Ta-C film deposited on substrate AISI 440 to improve its tribological property

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Due to possessing some advisable inherent properties of pliability, workability and adaptability, AISI 440 (9Cr18 martensitic stainless steel) is applicable for a variety of components in various service conditions, commonly used as a bearing material in the aerospace, nuclear and other special industries [1]. However, when using as precise frictional component, AISI 440 component easily encounter the early failure due to its poor tribological property [2]. Previous studies have revealed that failure of AISI 440 bearings mainly occurs on its surface or in its near surface region [3]. Consequently, enhancing the surface properties by surface treatment is a preferred method to prolong the lifetime and working reliability of such bearing and etc.

Tetrahedral amorphous carbon film (ta-C film) is a typical kind of hydrogen-free carbon film whose sp^3-bonds are among 70–90% and whose remarkable properties are approaching to that of diamond films, such as high hardness, optical transparency and chemical inertness. Comparing with diamond films, ta-C film can be synthesized through a relatively convenient and reliable deposition system, and the tribological performances of ta-C film are better than that of the diamond film due to sp^2bond (graphite-like configuration) existence [4]. Among the various attempts used to prepare the ta-C films, filtered cathodic vacuum arc system (FCVA) is particularly suitable for some experimental and industrial applications, and the obtained high microhardness and exceptional friction-wear resistance properties make ta-C films applicable for wear-resistant application [5].

This research focuses on synthesizing a novel ta-C film on 9Cr18 substrate by FCVA to improve the surface tribological properties of AISI 440 component so as to prolong its working lifetime. Our results exhibit that the microhardness and tribological properties of 9Cr18 component are significantly improved after depositing ta-C film.

Samples of 9Cr18 bearing steel were machined into a size of ϕ 45 mm $\times$ 6 mm from a 9Cr18 steel bar (composition in wt%: Fe, 79.65; Si, 0.80; Mn, 0.72; P, 0.04; S, 0.03; C, 0.96; Cr, 17.80), quenched-and-tempered, and then grounded and mechanically polished to mirror condition, whose surface roughness (R_a) as about 0.04 μm. Some samples were ultrasonically cleaned in an acetone bath; after drying with an infrared ray resource, the samples were put into vacuum chamber ready for deposition. In this case, microhardness of 9Cr18 samples were averagely HV620 at a load of 10 g.

MEVVA source and S-bend filter were used to produce carbon plasma from a graphite cathode target with diameter of 100 mm and purity of 99.9%, and a pulsed mode with a pulsed duration of 25 ms was employed in arc source operation. Pulsed frequency used in this experiment was 25 pulses/s, and MEVVA source was operated at a pulsed current of 100 A, whose schematic diagram was reported in elsewhere [5]. The unwanted neutral and macro-particles were filtered through the S-bend filter. Base pressure was 2×10^{-4} Pa. Before deposition, Cr interlayer about 200 nm and pre-implantation of carbon were conducted on 9Cr18 substrate to enhance the adhesion strength. Under above experimental conditions, ta-C films with different thickness of 300, 500 and 800 nm were deposited on 9Cr18 samples, of which 500 nm one was used for following investigation.

Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were utilized to analyze surface morphology of ta-C film; X-ray photoelectron spectroscopy (XPS) was employed to obtain the bonding structure; nano-indenter was adopted to measure the hardness and elastic modulus; Micro-scratch test was utilized to analyze the adhesion force between ta-C film and 9Cr18 substrate; Ball-on-disc tester equipped with a Si_3N_4 ball, diameter 6 mm, was employed to investigate the tribological performance of ta-C film, under loads of 1, 2 and 5 N and at a constant linear sliding speed about 0.65 m/s, i.e. about 1000 revolutions/min.

Fig. 1 shows topography of ta-C film on 9Cr18 substrate. Since the synthesized ta-C film owns an amorphous state and thus has a poor electrical conductivity for SEM observation. A platinum-sprayed treatment was conducted on ta-C film during actual observation to obtain a better distinguish-ability of SEM. In Fig. 1a, under enlargement factor 7000 of SEM, ta-C film exhibits a very smooth surface without visible "macro-particles" and other surface defects; actually, the similar observations were carried out under enlargement factors of 10000, 20000, 50000 respectively, and the obtained results were consistent. Fig. 1b shows AFM image of ta-C film on a micro area of 1.0 μm $\times$ 1.0 μm, although it seems rough, it is noteworthy that unit of Z

