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EFFECT OF SLIDING SPEED ON FRICTION AND WEAR BEHAVIOUR OF BORIDED GEAR STEELS

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ABSTRACT

In this study, the wear behaviour of GS18NiMoCr36 (GS18), GS22NiMoCr56 (GS22) and GS32NiCrMo6.4 (GS32) gear steels borided in Ekabor-II powder was investigated by conducting a series of experiments at temperatures of 1123, 1173 and 1223 K for 2 and 6 h. 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 wear tests were carried out in a ball-disc arrangement under a dry friction condition at room temperature with an applied load of 10 N and with sliding speeds of 0.2, 0.3 and 0.4 m/s at a sliding distance of 500 m. Wear surfaces of the samples at the different sliding speeds were inspected using SEM microscopy and X-ray energy dispersive spectroscopy (EDS). The friction coefficients of the GS18, GS22 and GS32 borided steels varied from 0.41 to 0.59, from 0.42 to 0.58 and from 0.36 to 0.54, respectively. As a result of wear, the friction coefficient was observed to decrease with an increase in the sliding speed of the borided gear steels while an increase was observed in wear resistance.

Keywords: boriding, gear steels, wear rate, sliding speed.

AIMS AND BACKGROUND

Boriding is a surface treatment which is technically well developed and widely used in industry to produce an extremely hard and wear-resistant surface layer on metallic substrates. Borided steel components display excellent performance in several tribological applications in mechanical engineering and automotive industries. Borided steels exhibit high hardness (about 2000 HV), high wear resistance, and improved oxidation and corrosion resistance[1–4]. The boriding process involves heating the material in the range of 973–1273 K for 1–12 h, in contact with a boronaceus solid powder, paste, liquid, gas plasma, plasma paste and fluidised bed boriding[5–7].

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Boriding of various steels has been an object of scientific interest for many years due to efforts to develop and optimise the surface techniques of these materials. The application of boriding is mostly aimed to reduce the friction coefficient of sliding couple tool/worked material and to improve the wear resistance[8]. For practical applications, the formation of a single-phase layer (Fe_2B) is more desirable than a dual-phase layer comprising FeB and Fe_2B. This is because, although the boron-rich FeB phase is harder, it is more brittle than the iron sub-boride, Fe_2B phase. Furthermore, crack formation is often observed at the FeB/Fe_2B interface of a dual-phase layer, as FeB and Fe_2B phases exhibit substantially different coefficients of thermal expansion. These cracks often lead to flaking and spalling when a mechanical load is applied. One of the important properties of a borided layer is that it keeps its hardness in subsequent heat treatment[9,10].

Studies are being performed with the aim to improve tribological performances of gear steels currently used in high-importance machine parts, especially in places exposed to wear. GS18NiMoCr36, GS22NiMoCr56 and GS32NiCrMo6.4 gear steels are commonly used in the industry which drive shafts, cam shafts, pulleys, machine slide-ways, tanks, weapons and parts for agricultural machinery. The wear behaviour of borided steels has been evaluated by a number of investigators[11–13]. However, there is no research on the effect of sliding speed on the wear behaviour of steels. The main objective of this study was to investigate the effect of sliding speed on the friction and wear behaviour of borided GS18, GS22 and GS32 gear steels.

EXPERIMENTAL

Boriding and characterisation. Table 1 gives the composition of untreated GS18, GS22 and GS32 gear steels. The test samples were cut into ∅25×8 mm dimensions and ground up to 1000 G and polished using diamond solution. Boriding heat treatment was carried out by using a solid boriding method with commercial Ekabor-II powders. All samples to be borided were packed in the powder mix and sealed in a stainless steel container. Boronising heat treatment was performed in an electrical resistance furnace under atmospheric pressure at 1123, 1173 and 1223 K for 2 and 6 h followed by cooling in air.

The microstructures of the polished and etched cross-sections of the samples 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 CuKα radiation. The distributions of alloying elements in the boride layer for GS18, GS22 and GS32 steels 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. Microhardness measurements were done from the surface to the interior along a line to see variations in the hardness of the boride layer, transition zone and matrix, respectively. The

Table 1. 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	0.4	0.3
GS22NiMoCr56	0.22	0.60	0.92	0.01	0.005	0.9	0.6	0.9
GS32NiCrMo6.4	0.32	0.60	0.98	0.01	0.003	3.4	1.0	0.6

microhardness of the boride layers was measured at 12 different locations at the same distance from the surface by means of a Shimadzu HMV-2 Vickers indenter with a load of 50 g and the average value was taken as the hardness.

Friction and wear. To perform friction and wear of borided samples a ball-on-disc test device was used. In the wear tests, WC-Co balls of 8 mm in diameter supplied by H.C. Starck Ceramics GmbH were used. Errors caused by the distortion of the surface were eliminated by using a separate abrasion element (WC-Co ball) for each test. The wear experiments were carried out in a ball-disc arrangement under a dry friction condition at room temperature with an applied load of 10 N and with sliding speeds of 0.2, 0.3 and 0.4 m/s at a sliding distance of 500 m. Before and after each wear test, each sample and abrasion element were cleaned with alcohol. After the test, the wear volumes of the samples were quantified by multiplying cross-sectional areas of wear by the width of the wear track obtained from a device Tribotechnic Rugosimeter. The wear rate was calculated with the following formula:

$$\text{wear rate} = \text{worn volume} / (\text{applied load} \times \text{sliding distance}),\ \text{mm}^3/\text{N m}. \qquad (1)$$

Friction coefficients depending on sliding distance were obtained through a friction coefficient program. Surface profiles of the wear tracks on the samples and surface roughness were measured by a Tribotechnic Rugosimeter. Worn surfaces were investigated by scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDS).

RESULTS AND DISCUSSION

Characterisation of boride coatings. The cross-sections of the optical micrographs of the borided GS18, GS22 and GS32 steels at temperatures of 1123, 1173 and 1223 K for 6 h are given in Fig. 1. As can be seen in Fig. 1*a–c*, the boride layer formed on GS18, GS22 and GS32 steels have saw-tooth morphologies. It was found that the coating/matrix interface and matrix could be significantly distinguished and the boride layer had a columnar structure[14,15].

