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Characterization of surface hardened layers on Q235 low-carbon steel treated by plasma electrolytic borocarburizing

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ABSTRACT

The Q235 low-carbon steel was hardened by plasma electrolytic borocarburizing (PEB/C) process. Surface borocarburizing was carried out in 15% borax aqueous solution with glycerin additive at 290 V under different treating time. The hardened layers on Q235 low-carbon steel were analyzed by SEM, XRD and microhardness test. Corrosion behavior of PEB/C layers was evaluated by potentiodynamic polarization and electrochemical impedance spectroscopy. Their wear performance under dry sliding was measured using a pin-disc friction and wear tester. It showed that the PEB/C layer consisted of a boride (Fe_2B) layer and a transition layer. The thickness of boride layer increased with the borocarburizing time and reached 8 μm after 30 min treatment. The highest microhardness of the boride layer was up to 1450 HV, which was much higher than that of bare Q235 steel with about 170 HV. The PEB/C treatment slightly improved corrosion resistance of Q235 low-carbon steel and the corrosion resistance of the PEB/C treated steel increased with increasing the borocarburizing time, which was ascribed to the formation of boride in the hardened layer. After the PEB/C treatment, the friction coefficient of Q235 low-carbon steel decreased from 0.63 to 0.16. The lowest wear rate of hardened layer under dry sliding against ZrO_2 ball was about 1.438×10^{-6} mm^3/N m, which was only 1/12 of the bare Q235 steel. The PEB/C treatment is an effective method to improve the wear resistance of carbon steel.

1. Introduction

Under severe conditions involving wear and corrosion, the performance of low-carbon steel components might substantially be degraded due to their low hardness and wear resistance. In the past, great effort has been devoted to enhancing the surface mechanical and tribological properties of low-carbon steels [1–4]. The conventional thermal diffusion processes like carburizing and nitriding remain as the most preferred option for treating a large amount of parts at reasonable costs [5–7]. In addition, the boriding on steels is another thermochemical surface hardening process with hardness of 1000–2500 HV [8,9], which is much higher than the hardness of carburizing and nitriding layers.

The conventional boriding processes include salt boronizing, plasma boriding, gas boriding and pack boriding [10–15]. However, these boronizing processes also take disadvantages such as long treating duration, environmental contamination, toxic and explosive nature. Due to the low solubility of boron atom in steel, the boronizing process is more difficult than carburizing and nitriding. Generally, the boronizing steel contains the FeB layer and Fe_2B layer. Although FeB phase is much harder and more common than Fe_2B phase in all kinds of boriding processes, it has low fracture toughness, hence it might fail or delaminate easily from the surface [11–15]. In order to reduce the brittleness of boride layer, the multi-component saturation of boron, carbon and nitrogen atoms are often considered [16,17].

In recent years, plasma electrolytic saturation technique is developed for rapid surface hardening of steels [18–23]. In the plasma electrolytic saturation process, the work piece as a cathode in electrolysis cell is connected to a DC power supply. Aqueous solution is heated to produce a gaseous medium around the work piece and then generate plasma discharges. The discharges around work piece in electrolyte heat the steel surface over 900 °C and enhance rapid diffusion of carbon, nitrogen or boron atoms into the steels. Tarakci et al. [19] and Xue et al. [20] investigated plasma electrolytic surface carburizing (PEC) on pure iron and stainless steel, respectively. Plasma electrolytic nitriding (PEN) and plasma electrolytic nitrocarburising (PEC/N) were also studied by Nie et al. [21,22] and Shen et al. [23]. However, the report about

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plasma electrolytic boronizing (PEB) or borocarburizing (PEB/C) is less [24,25].

In present study, the plasma electrolytic borocarburizing (PEB/C) treatment on Q235 low-carbon steel was carried out in 15% borax aqueous solution with glycerin additive at 290 V for 5 min, 15 min and 30 min. The microstructure, phase constituent, hardness, corrosion resistance and wear resistance of the PEB/C samples were analyzed.