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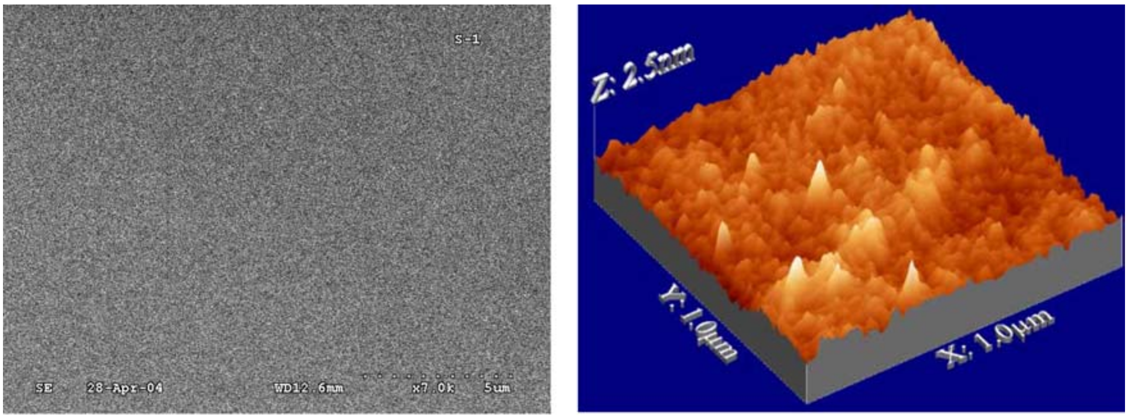


(a) SEM image (7000×) (b) AFM image

Figure 1 Topography of ta-C film on 9Cr18 substrate.

axis is nm; along Z axis, the measured average height is 4.9209 nm, and RMS roughness is 0.682 nm, i.e., this roughness value is even much less than that of polished 9Cr18 substrate, 0.04 μm, indicating ta-C film also plays a beneficial role of improving surface roughness of 9Cr18 substrate. It is believed that such favorable topography of ta-C film will be contributed to its wear resistance.

A typical X-ray photoelectron spectrogram of ta-C film is shown in Fig. 2. The C1s spectrum is deconvoluted into gaussian line shape, one peak at about 285.7 eV is attributed to sp^3 bond, and another peak at about 284.5 eV is attributed to sp^2 bond. In Fig. 2, the sp^3 content of ta-C film is high (about 78%), the others mainly are sp^2 bonds. After conducting similar XPS measurement for three times, it has been calculated that mean sp^3 content of ta-C film on 9Cr18 substrate is 75%.

Fig. 3 shows microhardness and adhesion force of ta-C film on 9Cr18 substrate through the nanoindentation and microscratch tests respectively. It can be seen from Fig. 3a that the hardness and elastic modulus of this ta-C film are 53.79 and 145.79 GPa respectively. Comparing with relatively low hardness of 9Cr19 substrate (about 6 GPa) in this experiment, the hardness of ta-C film is about eight times more than that of 9Cr19 substrate, so the hardness of 9Cr19 substrate has been developed in evidence under ta-C film action. Fig. 3b is one curve of penetration depth vs. scratch distance. After finding the critical change point of friction coefficient (corresponding figure is omitted) for C point in Fig. 3b, the critical load (L_c) of ta-C film can be obtained. Having conducted similar measurement for three times, the measurement results show that L_c of ta-C film on 9Cr19 substrate approaches 44 mN in average. Although the internal stress of ta-C film is high, the good adhesion strength of ta-C film has been obtained. Both the nanoindentaion and microscratch tests have revealed that ta-C film has a high microhardness and a good bearing capability.

The ball-on-disc tester was employed to investigate the frictional performance and endurance of ta-C film on 9Cr19 substrate. It can be seen from Fig. 4: coefficient of friction (COF) of ta-C film on 9Cr18 substrate possesses a low COF value of 0.1, almost one-sixth of that of 9Cr19 substrate (about 0.6) in this experiment; moreover, the COF of ta-C film is stabile up to 26,000 revolutions without failure under 5 N load. By right of these favorable tribological performances, it can be predicted that this ta-C film may be used as a