The boride layer thickness changes depending on boriding temperature and time are shown in Fig. 2. Depending on the process time, temperature and chemical composition of substrates, the depth of the boride layer ranged from 15 to 260 μm. Boride layers on the surface of the GS18 steel ranged from 35.14–260.32 μm, from 20.45–204.52 μm on the GS22 steel and from 15.68–175.81 μm on the GS32 steel. The boride layer thickness increases with increasing boriding temperature and time for each steel. The boride layer value of GS18 is higher than that of GS22 and

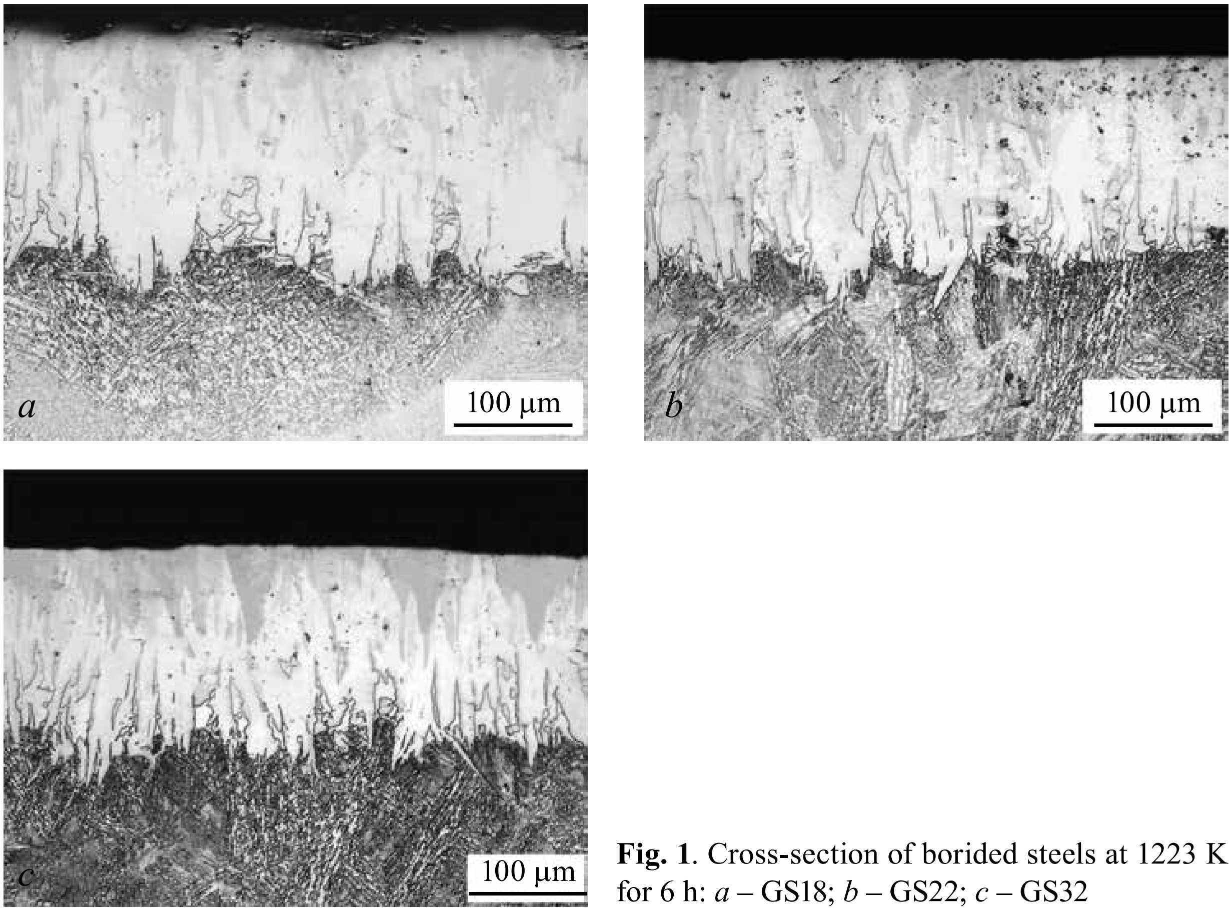


Fig. 1. Cross-section of borided steels at 1223 K for 6 h: *a* – GS18; *b* – GS22; *c* – GS32

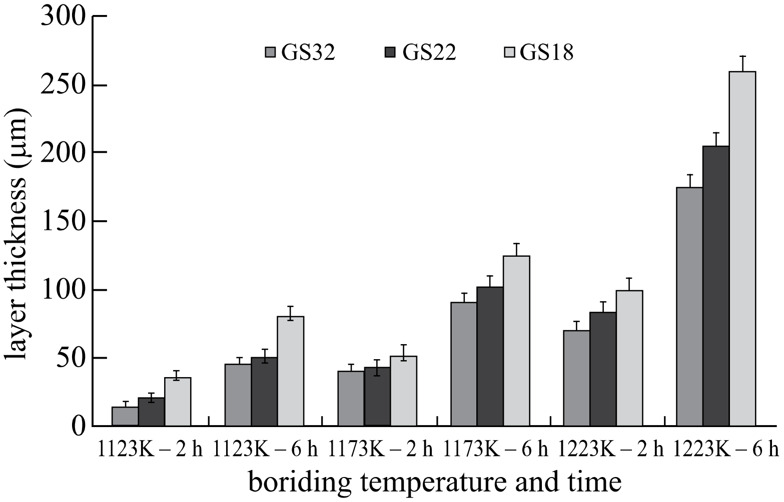


Fig. 2. Thickness values of boride layers with respect to boriding time and temperatures

GS32 due to its low content of alloying elements. Efe et al.[16] borided 31CrMoV9 and 34CrAlNi7 steels with Ekabor 2 boron powder at 1123–1223 K for 2–8 h and reported that some alloying elements (Cr and Ni) had a negative impact on the diffusion of boron atoms into the steel surface. As a result of the boriding process the boride layer thickness increases with increasing boriding temperature and time, and depends on the chemical composition of steel[17–19]. The X-ray diffraction patterns of the borided steels are given in Fig. 3. XRD patterns showed 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 GS18, GS22 and GS32 steels contained FeB, Fe_2B

and FeB, Fe$_2$B, CrB and FeB, Fe$_2$B, CrB, Cr$_2$B phases, respectively (Fig. 3*a*–*c*). With increasing boriding temperature and time, the Fe$_2$B phase content decreases and the

