.45.

1. Introduction

AISI 304 stainless steel is a commonly used stainless steel, as found not only in mundane employment, such as appliances and architecture, but also in sophisticated technology, such as nuclear reactors and cryogenic devices [1,2]. Besides its good corrosion resistance properties, AISI 304 stainless steel offers excellent formability, oxidation resistance, and weldability. Nonetheless, due to its austenitic matrix, the wear resistance of AISI 304 stainless steel is unsatisfactory for specific industrial applications which need wear resistance performance. It is well known that the wear performance of engineering materials can be improved by depositing appropriate coatings [3–7]. For instance, various ceramic nitride films such as CrN, TiN, ZrN, TiAlN, and their combinations can be used to prolong the lifetime of tool steels exposed to abrasive environments in many engineering applications [8–11]. In particular, both CrN and TiAlN thin films can grow in an analogous crystal structure and offer excellent corrosion and wear resistance [12–19]. In recent years, some researchers [20–22] have tried to synthesize Cr–Ti–Al–N quaternary coatings on various substrates mainly by magnetron sputtering method. Some of their conclusions revealed that the hardness and wear resistance of CrTiAlN coatings are superior than those of ternary nitride coatings such as CrTiN and CrAlN [20]; CrTiAlN coatings are reported to be more efficient in enhancing corrosion and wear resistance of titanium alloys as compared to CrN and TiN thin films [21]; and the use of CrTiAlN coatings could also improve the tribological property of Mg alloy [22]. While most CrTiAlN coatings are prepared by magnetron sputtering method, there is a lack of information on the deposition of CrTiAlN films via cathodic arc evaporation (CAE) technology [23]. The CAE method is particularly noteworthy because it offers several advantages such as a high deposition rate and good coating adhesion. Thus, the aim of this paper is to explore the deposition of CrTiAlN coatings on AISI 304 stainless steel using a CAE system controlled at the various bias parameters. Coating characteristics such as structure, chemical composition, average surface roughness, adhesion, hardness (*H*), elastic modulus (*E*), and *H*/*E* ratio were all analyzed. Furthermore, the wear tests were carried out to explore the bias effects on the tribological behavior of the coated steels.

2. Experimental procedure

2.1. Substrate and CAE treatment

The substrates were made of commercial AISI 304 stainless steel (18–20%Cr, 8–10.5%Ni, 0.08%C, 1.0%Si, 1.85%Mn, 0.03%S, 0.045%P, and balance Fe) and had a circular shape with a diameter of 20 mm and a thickness of 5 mm in size for the wear tests. Prior to the CAE process, the substrates were mechanically ground and polished to an average surface roughness of approximately 0.06 μm (Ra value). After a thorough wet cleaning in an ultrasonic bath, the specimens were then fixed in the vacuum chamber and subjected to an argon ion bombardment (ion etching) at a substrate

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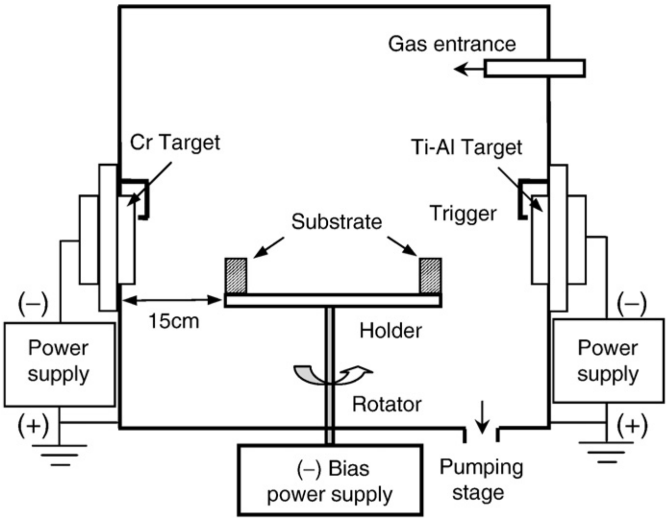

Fig. 1. Schematic diagram of the CAE system used in this study.

Table 1
Parameters of the coating process in this study.

Ar^+ bombardment	−1000 V bias for 10 min.
Base pressure (Pa)	5.3×10^{-3}
Ar partial pressure (Pa)	0.1
N_2 partial pressure (Pa)	1.2
Substrate temperature (°C)	200–230
Cathode current (A)	60
Substrate bias (V)	−90, −120, −150, −180
Holder rotation (rpm)	4
Deposition time (min)	40

bias of −1000 V for 10 min to ensure good adhesion of the deposited films. The argon pressure during the ion etching was set to 0.1 Pa. In addition, the pressure of N_2 reactive gas was kept at 1.2 Pa during the coating growth. Two targets, the chromium metal (99.99 at.%) and the titanium–aluminum alloy (50 at.% Ti–50 at.% Al), were placed on opposite walls of the vacuum chamber to carry out the coating experiment. In order to enhance the coating adhesion, a thin layer of CrN buffer (~0.1 μm) was formed on the specimens via the use of chromium target for 5 min prior to the deposition of CrTiAlN coatings. The variation of substrate bias voltage was mainly set to −90 V, −120 V, −150 V, and −180 V, respectively. The substrate temperature was also measured during CAE process by using a thermocouple located at the vicinity of the specimen's holder. A schematic diagram of the CAE system used in this study is shown in Fig. 1 and Table 1 lists the details of the processing parameters.

