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The friction and wear performance of DLC coatings deposited on plasma nitrided AISI 4140 steel by magnetron sputtering under air and vacuum conditions

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ABSTRACT

Diamond-like-carbon (DLC) coatings with high hardness and low friction coefficient exhibit excellent tribological performance under air and vacuum conditions. However, adhesion and cold welding problems in vacuum conditions lead to increase friction coefficient values. These negative effects can be eliminated by different methods such as forming interlayers between coating and substrate or ion treatment of the substrate. In this work, DLC coatings were deposited on untreated and plasma nitrided (at 400 °C, 500 °C and 600 °C for 1 h and 4 h) AISI 4140 steel substrates by magnetron sputtering technique. The effects of plasma nitriding treatment on the friction and wear properties of DLC coatings under air and vacuum conditions were investigated. The structural and mechanical properties of DLC films were examined by XRD, SEM, and microhardness tester, respectively. The friction and wear properties were determined by a tribotester under air and vacuum conditions. The microhardness of samples increased after surface treatments and the highest value was obtained from the sample plasma nitrided at 600 °C for 4 h plus DLC coated sample. The wear resistance of samples increased with increasing plasma nitriding time and temperature. Also, it was observed that the samples tested under vacuum condition showed better wear resistance than the samples tested under ambient air. Furthermore, increasing plasma nitriding time and temperature improved the wear performance of the material regardless of the test environment.

1. Introduction

Almost every engineering material or system suffers from its poor tribological properties and therefore, friction and wear reduction is one of the most important concerns of energy saving methods. For example, one third of automobiles spend their energy, which is obtained from fuel, for friction. For that reason, reduction of friction or in other words, improving tribological properties of materials is one of the most important challenges in industrial field. In order to overcome this deficiency, carbon or carbon-based materials have been widely used several decades due to their easily modified structure, good electrochemical and mechanical properties [1–3].

Diamond-like-carbon (DLC) films is one of the mostly used protective coatings in order to enhance the tribological behavior of materials in different industrial applications owing to their high hardness, chemical inertness, good wear resistance and low friction coefficient [4–7]. Although it has many advantages in terms of preventing wear loss, it can encounter some problems during its usage period. One of these problems is the adhesion between the substrate and DLC film. Intrinsic stresses and high stiffness between substrates and DLC films can cause to premature failure of coating system [8–11]. Also, cold-welding possibility, which results in high friction coefficient, is another important problem [12–15]. In order to improve the performance of DLC films, as a pre-treatment, plasma nitriding treatment is frequently used. In plasma nitriding treatment, nitrogen atoms penetrate to sub-surface regions of materials and then, they create hard nitrides within material in a plasma environment. Thus, a double-layer structure, which contains compound/white surface layer and diffusion zone, are obtained [16, 17]. When plasma nitriding is used prior to DLC coating, a layered structure is provided for DLC film and consequently, mechanical properties and tribological performance of DLC is improved due to increasing load bearing capacity [18–24].

Different studies were performed to investigate the effects of plasma nitriding pre-treatment on the mechanical [25, 26], tribological [19,

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Table 1
The wear test parameters.

Parameters	
Ball	Al_2O_3
Ball diameter (mm)	6
Laps	5000
Speed (mm/s)	60
Load (N)	2
Wear trace diameter (mm)	10

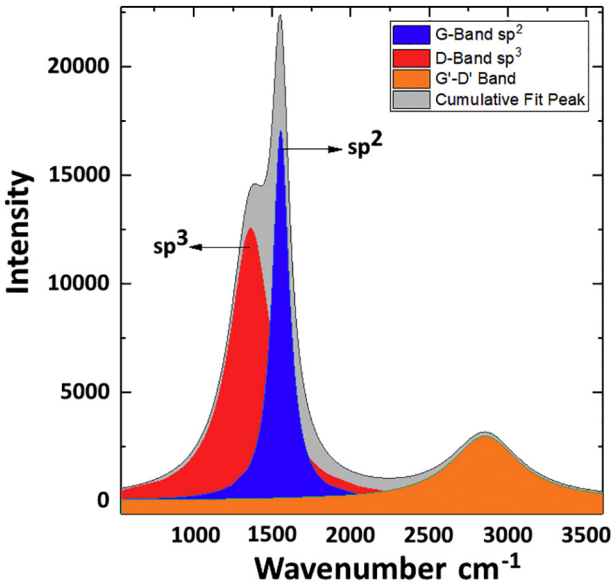

Fig. 1. The typical deconvoluted Raman spectra of DLC film.