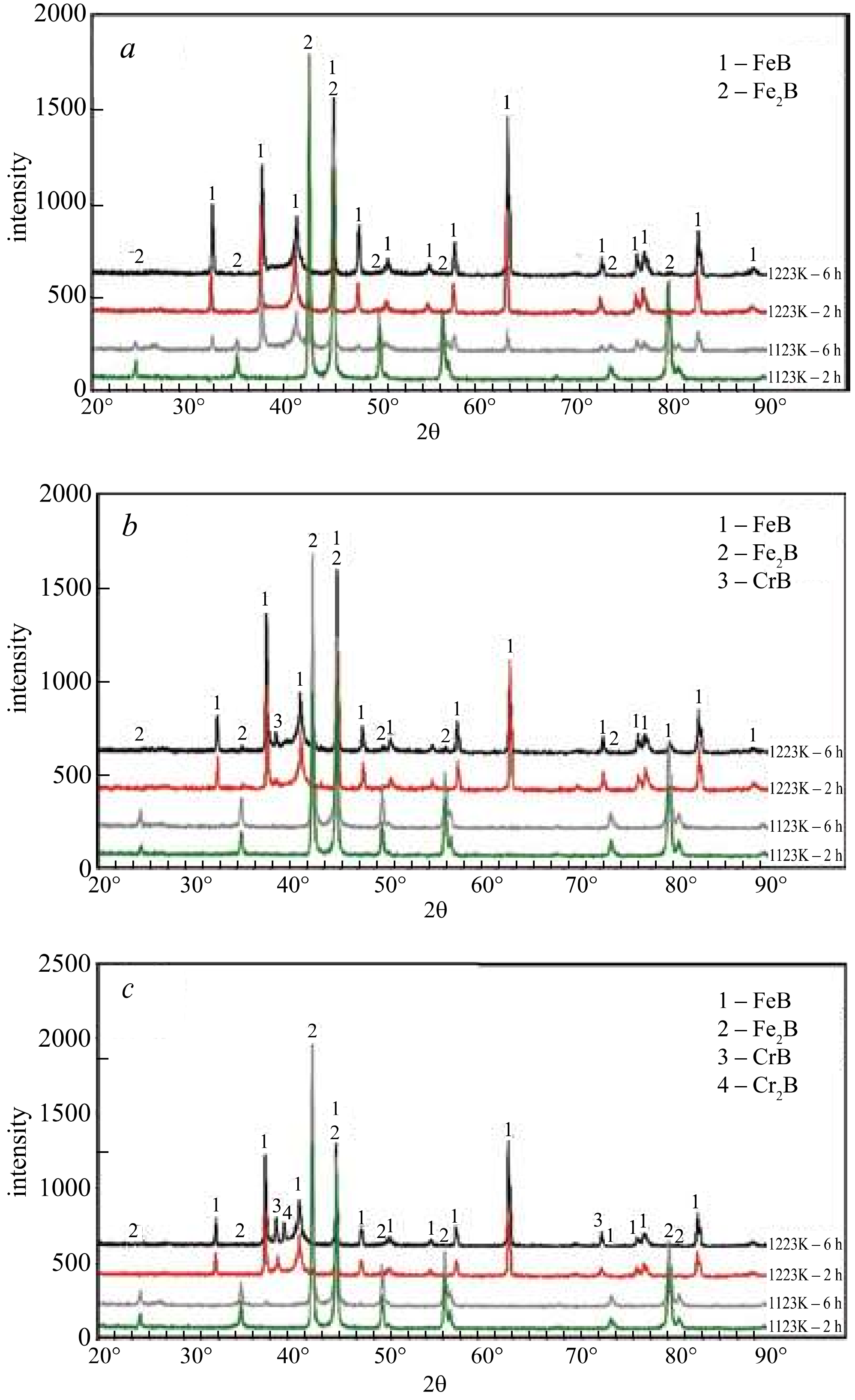


Fig. 3. X-ray diffraction patterns of borided steels at 1123 and 1223 K for 2 and 6 h: *a* – GS18; *b* – GS22; *c* – GS32

FeB and CrB phases content increases for the GS22 and GS32 steels (Fig. 3*b* and *c*). The boride layers mainly consist of intermetallic phases (FeB, Fe_2B and CrB) as a result of 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 to a large extent known by the help of these phases[20,21].

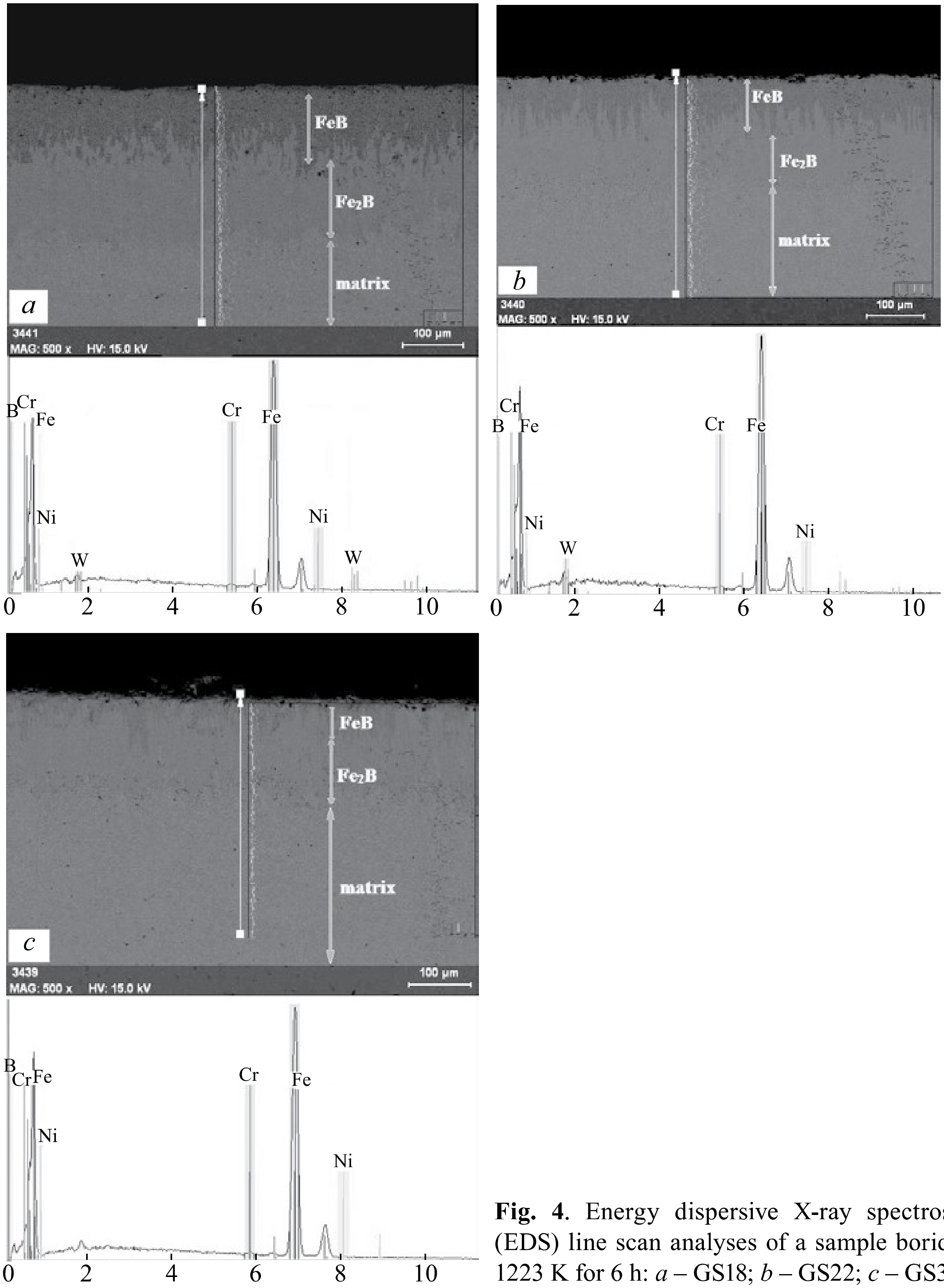


Fig. 4. Energy dispersive X-ray spectroscopy (EDS) line scan analyses of a sample borided at 1223 K for 6 h: *a* – GS18; *b* – GS22; *c* – GS32

EDS line analysis was performed to determine which element accumulated among the FeB phase and matrix in the steels (Fig. 4). In this region, Cr and small scales of W and Ni were determined. This might be indicated by the FeB and CrB phases, determined by an XRD pattern, in the outer layer of the boride coating. EDS analysis showed that iron concentration in the boride layer was lower in the outer layer of the boride coating than in the inner part. These observations were confirmed by the EDS analysis (Fig. 4*a*–*c*).