2.2. Analysis of coating characteristics

Field emission scanning electron microscope (FESEM, JOEL JSM-6700F, Japan) was used at an accelerating voltage of 15 kV to observe the cross-sectional morphology and to measure the coating thickness of the specimens. The X-ray diffractometer (XRD, MAC Science-M21X, Japan) was employed to identify the coating structure through the use of Cu-target Kα radiation at 40 kV and 30 mA at a low incident angle of 2° and in the scanning angular (2θ) range from 30 to 80° at 2°/min. The chemical composition of the coatings was determined by the electron probe microanalysis (EPMA, JEOL JXA-8600SX, Japan) for Cr, Ti, Al, and N elements. A surface roughness analyzer (Mitutoyo SV-400, Japan) was applied to measure the average surface roughness (Ra value) of the specimens. The adhesion strength quality (ASQ) [24] of the coatings was evaluated using the Rockwell C indentation testing with a load of 150 kg. In addition, nanoindentation experiments were performed using a nanoindenter (MTS XP system, USA) with a diamond Berkovich tip. The hardness and elastic modulus values of the coatings were obtained by

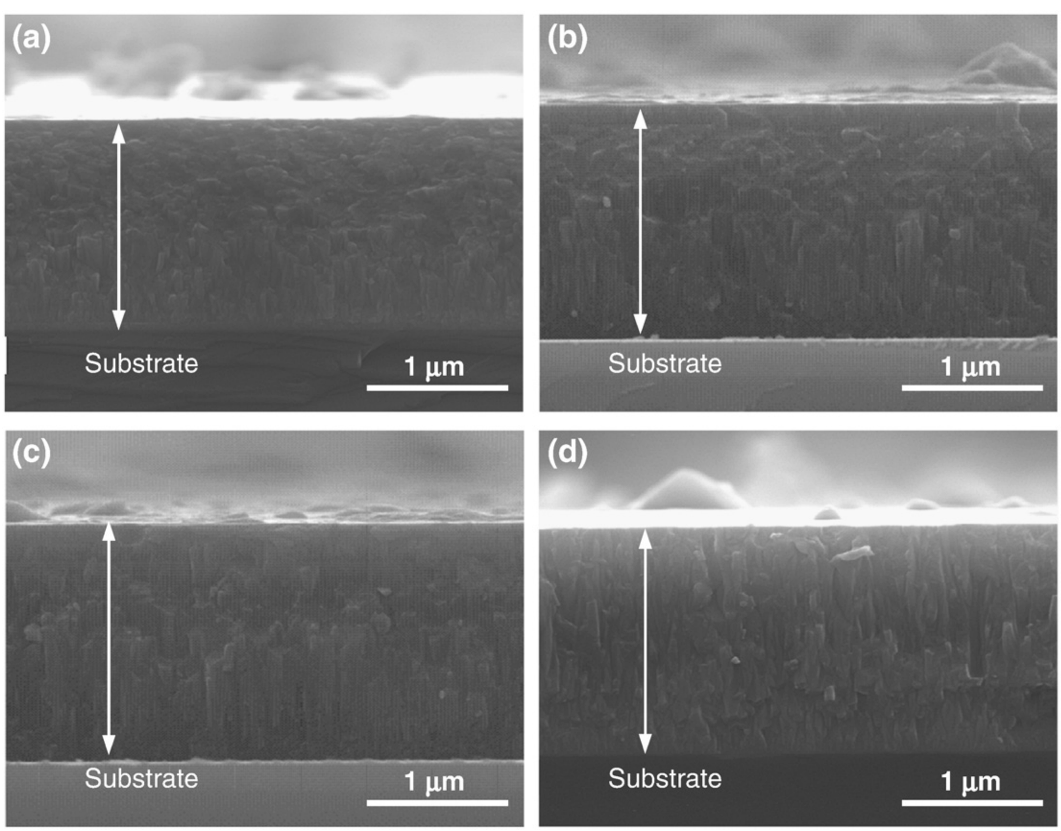

Fig. 2. Cross-sectional view of the CAE-treated specimens at the different bias values: (a) −90 V, (b) −120 V, (c) −150 V, and (d) −180 V.