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Effects of low-temperature duplex coatings on the abrasive and erosive behavior of ADI

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ABSTRACT

This study utilized electroless nickel (EN) and cathodic arc evaporation (CAE) technologies, which have the well-known advantage of low processing temperature (EN = 90 °C and CAE = 230 °C), to treat the austempered ductile iron (ADI) substrate. The eligibility of applying the EN and CAE-CrTiAlN duplex coatings on ADI, along with the coating properties, such as structure, roughness, and adhesion, was evaluated and analyzed. Wear and erosive tests were also performed to further understand the effects of the coatings on the abrasive and erosive behaviors of ADI. The results show that the unique microstructure of ADI does not deteriorate after EN and CAE treatments. With regard to erosion resistance, the duplex coated specimens perform better than do the uncoated and monolithic EN or CrTiAlN coated ones. Moreover, the duplex coatings achieve a remarkable reduction in ADI's friction coefficient from 0.85 to 0.6.

1. Introduction

It is well known that austempered ductile iron (ADI) contains acicular ferrite and high-carbon austenite constituents, aside from nodular graphite, in its microstructure. Compared to some steels, ADI possesses excellent mechanical strength and damping capacity at low cost. Therefore, the subject of much research is to develop ADI's applications in fields such as gears, heavy machinery, transportation industries, etc. [1,2]. However, ADI still faces some abrasive and erosive problems in applications due to a substantial amount of nodular graphite in its matrix.

Surface coating is often applied to cast irons to provide both a pleasing appearance and to improve functions. For instance, the electroless nickel (EN) method has been widely used to modify the corrosive property of cast irons [3]. However, any surface treatments at a high processing temperature may not be suitable for ADI because problems arise when the coating temperature is beyond the austempering temperature range (Ms ~ 450 °C). The high temperature could cause alterations in the ADI's microstructure, resulting in the mechanical deterioration of ADI. Fortunately, there is a suitable technique called the physical vapor deposition (PVD) method, which has a low coating temperature that can coat most metallic surfaces with various films [4,5]. For example, some ceramic nitride films such as CrN, TiN, TiAlN, and their combinations have been smoothly synthesized by the PVD cathodic arc evaporation (CAE) process to improve ADI's mechanical and corrosive properties as mentioned in previous studies [6–8]. In particular, it was found that the CrN coating with an EN interlayer demonstrated high performance in corrosion resistance. It was also reported that Cr–Ti–Al–N quaternary coatings deposited by PVD technology have been identified as one of the more promising protective coatings to serve as tool and nonferrous materials in recent years [9–12]. Despite all of these studies, there is still a lack of information related to the abrasive and erosive wear behaviors of CrTiAlN films as applied to ADI.

Thus, the present work aims to evaluate the eligibility of applying EN as an interlayer of CrTiAlN on ADI by coating it with EN and CAE-CrTiAlN duplex films. To understand the effects of the coatings on the abrasive and erosive wear behaviors of ADI, both abrasive and erosive wear tests were carried out. Also, coating properties such as surface roughness, adhesion, hardness (H), and elastic modulus were analyzed. In addition, the microstructures of ADI were investigated before and after the surface treatments.

2. Experimental procedures

In this study, an analysis of the ductile iron castings by a glow discharge spectrometer revealed that it consisted of 3.56 wt.% C, 2.83 wt.% Si, 0.22 wt.% Mn, 0.039 wt.% P, 0.008 wt.% S, 0.042 wt.% Mg, and Fe balanced. To obtain ADI substrates, the test specimens were cut and machined from the aforementioned to a size of 15 mm × 15 mm × 5 mm, then ground and polished after heat treatment. Following a previous study [13], a single austempering temperature of 360 °C was adopted in order to obtain the highly tough ADI in this trial. The heat treatment involved was carried out in the following orders: (1) preheated at 550 °C for 15 min, (2) austenitized at 900 °C for 1.5 h, (3) immediately quenched in a salt bath of 360 °C for 2 h, and finally (4) air-cooled to room temperature.

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Pre-coating substrates (Ra = 0.35 μm) were thoroughly degreased, ultrasonically cleaned, rinsed with alcohol, and dried by warm air. The various surface treatments given are separately described in the following paragraphs. In the EN process, complex plating solutions (Vand-Aloy 6000) were brought into contact with the specimen's surface, with the solutions acting as a catalyst or the surface pretreated with a catalytic material, under the following plating conditions: containing pH = 5.0, temperature = 90 °C, and rate = 0.35 μm/min. The metallic ion (Ni^{2+}) in the plating solution was reduced and deposited onto the specimen. In the CAE process, two types of the specimens – with and without the EN interlayer – were affixed to the chamber holder for the deposition of the CrTiAlN coating. Two targets of chromium (99.99%) metal and 50%Ti–50%Al alloy, placed on the opposite walls of the vacuum chamber, as well as the reactive gas of N_2 were used to deposit the CrTiAlN film. Consequently, three types of coated specimens were designed as EN-ADI, CrTiAlN-ADI, and CrTiAlN/EN-ADI in this study. The distance between the substrate and the target was about 15 cm and the vacuum pressure was equal to 1.3×10^{-3} Pa. Prior to the deposition, the bombardment of argon ions at a bias of −1000 V for 10 min was carried out to further ensure a good adhesion of the deposited films. The deposition parameters are listed in Table 1.

