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TECHNICAL NOTE

Investigation of Corrosion Behavior of Borided Gear Steels

Muzaffer Erdoğan · Ibrahim Gunes · Alper Dalar

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Abstract In this study, corrosion behaviors of GS18NiMoCr36 (GS 18) and GS32NiCrMo6.4 (GS 32) gear steels borided in Ekabor-II powder at the temperature of 950 °C for 2 and 6 h were investigated in a 6 % M HCI acid solution. The boride layer was characterized by optical microscopy, X-ray diffraction technique and the Micro-Vickers hardness tester. X-ray diffraction analysis of boride layers on the surface of the steels revealed the existence of FeB, Fe_2B, CrB and Cr_2B compounds. The thickness of the boride layer increases by increasing boriding time for gear steels. The hardness of the boride compounds formed on the surface of the steels GS 18 and GS 32 ranged from 1,728 to 1,905 $HV_{0,05}$ and 1,815 to 2,034 $HV_{0,05}$ respectively, whereas Vickers hardness values of the untreated steels GS 18 and GS 32 were 335 $HV_{0,05}$ and 411 $HV_{0,05}$, respectively. The corrosion resistance of borided gear steels is higher compared with that of unborided steels. The boride layer increased the corrosion resistances of gear steels 4–6-fold.

Keywords Gear steels · Boride layer · Micro-hardness · Corrosion

1 Introduction

Boriding is a diffusion surface treatment, which is defined as the enrichment of the surface of a workpiece with boron by means of thermo-chemical treatment. It is well known that the boronized layer has high hardness, high hot hardness and good wear resistance, corrosion resistance and oxidation resistance [1–3]. The boriding process involves heating the material between 700 and 1,000 °C for 1–12 h, in contact with a boronaceus solid powder, paste, liquid, gas plasma, plasma paste and fluidized bed boriding [4–6]. Due to their relatively small size and very mobile nature, boron atoms can diffuse easily into ferrous alloys forming FeB and Fe_2B intermetallic, non-oxide and ceramic borides. The diffusion of B into steel results in the formation of iron borides (FeB and Fe_2B) and the thickness of the boride layer is determined by the temperature and time of the treatment [7, 8].

The corrosion behavior of borided gear steels has not yet been explored extensively, and only a few studies have been reported [9–13]. In these studies, the corrosion resistance of some diverse borided steels was evaluated in several acid solutions (H_2SO_4, and H_3PO_4) for different exposure periods using two different methods: the potentiodynamic polarization experiment and the immersion corrosion test [14, 15]. Studies have been performed with the aim of improving corrosion resistance of gear steels currently used in high-importance machine parts. Surface modification of gear steels is a great focus of interest [16]. GS 18 and GS 32 gear steels are commonly used in the industry in which drive shafts, camshafts, pulleys, machine slide-ways, tanks, weapons and parts for agricultural machinery are produced.

In the present study, the corrosion resistance behaviors of the borided GS 18 and GS 32 gear steels in a 6 % M HCI acid solution are examined. The purpose of the study is to find out whether iron boride diffusion coatings could protect steels from aggressive corrosion environments or not.

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2 Experimental Details

2.1 Boriding and Characterization

Table 1 presents the composition of the untreated GS 18 and GS 32 gear steels. The test specimens were cut into Ø25 × 8 mm dimensions, ground up to 1000G and polished using diamond solution. The boriding heat treatment was carried out in a solid medium containing an Ekabor-II powder mixture placed in an electrical resistance furnace operated at the temperature of 950 °C under atmospheric pressure. Test specimens were sealed in a stainless steel container together with the Ekabor II powder mixture. The holding times for the steel were 2 and 6 h. Following the completion of the boriding process, test specimens were removed from the sealed container and allowed to cool down in still air. The microstructures of polished and etched cross-sections of the specimens were observed under an Olympus BX-60 optical microscope. The presence of borides formed in the coating layer was confirmed by means of X-ray diffraction equipment (Shimadzu XRD 6000) using Cu Kα radiation. The distributions of alloying elements in the boride layer (which elements accumulated in boride teeth and between them) for GS 18 steel were determined by EDS (LEO 1430VP) from the surface to the interior. The thickness of borides was measured by means of a digital thickness measuring instrument attached to an optical microscope (Olympus BX60). Thickness values given in the results section are averages of at least 20 measurements. The hardness measurements of the boride layer on each steel and untreated steel substrate were made on the cross-sections using a Shimadzu HMV-2 Vickers indenter with a 50 g load.