Microhardness measurements were carried out on the cross-sections from the surface to the interior along a line (Fig. 5*a*–*c*). The hardness of the boride layer formed on the GS18 steel varied between 1624 and 1905 $HV_{0.05}$. The hardness of the boride layer on the GS22 steel varied between 1702 to 1948 $HV_{0.05}$, and the hardness of the boride layer on the GS32 steel varied between 1745 to 2034 $HV_{0.05}$, respectively. On the other hand, the Vickers hardness values were 335 $HV_{0.05}$, 358 $HV_{0.05}$ and 411 $HV_{0.05}$, for the untreated GS18, GS22 and GS32 gear steels, respectively. When the hardness of the boride layer is compared with the matrix, the boride layer hardness is approximately 5 times greater than that of matrix.

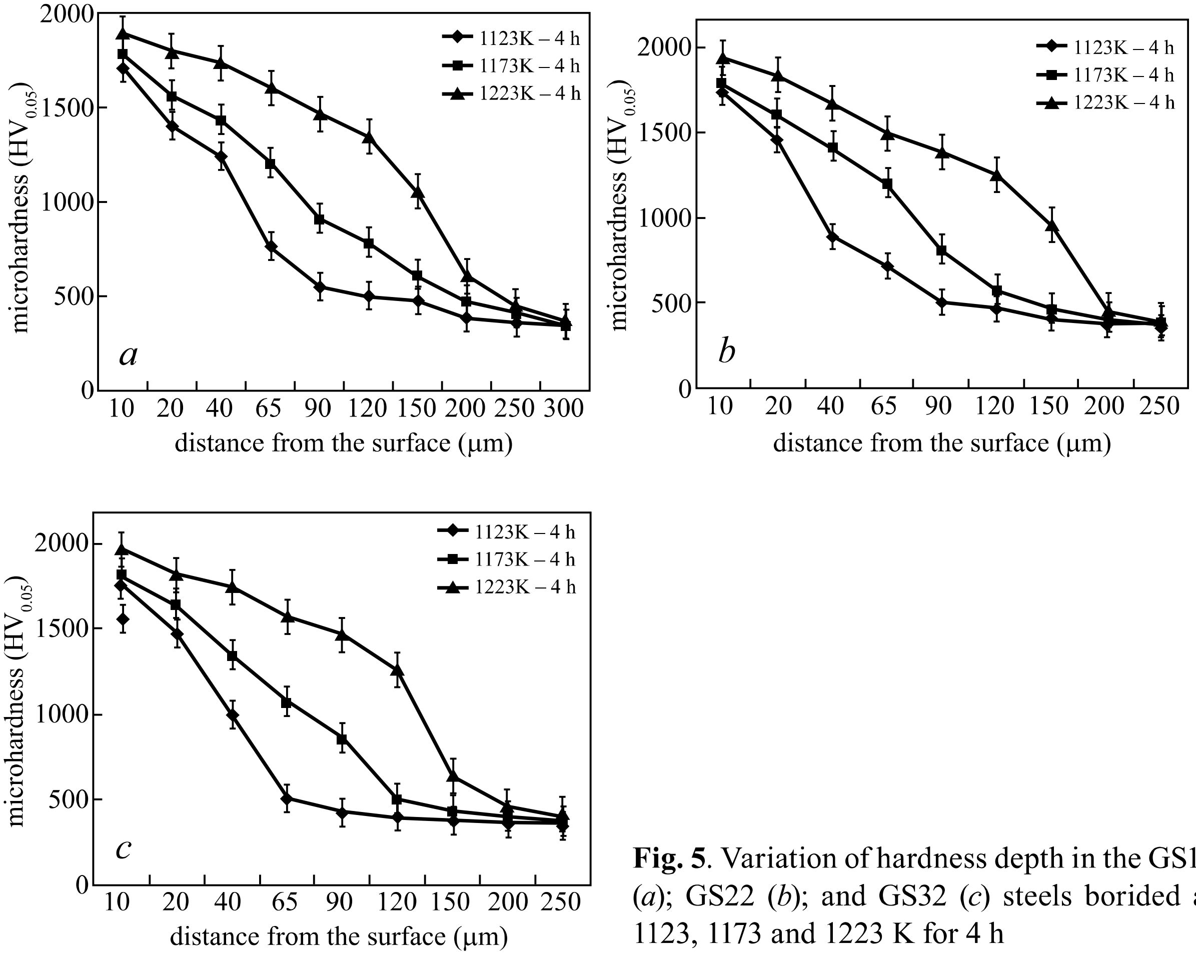


Fig. 5. Variation of hardness depth in the GS18 (*a*); GS22 (*b*); and GS32 (*c*) steels borided at 1123, 1173 and 1223 K for 4 h

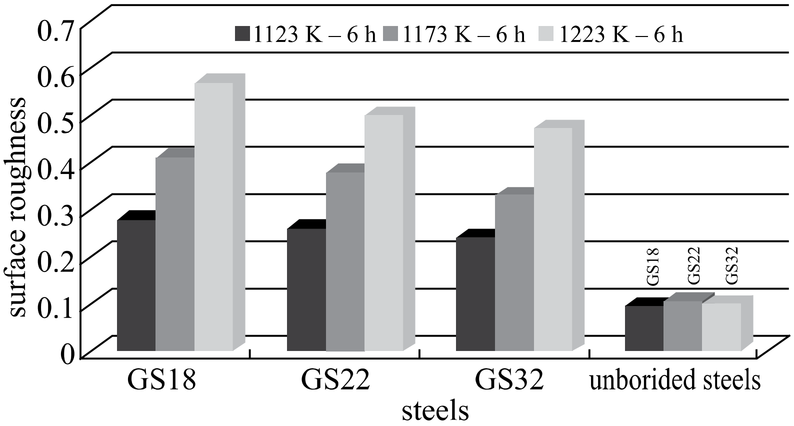


Fig. 6. Surface roughness values of the steels depending on the boriding temperature and time

Friction and wear behaviour. Figure 6 shows the surface roughness values of the borided and unborided gear steels. For each of the 3 steels, it was observed that surface roughness values increased with an increase in the boriding temperature (Fig. 6). This result indicates that the increase in boride coating thickness affects the surface roughness. The relationship between roughness and thickness in this study is in a good agreement with that of many coating methods[19,21,22]. This case can be attributable to the intrinsic properties of the phases formed. But it is difficult to clarify the reason for the relation between roughness and phases in boride layers revealed in this experiment, so it is not discussed here.