2. Experimental details

As-received Q235 low-carbon steel sheet has a nominal composition (wt.%): 0.14–0.22 C, 0.30–0.65 Mn, ⩽0.30 Si, ⩽0.045 P, ⩽0.055 S, Fe rest. The Q235 steel specimens (55 mm × 16 mm × 1.5 mm) were polished with SiC emery paper up to 1000-grit size. The plasma electrolytic borocarburizing (PEB/C) treatment of these steel samples was performed in 15% borax solution with glycerin additive using a DC power supply unit at applied voltage of 290 V for 5 min, 15 min, and 30 min. The Q235 steel sample and stainless bath acted as cathode and anode, respectively. The negative bias voltage on Q235 steel cathode was initially set in the range of 120–140 V to give rise to a plasma envelope around the samples. When the envelope becomes stable, the voltage was adjusted to 290 V for stable discharge. At the expected time, the power supply was suddenly broken down and the discharge stopped, then the steel samples were automatically quenched in the solution. Following quenching, the samples were removed from the electrolyte and cleaned in running water.

The surface morphology and microstructure of cross-sectional PEB/C treated steel were observed using a Hitachi S-4800 scanning electron microscope (SEM) with EDS composition analyses. The hardness profiles of cross-section of hardened layers were measured using a HX-1 microhardness tester with 25 g load and 15 s dwell time. The phase components of hardened layers were characterized by X'PERT PRO MPD X-ray diffraction (XRD).

The 1–3 μm top surface layer of the PEB/C samples was polished, and a hard and dense borocarburizing layer was left for wear tests. A HT-1000 pin-on-disc friction and wear tester was used to evaluate tribological properties of bare Q235 steel and PEB/C samples under dry sliding with 5 N load and 300 rpm rotating rate against ZrO_2 ceramic ball of 4.763 mm in diameter at ambient temperature. The wear track radius is 5 mm and the sliding time is 10 min. The friction coefficient (μ) was automatically recorded during sliding wear test. The cross-sectional area (S) of wear tracks was measured by a TR200 surface profilometer, thus the wear volume (V) and wear rate (k, mm^3/N m) were calculated from this cross-sectional area according to the formula of $k = V/Fl = \pi dS/Fl$. Where d is wear track diameter, F is normal load and l is total sliding distance of ZrO_2 ball. Finally, the typical morphologies of wear tracks were analyzed by SEM.

The potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) were carried out to evaluate the corrosion resistance of polished PEB/C hardened layers using a PARSTAT 2273 electrochemical workstation in 3.5 wt.% NaCl solution. A conventional three-electrode cell with the bare steel or polished PEB/C samples as the working electrode (0.5 cm^2 exposed area), a platinum coil as the auxiliary electrode and a saturated calomel electrode (SCE) as the reference electrode, was used. The working electrode was immersed in 3.5 wt.% NaCl solution for 30 min exposure duration before tests. Then potentiodynamic polarization tests were performed at a scan rate of 1 mV/s. EIS tests were performed at open circuit potential with AC amplitude of 10 mV over the frequency range of 1 MHz to 0.01 Hz.

3. Results and discussion

3.1. Morphology and microstructure of PEB/C steel

Fig. 1 shows the surface morphologies of PEB/C Q235 low-carbon steel with 5 min, 15 min, and 30 min treatment at 290 V in borax solution with additive. It is evident that many particles and holes caused by strong plasma discharge etching appear on the surface of PEB/C samples. These particles' dimension increases with the treating time. By increasing the treating time, effect of plasma discharge etching on the steel surface is more serious, which results in a surface roughening of PEB/C steel. As shown in Fig. 2, the PEB/C samples with different treating time have a higher surface roughness (R_a) up to 1.57 μm compared to the bare Q235 low-carbon steel (R_a = 0.108 μm). The surface roughness increases with increasing the discharge time, which approximately reveals a parabola relationship. That is consistent with the surface morphologies of different treating time in Fig. 1.