The optical microscopy was utilized to identify the microstructure of ADI substrates before and after CAE treatment. From two different positions, the specimen's interior and exterior, two sets of the X-ray diffraction (XRD) pattern were separately obtained by using a Rigaku D/MAX-3A diffractometer with Cu K_α radiation for analyzing the coating types and calculating the amount of retained austenite in ADI [14]. SEM was employed to investigate the thickness and cross-sectional morphology of the coatings. A profilometer surfacorded analyzer (Mitutoyo Serftest SV-400) was used to measure the surface average roughness (Ra value) of the specimens within a certain scanning range about 10 mm. The coating adhesion strength quality (ASQ) was evaluated utilizing the Rockwell-C adhesion test with a load of 1470 N [15]. The nanohardness (H), elastic modulus (E), and H/E values of the films were measured using a nanoindenter (MTS XP system, USA) under an applied load of 4 mN corresponding to an indentation depth of approximately 100 nm, where the substrate effect was negligible [16]. For each coating condition, the values of H and E reported were averages of 20 indentations. For a comparison, the surface hardness of the specimens was also obtained by performing Vickers microhardness tests using a load of 0.1 N. Five tests were carried out and averaged to represent the surface hardness of the coated specimens in each condition.

In addition, the wear testing was divided into two types: the abrasion test and the dynamic erosion test. The abrasion tests of the coated and uncoated ADIs were performed on a ball-on-disc tribometer (CSM Instruments, Switzerland). The tests were conducted with no lubricant along a circular track of 30 mm diameter against a 6.0 mm diameter WC ball at 0.3 m/s under a normal load of 10 N in the ambient atmosphere. The relationship between the friction coefficient and the travel distance was continuously recorded during the tests. Another wear-testing type, using a dry particle erosion tester, was adopted to evaluate the dynamic wear behaviors of all the specimens. Al_2O_3 angular particles (~177 μm in size and Moh's hardness scale at 7) of about 5 g were used as the eroding carriers to impinge the specimen for the observation on its eroded surface. The erosion pressure was controlled at a constant value of 3 kg/cm^2 by using an air compressor. The average particle velocity at a distance of 30 mm between the nozzle tip and the specimen was 83.2 ms^{-1}. The internal diameter of the employed nozzle was 5 mm and the impact angle was fixed at a normal impingement of 90°.

Table 1
Parameters of the coating process in this study.

Coating type	CrTiAlN
Two targets	Cr (99.99 at.%) and Ti(50 at.%)–Al(50 at.%)
Working pressure (Pa)	0.2
Substrate temperature (°C)	230
Substrate bias voltage (V)	−150
Evaporation current (A)	60
Reactive gas (flow rate, sccm)	N_2 (300)
Holder rotation (rpm)	4
Evaporation time (min)	35

3. Results and discussion

3.1. Substrate microstructure

Fig. 1 shows a comparison of microstructures between the uncoated and CAE-coated ADI substrates. It was observed that the microstructure of the coated specimen was analogous to the uncoated — all were comprised of acicular ferrite and retained austenite phases besides nodular graphite (Fig. 1a *vs.* Fig. 1b) [13]. Moreover, the content of austenite measured in each matrix was closely maintained at an amount of 26.2–26.4 vol.% before and after the coating treatment. Therefore, both EN and CAE-CrTiAlN processes applied in ADI are not detrimental to the ADI's microstructure.

3.2. Coating properties

The coating properties of ADI, such as coating thickness, surface roughness, adhesion, hardness, elastic modulus, and H/E ratio, obtained in this study are all listed in Table 2. Fig. 2 shows the XRD patterns of the coated and uncoated specimens in this experiment. One can see that the EN film exhibits a typical amorphous structure [6]. By contrast, the XRD patterns of the CrTiAlN film display the same peaks of CrN and TiAlN crystal planes because both have almost the same orientation planes of (111), (200), and (220) at degrees of 37.15°, 43.3°, and 63°, respectively. The result is consistent with the studies by Yang and Tam [9,10]. Thus, it can be deduced that the CrTiAlN coating consists mainly of the mixture of both CrN and TiAlN phases. Fig. 3 shows the SEM cross-sectional view of the coated

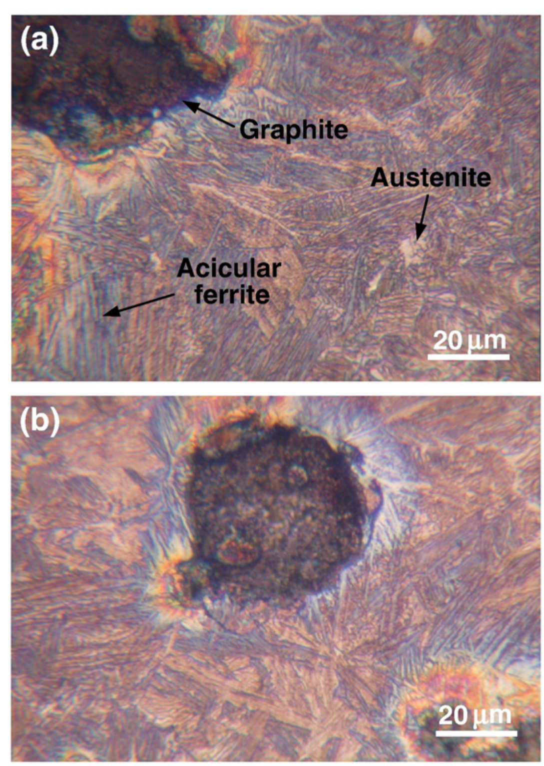

Fig. 1. Microstructure of ADI before and after CAE coating: (a) ADI and (b) CrTiAlN/EN-ADI.