Table 2. Friction coefficients of the borided gear steels at different sliding speeds

Steels	Boriding temperature (K) and time (h)	Coefficient friction		
		sliding velocity (m/s)		
		0.2	0.3	0.4
GS18NiMoCr36	1123 – 2	0.52	0.5	0.45
	1123 – 6	0.56	0.53	0.42
	1173 – 2	0.53	0.49	0.45
	1173 – 6	0.55	0.52	0.43
	1223 – 2	0.55	0.50	0.44
	1223 – 6	0.59	0.55	0.42
GS22NiMoCr56	1123 – 2	0.54	0.49	0.43
	1123 – 6	0.55	0.51	0.44
	1173 – 2	0.52	0.49	0.45
	1173 – 6	0.57	0.52	0.47
	1223 – 2	0.51	0.48	0.42
	1223 – 6	0.58	0.53	0.41
GS32NiCrMo6.4	1123 – 2	0.51	0.45	0.38
	1123 – 6	0.54	0.48	0.36
	1173 – 2	0.52	0.51	0.42
	1173 – 6	0.53	0.51	0.44
	1223 – 2	0.49	0.45	0.37
	1223 – 6	0.51	0.46	0.39

Table 2 shows the friction coefficients of the borided gear steels at different sliding speeds. The friction coefficients of the GS18, GS22 and GS32 borided steels varied from 0.41 to 0.59, from 0.42 to 0.58 and from 0.36 to 0.54, respectively. A slight reduction was observed in the friction coefficients of the the borided gear steels with an increase in the boriding temperature and time. The friction coefficient values obtained at 0.2 and 0.3 m/s sliding speeds were found to be close to each other. At high sliding speed (0.4 m/s), a considerable number of reductions were observed in the friction coefficient values. The reason behind this may be the oxides on the surface of the sample. During the wear test, oxides formed on the steel surface allow for low friction coefficients. The wear tracks on the samples may be oxidised due to frictional heat[23–25]. Previous studies[26–29] reveal that boride coatings are oxidised and oxidation wear appears to be the probable wear mechanism.

Figure 7*a–c* shows the effect of sliding speed on the wear rate of the gear steels borided at different temperatures and time periods. Reductions in the wear rates of the steels were observed with the increase in the boriding temperature. Due to the toughness of the FeB and CrB phases, the steels showed more resistance to wear. The lowest wear rate was obtained in the GS32 steel borided at 1223 K for 6 h while the highest wear rate was obtained in the GS18 steel borided at 1123 K for 2 h. The microhardness value of GS32 is higher than that of GS18 due to its high nickel and chromium content. The wear test results indicated that the wear resistance of borided steels increased considerably with increasing boriding temperature and time. It is well known that hardness of the boride layer plays an important role in the improvement of abrasive wear resistance. As shown in Figs 5 and 7, the relationship between the surface microhardness and the wear resistance

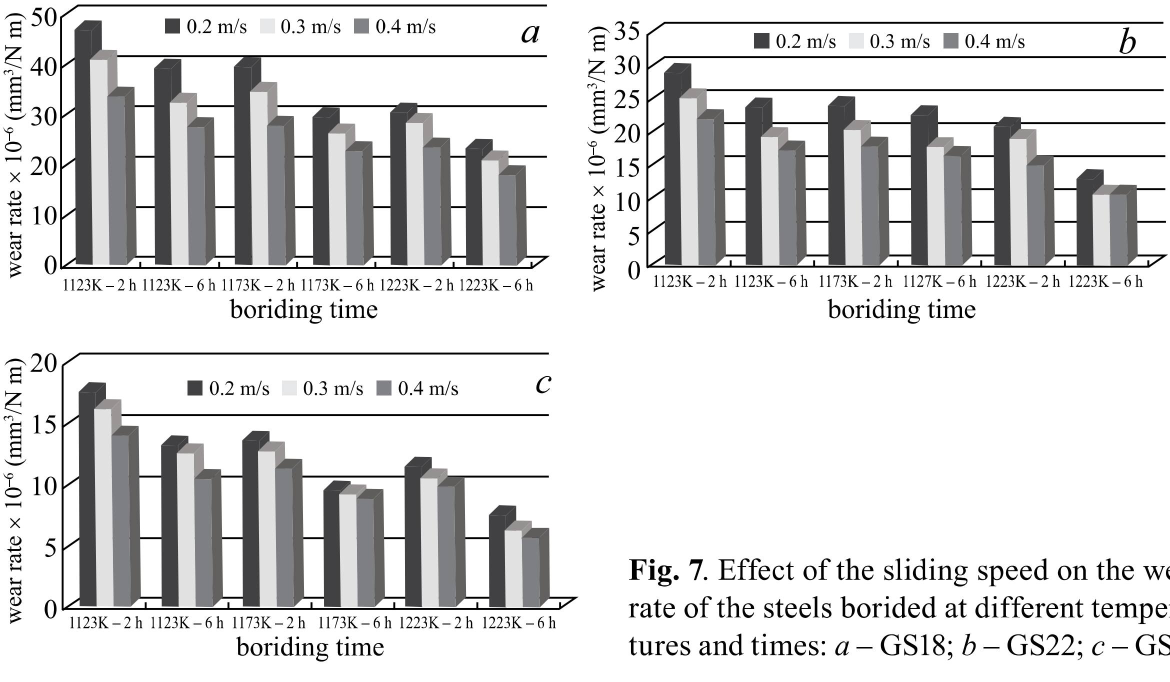


Fig. 7. Effect of the sliding speed on the wear rate of the steels borided at different temperatures and times: *a* – GS18; *b* – GS22; *c* – GS32