2.2 Corrosion Test

The acid solution used was 6 % M HCI. The aforementioned cylindrical borided specimens and non-borided specimens were weighted before immersion, with an accuracy of 0.01 mg. At specific time intervals the specimens were withdrawn from the solutions and weighted without any additional treatment. Thus, the weight loss in relation to the initially exposed surface was continuously recorded. The immersion tests were repeated 14 times and mean values were used for the acquisition of weight loss curves. Before and after each corrosion test, each sample was cleaned with alcohol.

Table 1 The chemical composition of test materials (wt%)

Steels	C	Si	Mn	P	S	Cr	Ni	Mo
GS18NiMoCr36	0.18	0.58	0.90	0.01	0.015	0.6	0.6	0.3
GS32NiCrMo6.4	0.32	0.60	0.98	0.01	0.003	3.4	1.0	0.6

3 Results and Discussion

3.1 Characterization of Boride Coatings

The cross-section of the optical micrographs of the borided GS 18 and GS 32 steels at the temperature of 950 °C for 2 and 6 h are shown in Figs. 1 and 2. As can be seen in Fig. 1a–d, the boride layer formed on the GS 18 and GS 32 steels have a saw tooth morphology.

It was found that the coating/matrix interface and matrix could be significantly distinguished and the boride layer had a columnar structure. In order to decide whether a uniform boride layer thickness exists in all the specimens, boriding time was monitored regarding the difference in columnar structures. The depth of the boride layers on the surface of the GS 18 and GS 32 steels, depending on the processing time and chemical composition of substrates, ranged from 108.64 to 260.32 μm, from 78.56 to 175.81 μm on GS 32 steel. Micro-hardness measurements were carried out from the surface to the interior along a line in order to see the variations in the boride layer hardness, transition zone and matrix, respectively. Micro-hardness of the boride layers was measured at 12 different locations at the same distance from the surface and the average value was taken as the hardness. Micro-hardness measurements were carried out on the cross-sections from the surface to the interior along a line; see Fig. 3. The hardness of the boride layer formed on the GS 18 steel varied between 1,728 and 1,905 $HV_{0,05}$ and the hardness of the boride layer on the GS 32 steel varied between 1,815 and 2,034 $HV_{0,05}$, respectively. On the other hand, Vickers hardness values were 335 $HV_{0,05}$ and 411 $HV_{0,05}$, for the untreated GS 18 and GS 32 gear steels, respectively. When the hardness of the boride layer is compared with the matrix, boride layer hardness is approximately five times greater than that of the matrix.

In this study, the presences of borides were identified using XRD analysis in Fig. 4a, b. XRD patterns show that the boride layer consists of borides such as AB and A_2B (A = Metal; Fe, Cr). XRD results showed that boride layers formed on the GS 18 and GS 32 steels contained the FeB, Fe_2B and FeB, Fe_2B, CrB, Cr_2B phases, respectively in Fig. 4a, b. With increasing time and temperature, the Fe_2B phase content decreases and the FeB and CrB phases content increases for the GS 32 steel. The boride layers mainly consist of intermetallic phases as a result of the diffusion of boron atoms from the boriding compound to the metallic lattice with respect to the holding time. The properties of these boride layers are known to a large extent with the help of these phases [17–19].

