

Abrasive wear resistance of boronized carbon and low-alloy steels

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Abstract

In this study, the abrasive wear resistance of previously boronized 1020, 1045, 4140 and 4340 steels were determined. The boronizing treatments were performed in a mixture of dried borax and SiC at temperatures of 1223, 1273 and 1323 K, during 2, 4 and 8 h. On the surface of each steel, a monophase layer of Fe_2B was obtained. The abrasive wear tests were performed by using a rubber-wheel apparatus (ASTM-G65 standard) operating with quartz sand and a force between wheel and specimen of 130 N. As a result, boronized 1020 steel exhibited the greatest abrasive wear resistance.

Keywords: Boronizing; Boriding; Abrasive wear; Wear resistance; Fe_2B phase

1. Introduction

Boronizing, or boriding, is a thermochemical treatment that diffuses boron through the surface of metallic substrates. As boron is an element of relatively small size it diffuses into a variety of metals; including ferrous, nickel and cobalt alloys, metal-bonded carbides and most refractory alloys [1]. Typically, boronizing is carried out in the 1113–1323 K temperature range by using solid, liquid or gaseous boron-rich atmospheres [2].

Boronizing has been found to be an effective method for significantly increasing the surface hardness and the wear resistance of metals [3–6]. In the case of low carbon steel boronized by using boron carbide (B_4C) at 1223 K during 1.5 h, the maximum microhardness can reach 1700 and 1850 HV for 1020 and 5115 steel, respectively [6].

On the surface of boronized ferrous alloys, generally a boron-compound layer is developed. This compound layer (or boride layer) is normally composed of two sublayers; the outermost and the innermost are rich in FeB and Fe_2B , respectively [4,7]. Underneath the compound layer the diffusion zone hardly exists because the solubility of boron in Fe is very small [8]. Since the FeB phase is more brittle and harder, and has a higher coefficient of thermal expansion than the Fe_2B one, the cracking of the double-phase boride layer is often observed [2,5,8].

To reduce the brittleness of the double-phase boride layer, several kinds of pre- or post-boronizing treatments have been investigated: carburizing, laser treatment, quenching, ions implantation and gas nitriding [9–11]. By boronizing a carburized steel, a reduction of the microhardness gradient across the case is obtained. In laser treatment, the coarse and columnar structure of the boride layer can be changed into a fine grain structure. In quenching, the hardness gradient between the boride layer and substrate can be reduced. In N ions implantation, part of FeB and Fe_2B is discomposed and $c\text{-BN}$, FeN and Fe_{2-3}N compounds could be formed. In gas nitriding, the outermost sublayer (FeB) can be transformed into the ductile Fe_4N phase, whereas the innermost sublayer (Fe_2B) can be transformed into the Fe_4N and B_{25}N phases. Recently, Gopalakrishnan et al. [12] showed that if boronizing is performed by cyclically interrupting the process, a change in the morphology of the typical boride needles is produced and an improvement in some mechanical properties (toughness and ductility) is obtained.

On the other hand, it has been shown that in a ferrous alloy, the content of some elements, such as C, Cr and Ni, has a great influence on the boride layer. With the increase of the C content, the thickness of this layer decreases and its hardness either increases [5], or first decreases (up to 0.5% C) and then increases [4]. As carbon does not dissolve significantly in FeB and Fe_2B , C is driven ahead of the boronized layer, forming a polyphase zone rich in carbides and borocarbides (Fe_3C , Cr_{23}C_6 , Fe_7C_3 and $\text{Fe}_3(\text{B},\text{C})$) between the Fe_2B sublayer and the matrix [5,8]. This would explain why the boride layer on high carbon steel is

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very brittle and poorly bonded to the base metal [4]. One effect of Cr is to increase the amount of the FeB phase in the boride layer [4]. Other effects are to increase the hardness and the brittleness of the surface layer and to produce a layer that is not very compact on the outside [4,5]. In the case of Ni, by increasing its percentage the compound layer becomes more regular and thinner [5].

In most of the studies mentioned above, B_4C was the boronizing agent (other agents were BCl_3 and ferroboron alloy). Due to the problems associated with the cracking of the boride layer, it seems advisable to study the possibility of using another boronizing agent that generates a low boronizing potential [8], in order to form a surface layer of Fe_2B boride only.

Thus, in this study, we decided to use borax as the boronizing agent and evaluated the abrasive wear resistance of carbon and low-alloy steels, heat treated by using this agent.

2. Experimental

Flat samples with a 25 mm diameter and a thickness of 5 mm were prepared from the steels listed in Table 1. The microhardness of the as-received steels is given in Table 2. Before boronizing, the samples were polished to a mirror-like finish and cleaned with acetone. Boronizing was performed by putting the study samples and the chemical agents (Table 3) into a sealed steel crucible, which was then heated in an electrical resistance furnace. The treatment temperature was in the 1223–1323 K range and the duration was between 2 and 8 h. The abrasion tests were performed by using a rubber-wheel apparatus, in accordance with the ASTM-G65 standard, operating at a peripheral wheel speed of 2–2.5 m/s and with a force against the samples of 130 N. Quartz sand (200 μm) was used as the abrasive agent. The samples' mass loss was measured each 60 s.