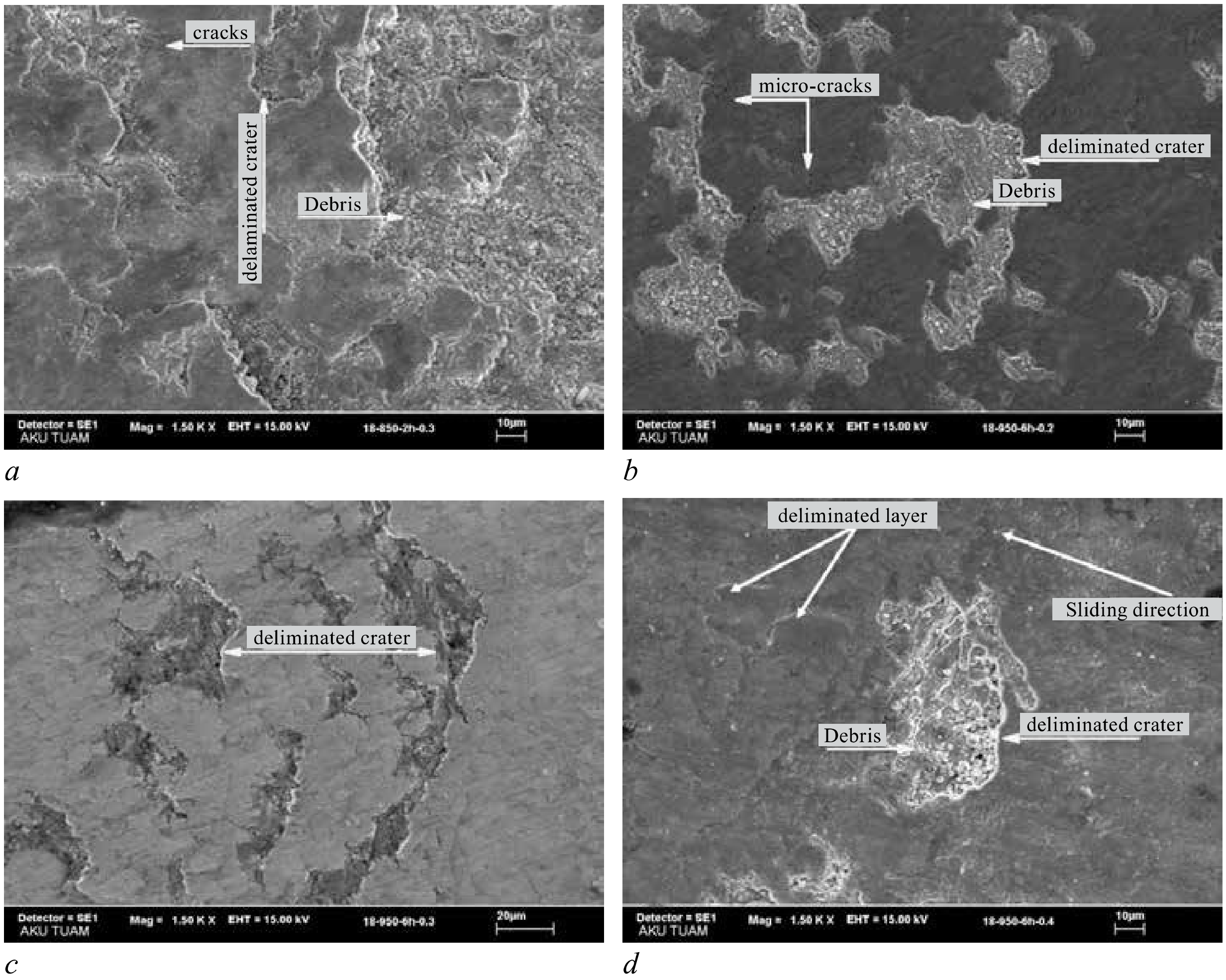
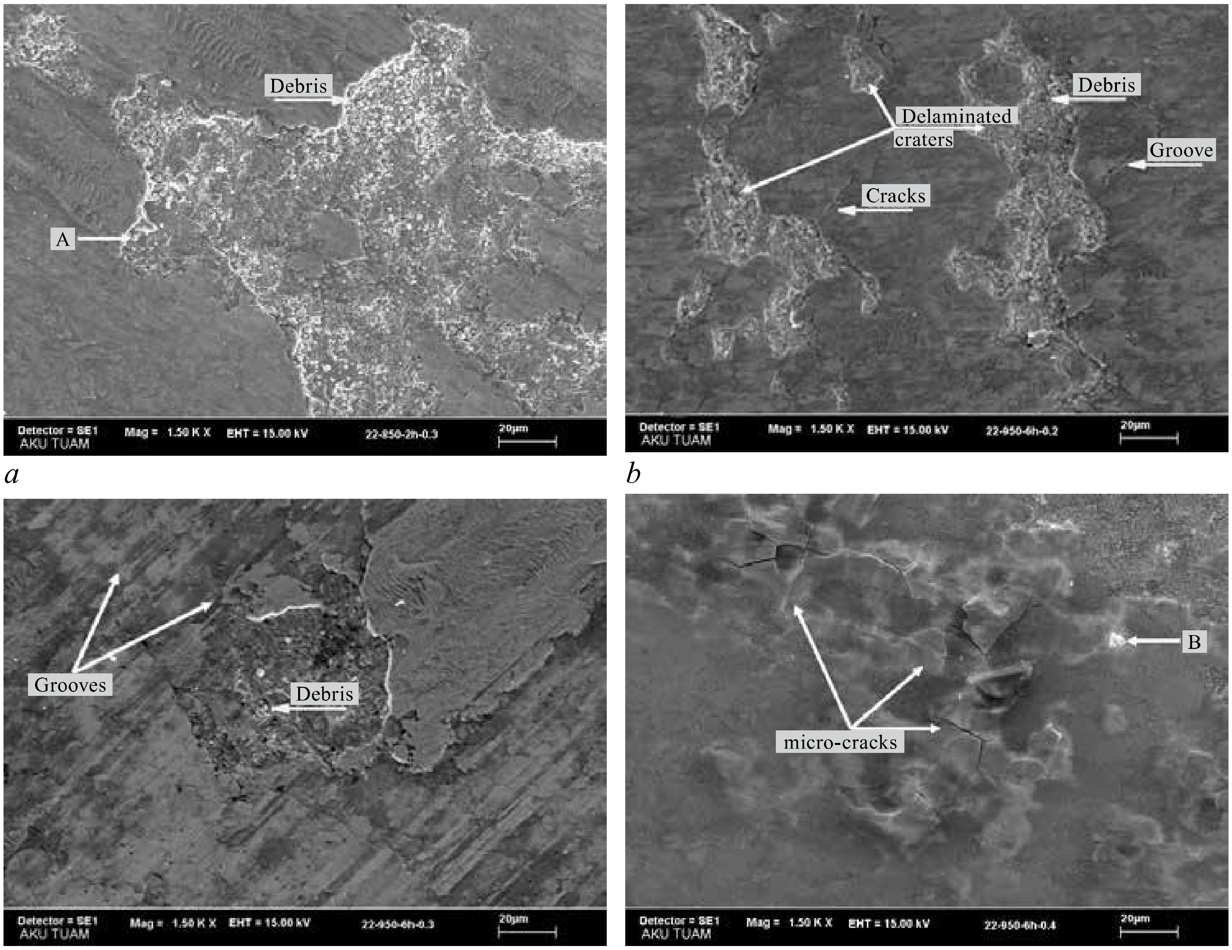


Fig. 8. Sliding speed dependent SEM micrographs of the wear surfaces of the GS18 steel borided at different temperatures and times: *a* – 1123K – 2 h, 0.2 m/s; *b* – 1223K – 6 h, 0.2 m/s; *c* – 1223K – 6 h, 0.3 m/s; *d* – 1223K – 6 h, 0.4 m/s

of the borided samples also confirms that the wear resistance was improved with the hardness increasing. This is in agreement with reports of previous studies[30–32]. In addition, reductions in wear rates were observed with the increasing rate of sliding speed. The oxides formed on the samples borided at high sliding speeds may have caused a reduction in the friction coefficient and an increase in the wear rate because oxides on the sample surface act as a solid lubricant. Straffelini et al.[33] investigated the impact of sliding speed and contact pressure on oxidative wear of austempered ductile iron and reported that the friction coefficient and wear rate decreased with an increasing rate of sliding speed.