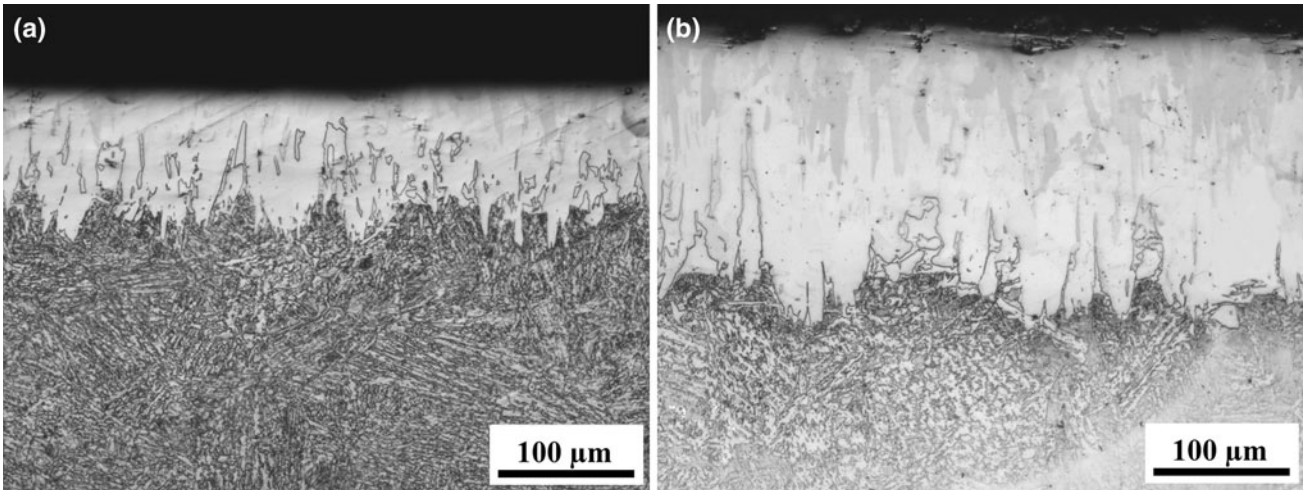


Fig. 1 The cross-section of borided GS 18 steel at 950 °C (**a**) 2 h, (**b**) 6 h

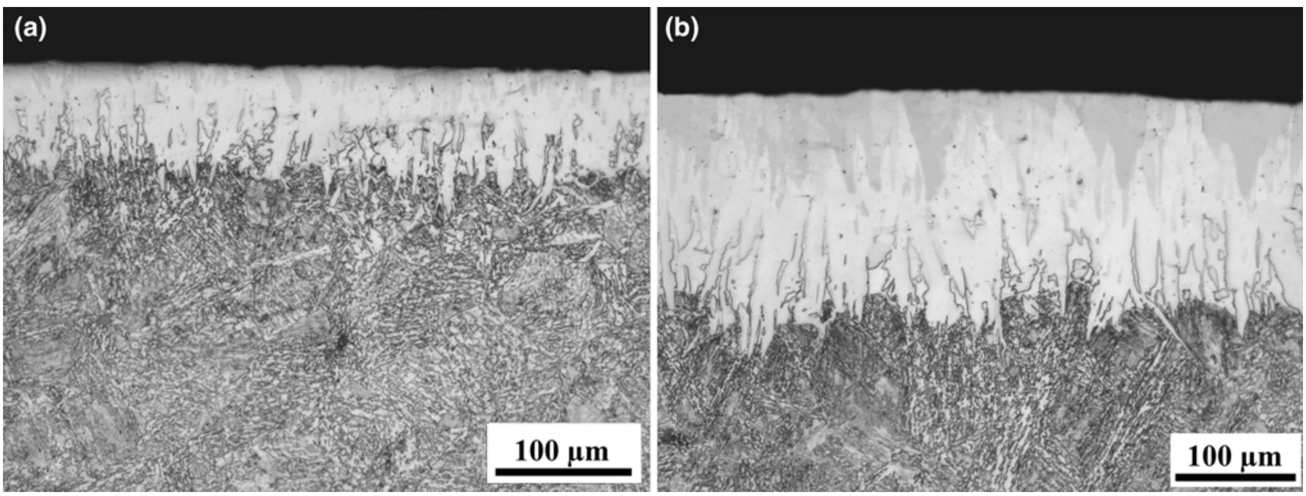


Fig. 2 The cross-section of borided GS 32 steel at 950 °C (**a**) 2 h, (**b**) 6 h