Table 2
Characteristic parameters of DLC film obtained from Raman spectra.

	Peak position (cm^{-1})		FWHM		I_D/I_G
	D-band	G-band	D-band	G-band	
DLC	1362	1553	323.71	130.23	0.74

22, 27–29] and electrochemical properties [20] of materials and these studies mainly pointed out that these properties can be enhanced with the duplex treatment consisting of plasma nitriding and DLC. On the other hand, the working environment/condition of this duplex coating system (plasma nitriding + DLC) is another main factor that affects the performance and life of them. The earlier studies showed that the friction and wear behavior of plasma nitrided, DLC coated or duplex treated materials can be improved if an additional lubricant or aqueous media is used [21, 30–36]. In our previous works, we investigated the sliding (under dry, saltwater and lubricant conditions) and adhesion properties of plasma nitrided + DLC coated AISI 4140 [10, 31]. We found that ε-$Fe_{2-3}N$ phase at 400 °C and 500 °C, and γ′-Fe_4N phase at 600 °C for 1 h treated samples were dominant phases. On 4 h treated samples, the intensity of γ′-Fe_4N phase increased in all temperatures [16, 17]. It was found that the hardness and load bearing capacity of DLC film increased due to nitride phases, which provided a hard and durable structure between substrate and DLC film, and this increment thus improved the wear resistance and adhesion properties of material. Also, DLC films show low friction behavior under vacuum conditions [37]. However, the literature survey shows that the friction and wear behavior of duplex treated (plasma nitriding + DLC) materials haven't been examined in detail in terms of different plasma nitriding times and temperatures. For that reason, this study focuses on the investigation of friction and wear behavior of plasma nitrided and DLC coated AISI 4140 alloy under different environments. Therefore, AISI 4140 steel samples were plasma nitrided at 400 °C, 500 °C and 600 °C for 1 h and 4 h and then, DLC films were produced on samples by physical vapor deposition (PVD) magnetron sputtering method. The friction/wear tests were performed by a ball-on-disk tribotester under air and vacuum conditions. XRD, SEM and microhardness tester were used to examine the structural, morphological and mechanical properties of samples.

2. Experimental

In this study, AISI 4140 steel (wt%, 0.36 C, 0.80 Mn, 0.014 Cr, 0.005 Si, 0.30 Ni, 0.85 Mo, 0.075 V, 0.07 S, 0.143 Cu, Balance Fe) substrates with 20 × 20 × 4 mm^3 dimensions were used for plasma nitriding, DLC coating and plasma nitriding + DLC coating. The substrates were grinded using SiC emery papers with 1200 mesh grit, and after polished by alumina powder (grain size of 1 μm), cleaned with ethanol, and dried. Firstly, the substrates were placed in plasma nitriding chamber

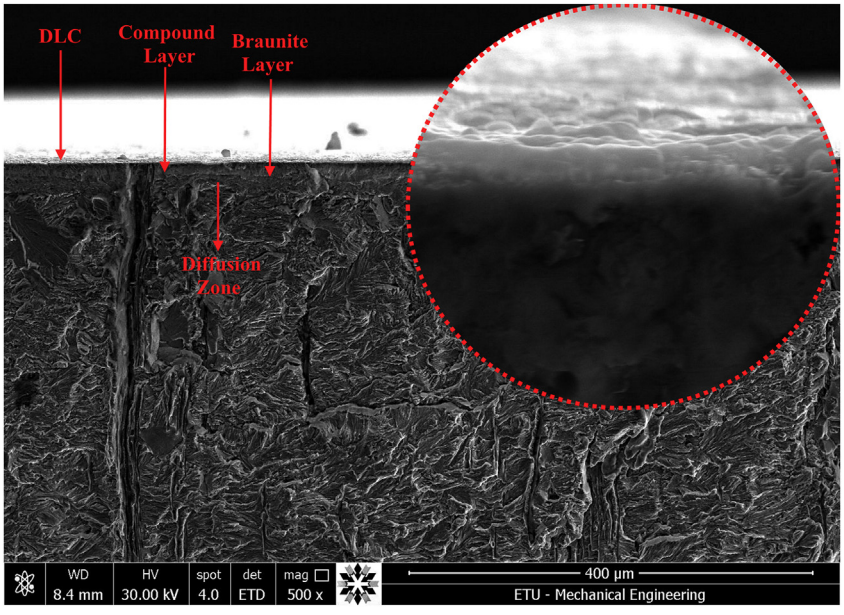

Fig. 2. Cross-section SEM image of plasma nitrided (600 °C and 4 h) plus DLC coated AISI 4140 sample.