The SEM micrographs of the worn surfaces of the borided gear steels are illustrated in FiGS8–11. Figure 8 shows the SEM micrographs of the wear surfaces of the GS18 steel worn at different sliding speeds. The wear region of the borided samples, debris, surface grooves and cracks on the layer are observed (Fig. 8*a*–*d*). It was observed that delamination wears, which are formed as a result of the progress of micro-cracks, occurred on the wear tracks of the borided samples



a *b* *c* *d*

Fig. 9. Sliding speed dependent SEM micrographs of the wear surfaces of the GS22 steel borided at different temperatures and times: *a* – 1123K – 2 h, 0.2 m/s; *b* – 1223K – 6 h, 0.2 m/s; *c* – 1223K – 6 h, 0.3 m/s; *d* – 1223K – 6 h, 0.4m/s

(Fig. 8*a*–*d*). The wear intensity on the surfaces of the borided samples was observed to decrease with an increase in the sliding speed (Fig. 8*a*–*d*). Oxidation on the surfaces of the samples increased with an increase in the sliding speed. This led to a smoother appearance of the surface in the wear region (Fig. 8*d*).

Figure 9 shows the SEM micrographs of the wear surfaces of the GS22 steel worn at different sliding speeds. In Fig. 9*a*, the worn surface was rougher and coarser wear debris particles were present. Figures 9*b* and *c* showed that worn surfaces were essentially composed oxide debris, small holes. The SEM micrograph indicated microcracks along the wear track in Fig. 9*d*. EDS analysis of points A and B in Fig. 9*a* and *d* are given in Fig. 10*a* and *b*. Fe-based oxide layers formed as a result of the wear test. The spallation of the oxide layers in the sliding direction and their orientation extending along the wear track were identified.

Figure 11 shows the SEM micrographs of the wear surfaces of the GS32 steel worn at different sliding speeds. The micrograph of the worn surfaces of the borided GS32 steel clearly indicated that fine wear debris particles formed by brittle

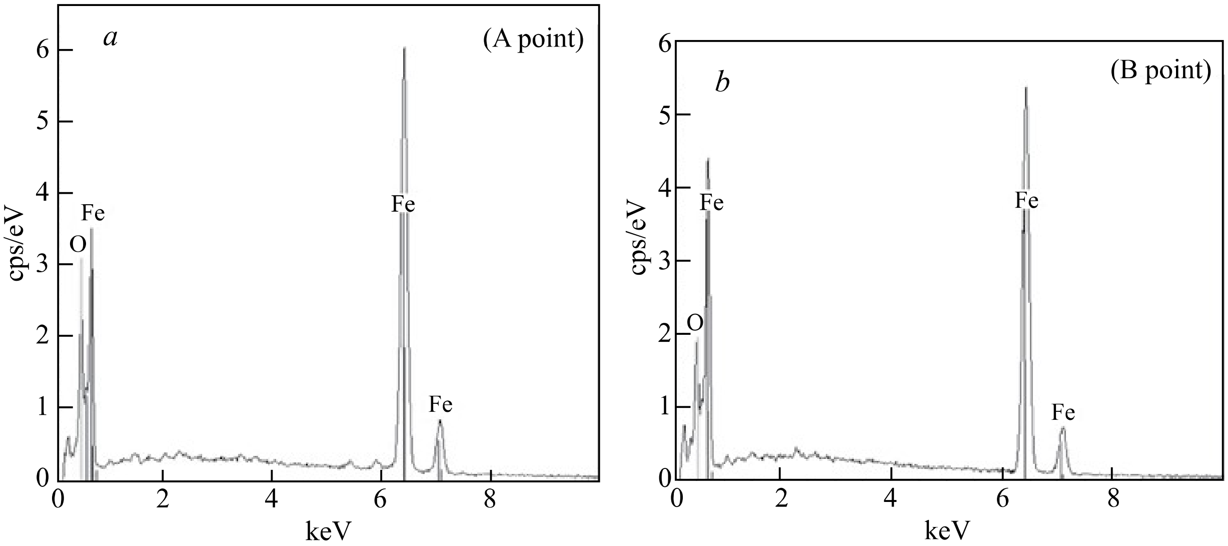
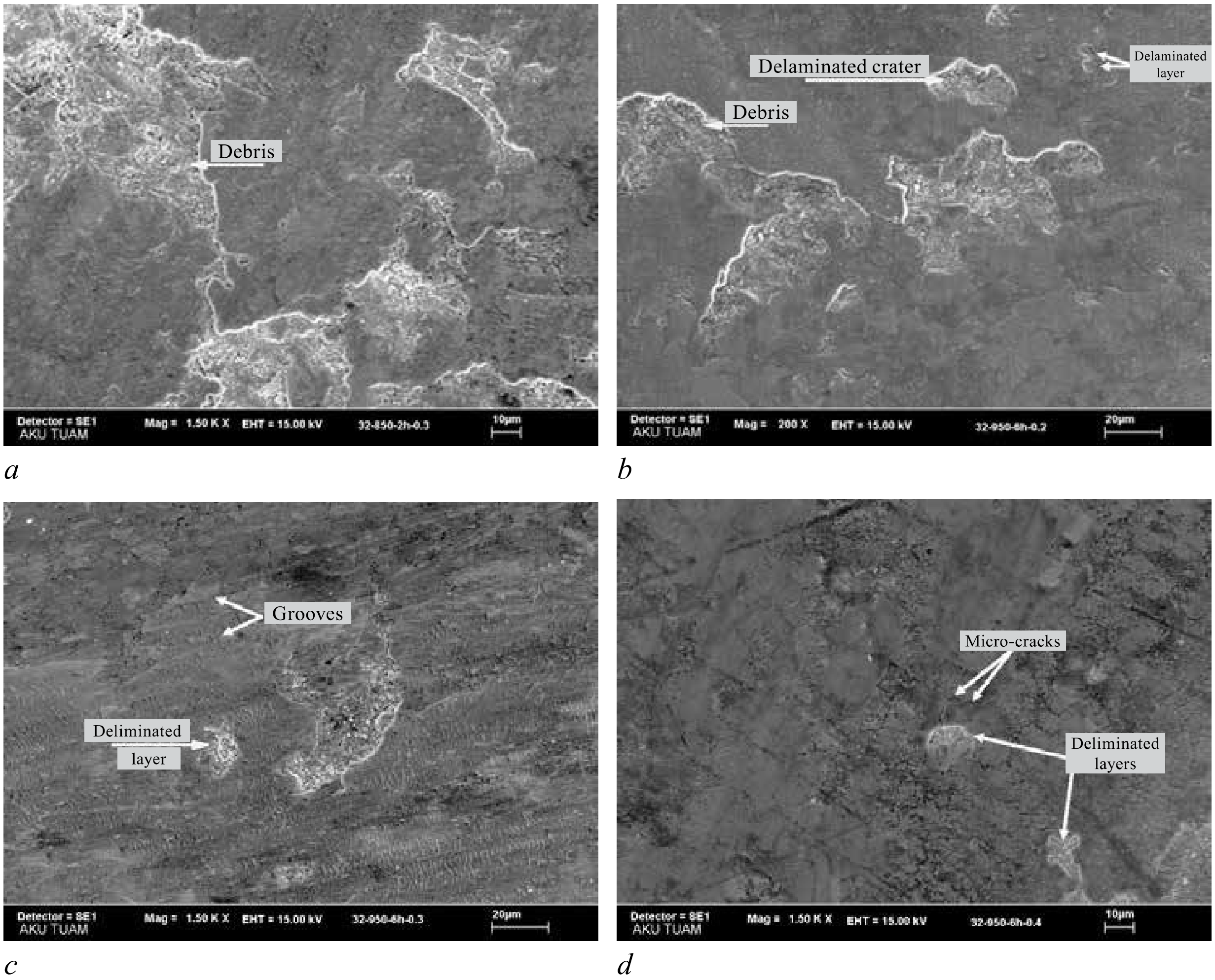