3.2 Corrosion Behavior

Figures 5 and 6 show the EDS analyses carried out on the GS 18 and GS 32 steels borided at the temperature of 950 °C for 2 and 6 h after the corrosion tests. Oxides were observed on the surface of the specimen after the corrosion test. Oxide peak intensities formed on the surface of the specimens were found to decrease with the increase in boriding time (Fig. 5a, b and Fig. 6a, b). After the corrosion test, porosity and pits were observed to form on the borided specimen. The corrosion resistance of boron-coated steel usually depends on the characteristic features of coatings such as the number of microcracks and porosities. These porosities negatively affect the firmness of coatings and significantly reduce the corrosion resistance. The number of these voids is associated with the microstructure of the coating [14, 20, 21]. Figure 7 shows the surface roughness values of the borided gear steels, before and after corrosion tests. For the gear steels, it was observed that surface roughness values increased after corrosion tests (Fig. 7a, b). This result indicates that the increase in boride layer thickness affects both the surface roughness and corrosion resistances of gear steels. At the end of these tests, the variation of weight loss depending on time was obtained and given in Fig. 8 for the 6 % M HCI solution. Weight loss in the untreated specimen after the corrosion was observed to increase rapidly with the increase in processing time. It was detected that while the weight loss in the corrosion test solution during 120 h was 78.62 mg, the corrosion weight loss of the raw specimen increased to 194.38 mg. after 240 h for GS 18 (Fig. 8a). The lowest weight loss was observed in the borided

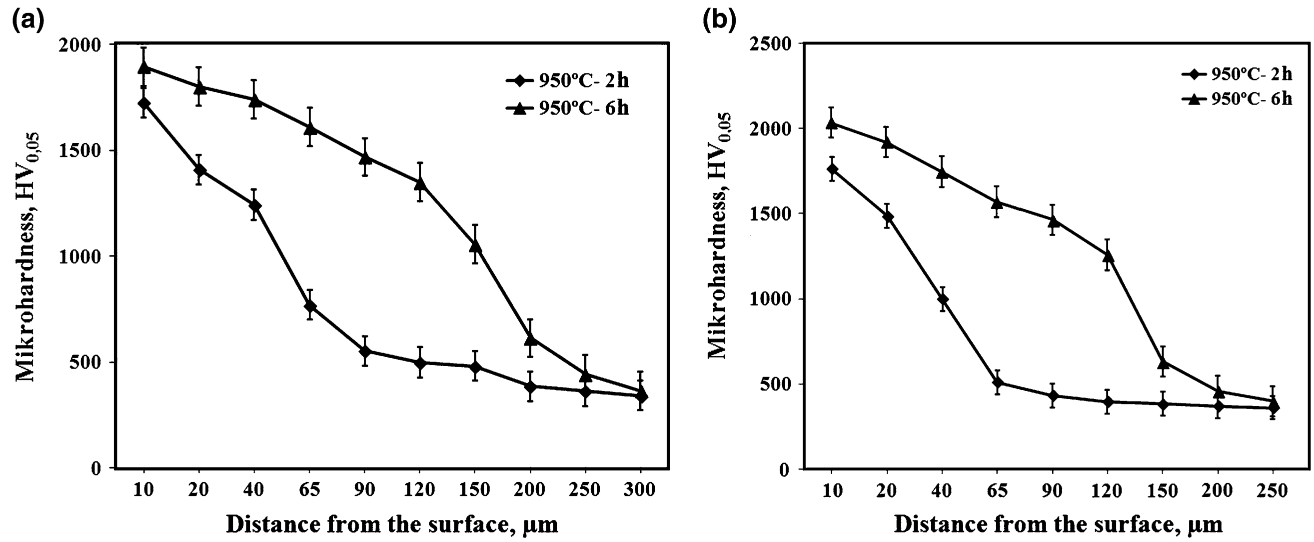
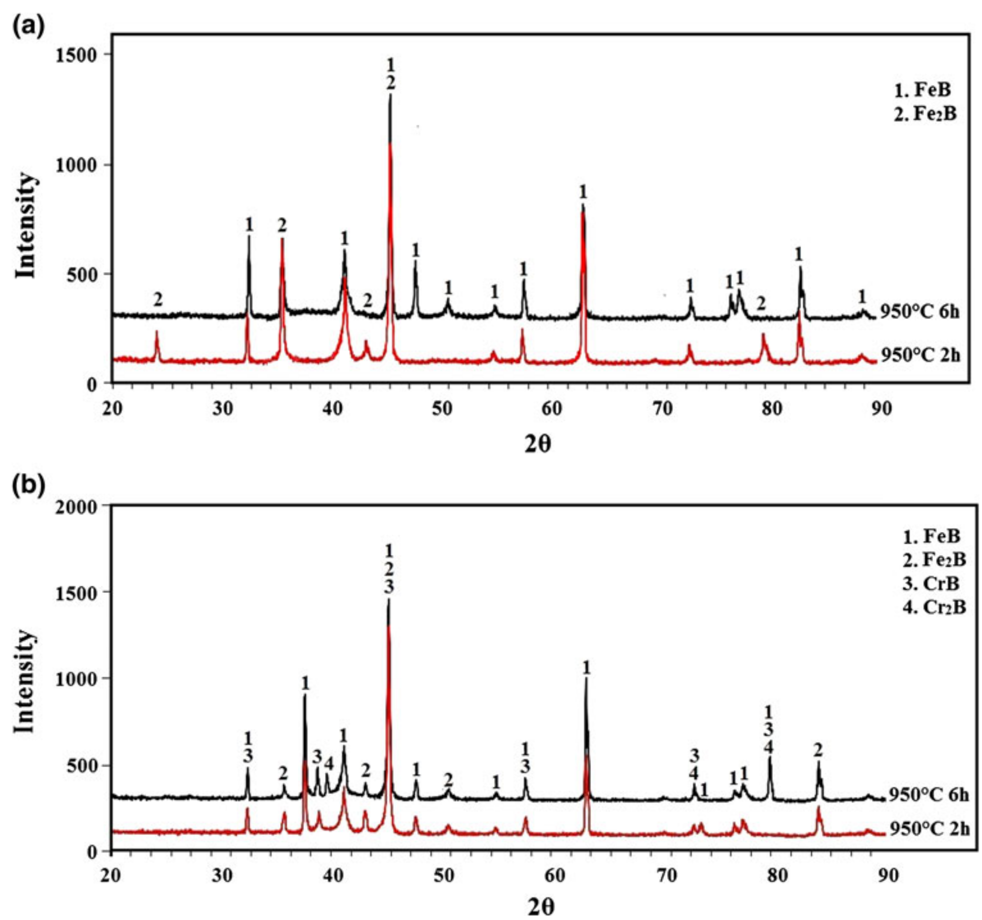