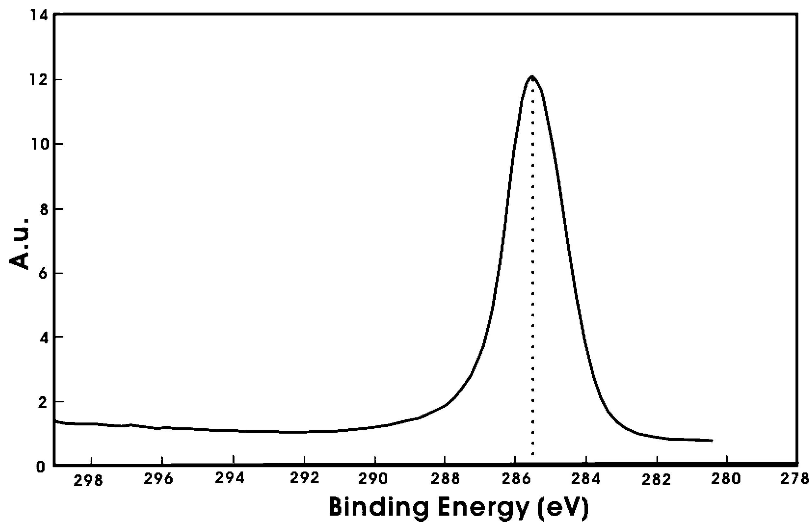
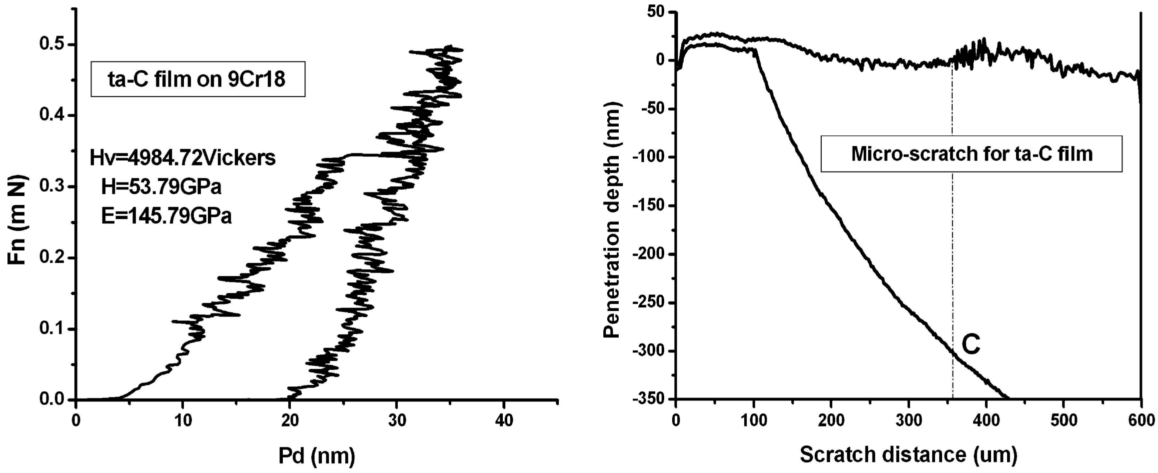


Figure 2 Typical X-ray photoelectron spectrogram of ta-C film on 9Cr18 substrate.



(a) Load-displacement curve of ta-C film (b) Scratch curve of ta-C film

Figure 3 Microhardness and adhesion measurement on ta-C film by nanoindent and microscratch tests.

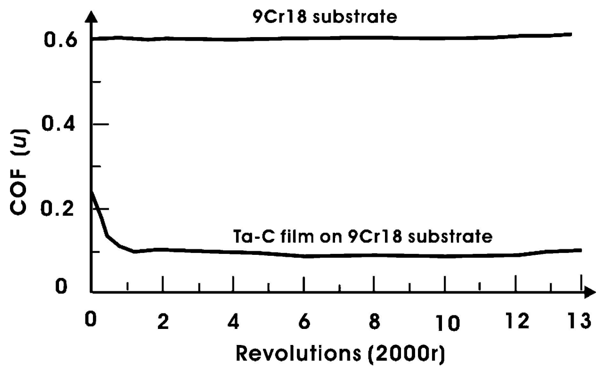


Figure 4 Ball-on-disc test result of ta-C film (applied load 5 N).

good candidate of protective coating for many bearing components in industry applications.

In summary, a new kind of tetrahedral amorphous carbon film has been deposited on 9Cr19 substrate by using FCVA system. This ta-C film possesses some favorable characters: a very smooth surface morphology, a high mean sp^3 content of 75%, a high microhardness and elastic modulus of 53.79 and 145.79 GPa respectively, good adhesion force of L_c 44 mN in average, a low friction coefficient of 0.1 and a longer endurance of stabile 26,000 revolutions. Due to these advisable performances, it is believed that such ta-C film may be a good solution for improving the surface tribology property and developing the working lifetime of precise AISI 440 bearing components in industry applications.

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