Fig. 10. EDS analysis of the worn surfaces of the GS22 borided steel: *a* – A point; *b* – B point



a *b* *c* *d*

Fig. 11. Sliding speed dependent SEM micrographs of the wear surfaces of the GS22 steel borided at different temperatures and times: *a* – 1123K – 2 h, 0.2 m/s; *b* – 1223K – 6 h, 0.2 m/s; *c* – 1223K – 6 h, 0.3 m/s; *d* – 1223K – 6 h, 0.4m/s

and fine delamination fracture probably due to the brittle CrB phase in Fig. 11*a*–*c*. At the same sliding speed (0.3 m/s) GS32 steel showed more resistance to wear as a result of the increase in the boriding temperature (Fig. 11*a*, *c*). There were microcracks, abrasive particles and small holes on the worn surface of the boride coatings (Fig. 11*d*). In the wear region of borided GS32 steel, there were cavities probably formed as a result of layer fatigue (Fig. 11*a*) and cracks concluded in delaminating wear (Fig. 11*d*) in the shape of a network beginning from the edges of these cavities were observed.

CONCLUSIONS

The following conclusions may be derived from the present study.

1. The multiphase boride coatings that were thermo-chemically grown on the GS18, GS22 and GS32 steels were constituted by the FeB, Fe_2B and FeB, Fe_2B, CrB and FeB, Fe_2B, CrB, Cr_2B phases, respectively.
2. The surface hardness of the borided GS18 steel was in the range of 1624–1905 $HV_{0.05}$, while the untreated GS18 steel substrate was 335 $HV_{0.05}$. The surface hardness of the borided GS32 steel was in the range of 1745–2034 $HV_{0.05}$, while the untreated GS32 steel substrate was 411$HV_{0.05}$.
3. Surface roughness values of the GS18, GS22 and GS32 steels increased with an increase in the boriding temperature.
4. The friction coefficients of the GS18, GS22 and GS32 steels borided depending on sliding speed varied from 0.41 to 0.59, from 0.42 to 0.58 and from 0.36 to 0.54, respectively.
5. At the same sliding speeds, the wear rates of the steels decreased with the increase in the boriding temperature and time.
6. As a result of an increase in the sliding speed, it was observed that the friction coefficient decreased while wear resistance increased in the GS18, GS22 and GS32 borided gear steels.

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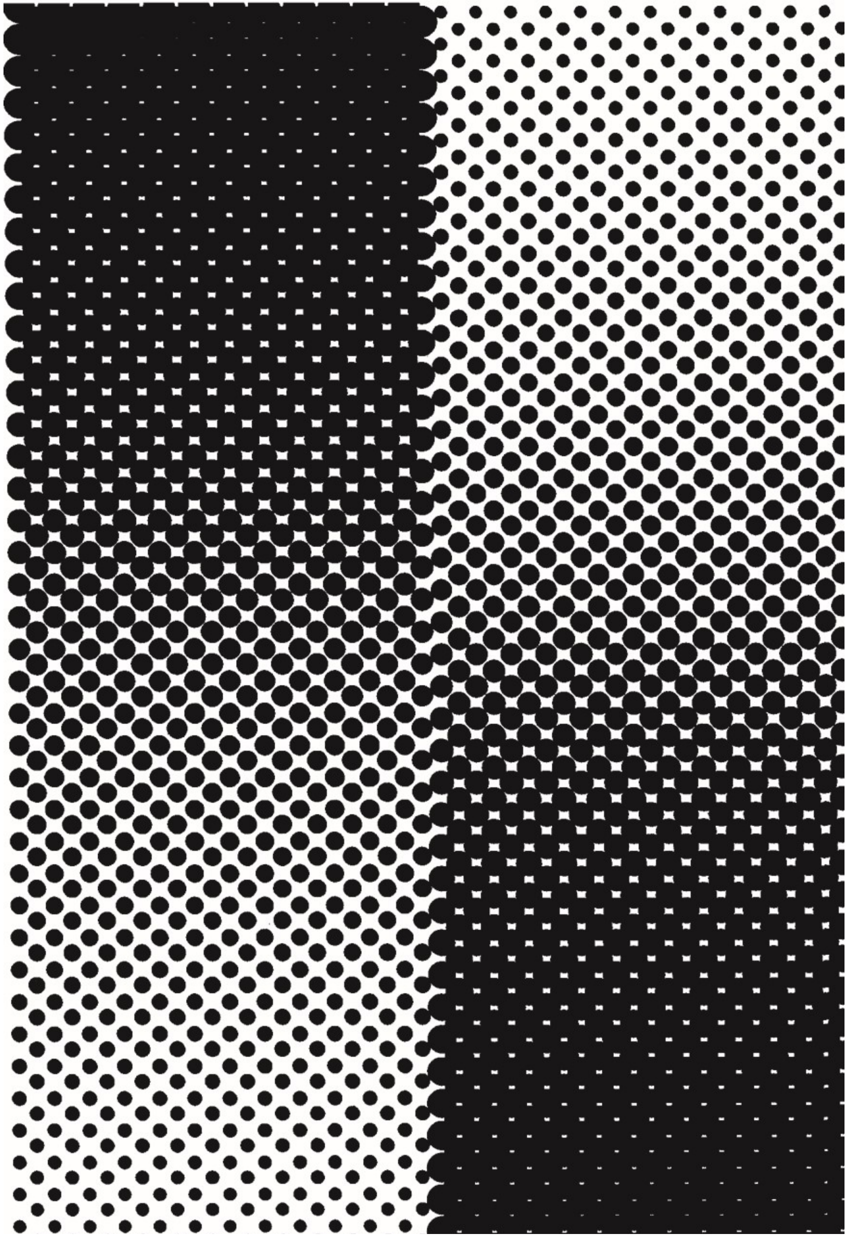

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