Fig. 3 The variation of hardness depth in the borided steels at 950 °C for 2 and 6 h (**a**) GS 18, (**b**) GS 32

Fig. 4 X-ray diffraction patterns of borided steels at 950 °C for 2 and 6 h (**a**) GS 18, (**b**) GS 32



specimen (34.82 mg.) at a temperature of 950 °C for 6 h for GS 18 steel. While the weight loss of the unborided specimen was 194.38 mg. this value dropped to 34.82 mg. as a result of the borided process for GS 18 steel. The highest value of weight loss was observed in the unborided specimen (132.76 mg.), while the lowest weight loss was

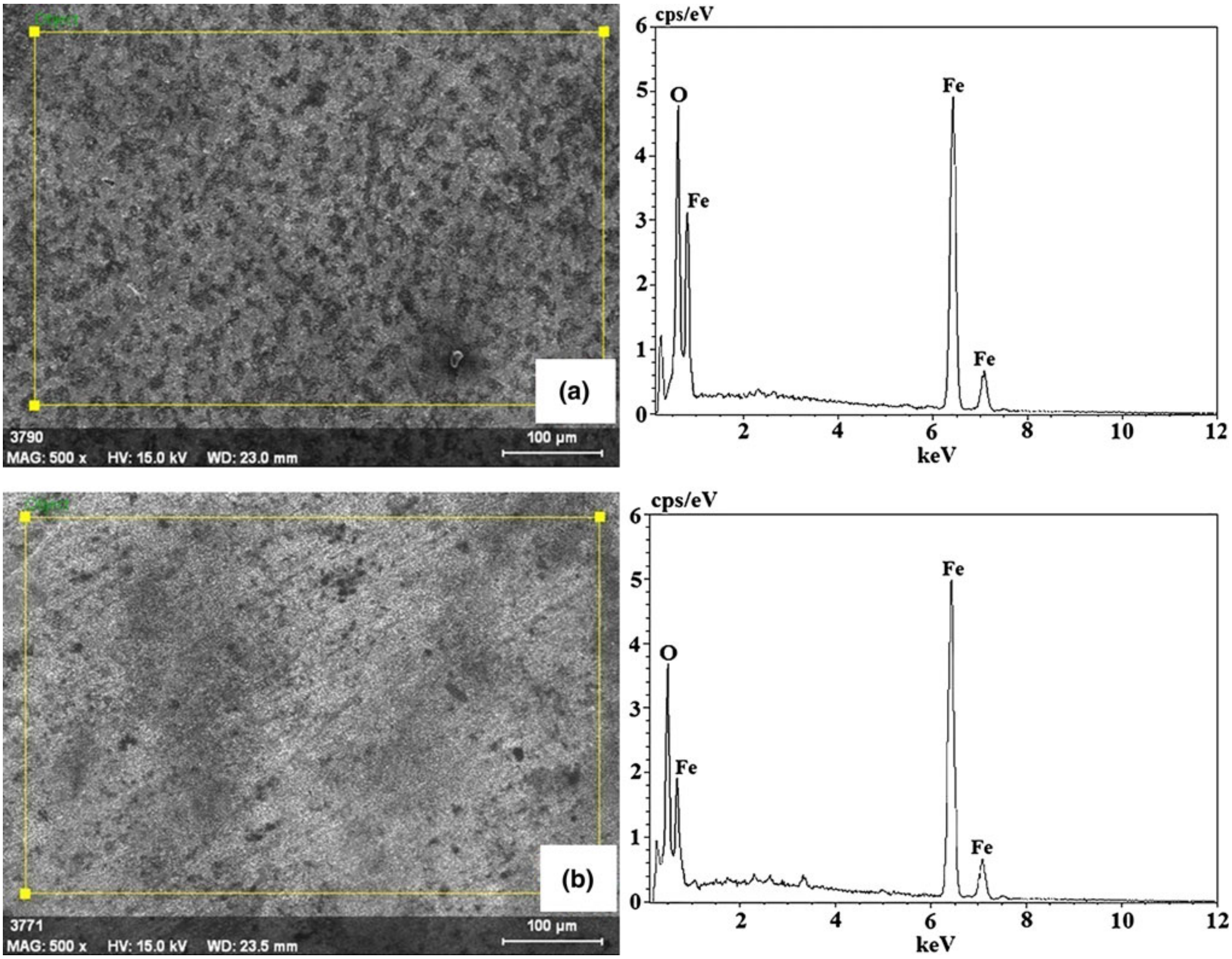


Fig. 5 EDS analyses of GS 18 steel surface in 6 % M HCl solution (**a**) 950 °C—2 h, (**b**) 950 °C—6 h

observed in the borided specimen (20.94 mg.) at a temperature of 950 °C for 6 h in GS 32 steel (Fig. 8b). The solubility of corrosion in the untreated specimen doubled. As shown in the corrosion graphic curves, the solubility of corrosion decreased with the increase in the boron layer thickness of the specimens. In addition, it was observed that the decreased solubility of corrosion in the borided specimens led to a decrease in the amount of material loss. The solubility of corrosion in the specimens borided at 950 °C for 2 and 6 h was observed to be six times lower than in the untreated specimens. As result the corrosion resistances of the GS 18 and GS 32 gear steels increased with the increase in boriding time.

4 Conclusions

The following conclusions may be derived from the present study.

1. As a result of metallographic examinations of the borided specimens, it was observed that the coating-matrix interface morphology has a saw smooth morphology.
2. Depending on the process time, temperature and chemical composition of substrates, the depth of the boride layers on the surface of the GS 18 steel ranged from 108.64 to 260.32 µm and from 78.56 to 175.81 µm on GS 32 steel.
3. The multiphase boride coatings that were thermo chemically grown on the GS 18 and GS 32 steels were constituted by the FeB, Fe_2B and FeB, Fe_2B, CrB, Cr_2B phases, respectively.
4. The surface hardness of the borided GS 18 steel was in the range of 1,728–1,905 $HV_{0,05}$, while for the untreated GS 18 steel substrate it was 335 $HV_{0,05}$. The surface hardness of the borided GS 32 steel was in the range of 1,815–2,034 $HV_{0,05}$, while