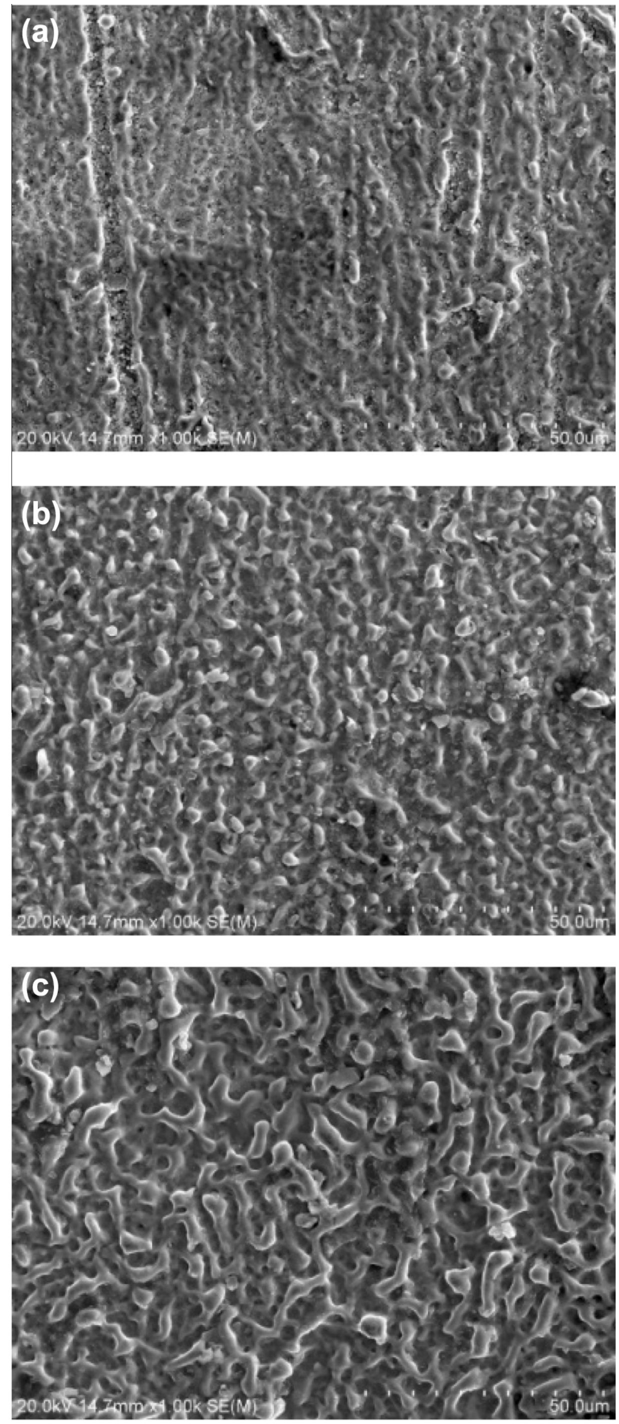

Fig. 1. Surface topography of PEB/C samples treated at 290 V for (a) 5 min, (b) 15 min and (c) 30 min.

The cross-sectional microstructures and composition profiles of the PEB/C Q235 low-carbon steel formed at 290 V for 5 min, 15 min and 30 min as shown in Fig. 3. The surface hardened layers of PEB/C steel for 15 min and 30 min treatment contain a boride layer and a transition layer (see Fig. 3c and e), but Fig. 3a shows the boride layer for 5 min sample is hardly observed. It is believed that 5 min treating time is not long enough to form an integrated boride layer. As shown in Fig. 3d–f, the B concentration in the boride layer for 15 min and 30 min samples is higher than that in the transition layer, but in the top surface layer with 1–3 μm thick, the C and O