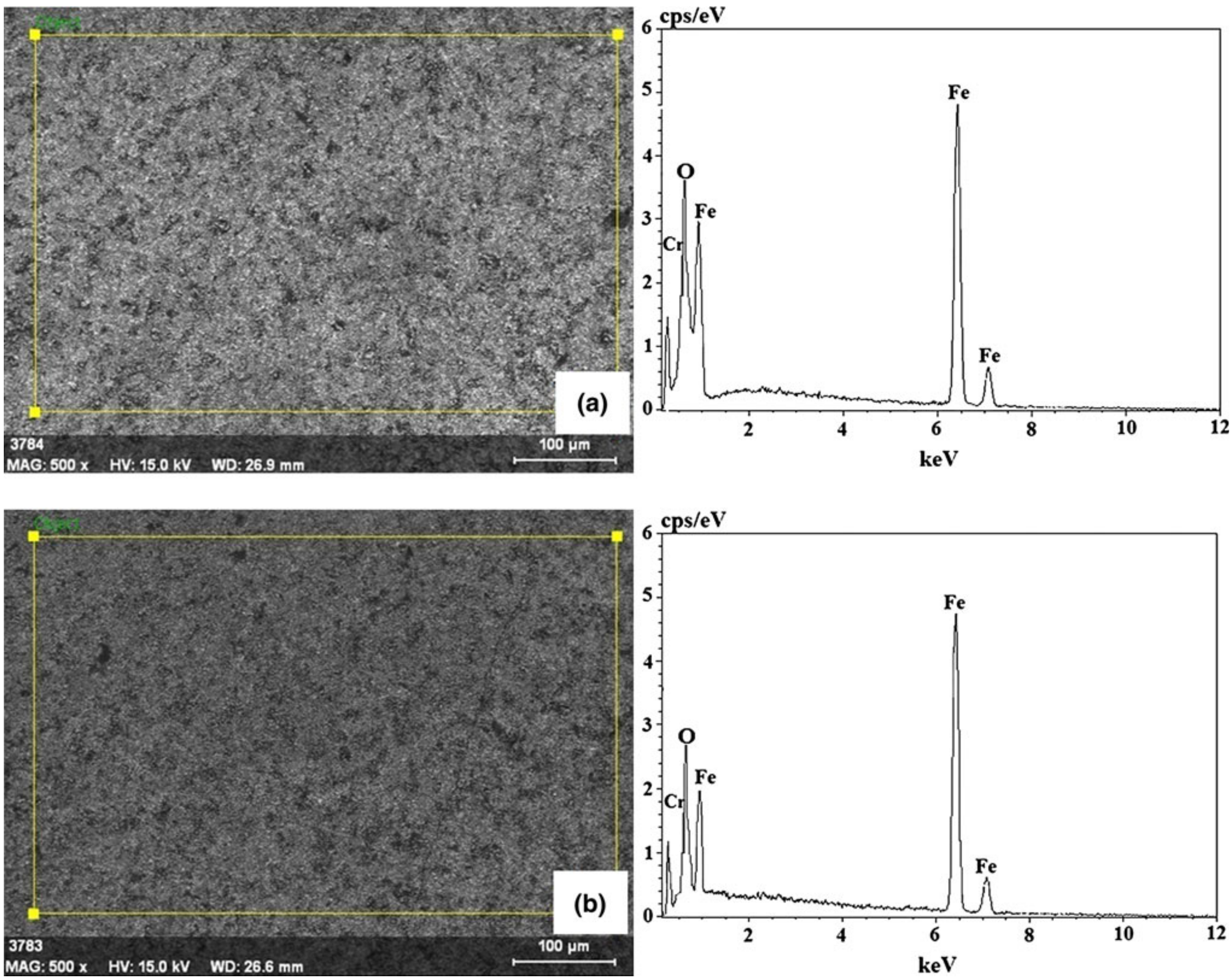


Fig. 6 EDS analyses of GS 32 steel surface in 6 % M HCl solution (**a**) 950 °C—2 h, (**b**) 950 °C—6 h

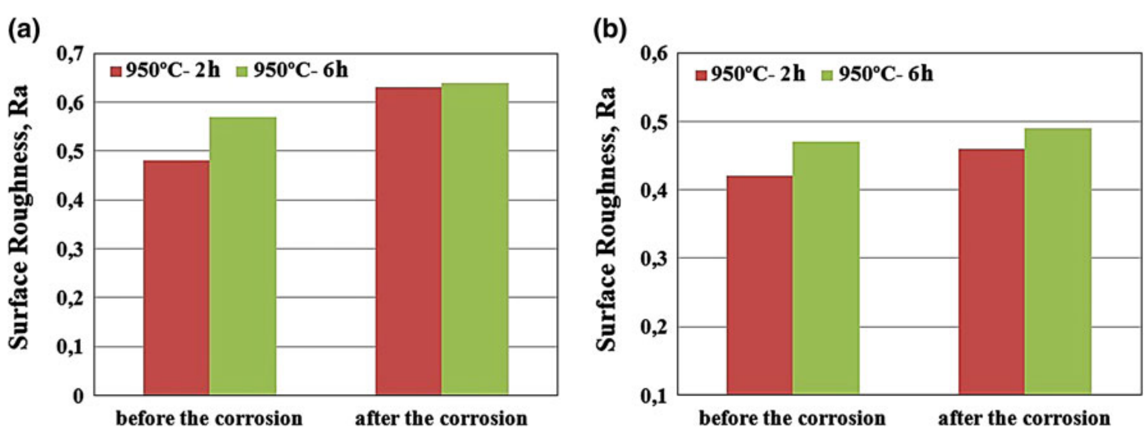


Fig. 7 The variations in the surface roughness values of the borided gear steels, before and after corrosion tests (**a**) GS 18, (**b**) GS 32

for the untreated GS 32 steel substrate it was 411 $HV_{0,05}$.

5. The boride layer increased the corrosion resistances of gear steels 4–6-fold.
6. The superior properties of the GS 18 and GS 32 gear steels as well as poor corrosion properties were improved by the boriding process.

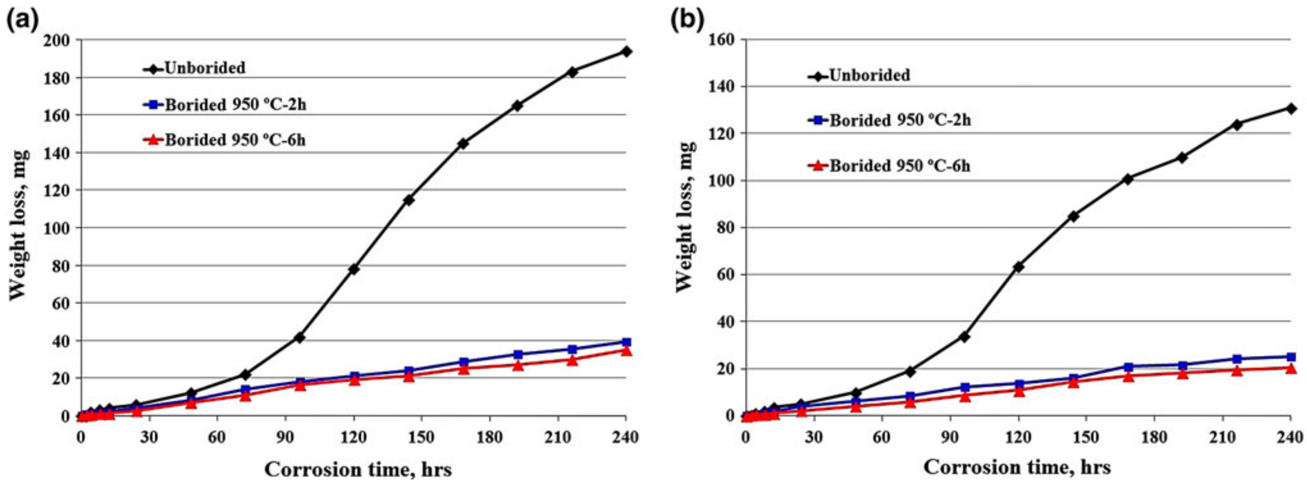


Fig. 8 Weight loss of immersion tests of the borided gear steels in 6 % M HCI solution (**a**) GS 18, (**b**) GS 32

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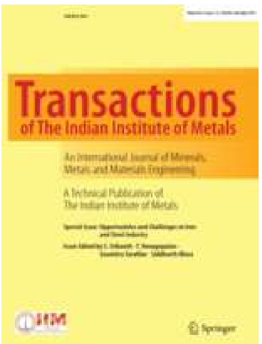

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