Table 1
Nominal compositions (wt.%) of tested steels

Steel	C	Mn	Cr	Mo	Ni	Si	Fe
1020	0.20	0.45	–	–	–	0.2	Balance
1045	0.45	0.75	–	–	–	0.2	Balance
4140	0.4	0.65	1.0	0.2	–	0.2	Balance
4340	0.4	0.7	0.8	0.25	1.8	0.2	Balance

Table 2
Microhardness ($HV_{0.1}$) of as-received steels

Steel	Microhardness
1020	250
1045	260
4140	370
4340	330

Table 3
Compositions (wt.%) of boronizing mixtures

Mixture	Borax	SiC	NH_4Cl	$NaCl$
M1	88.26	9.06	1.22	1.46
M2	73.26	24.06	1.22	1.46
M3	63.26	34.06	1.22	1.46

3. Results and discussion

3.1. Microstructural observations

Fig. 1(a–c) show optical micrographs of samples of SAE-1020 steel, boronized at 1273 K during 4 h in M1, M2 and M3 mixtures (see Table 3). It is observed that the boride layer had a

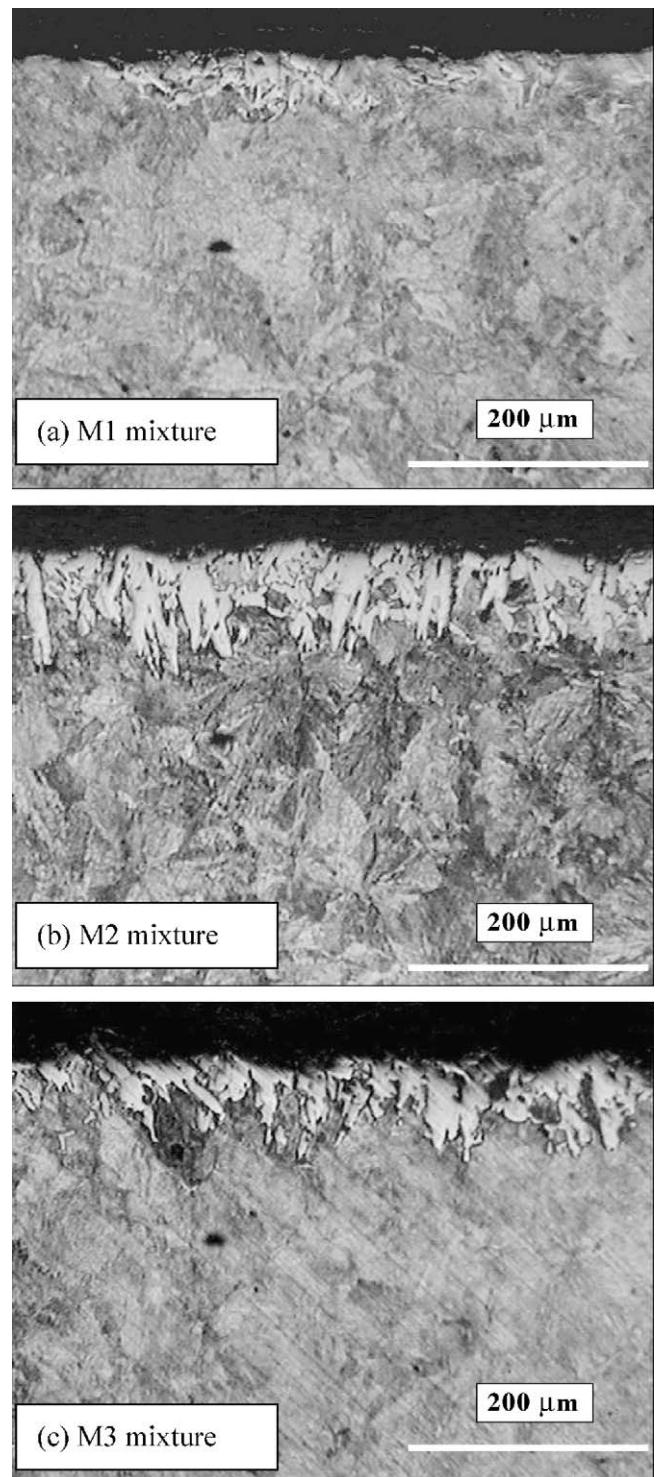
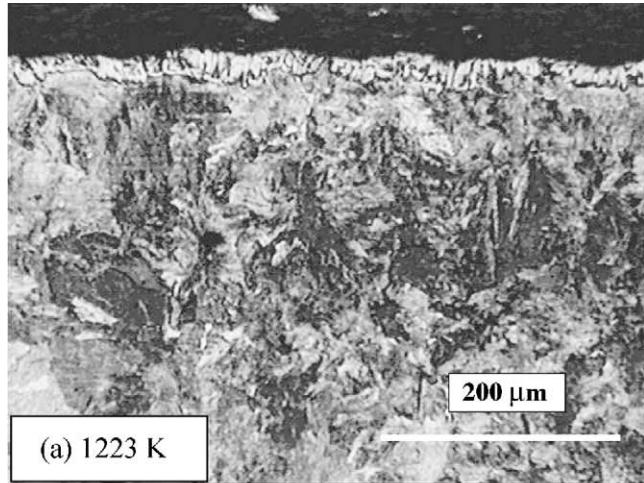


Fig. 1. Optical micrographs of 1020 steel boronized at 1273 K during 4 h in different mixtures.

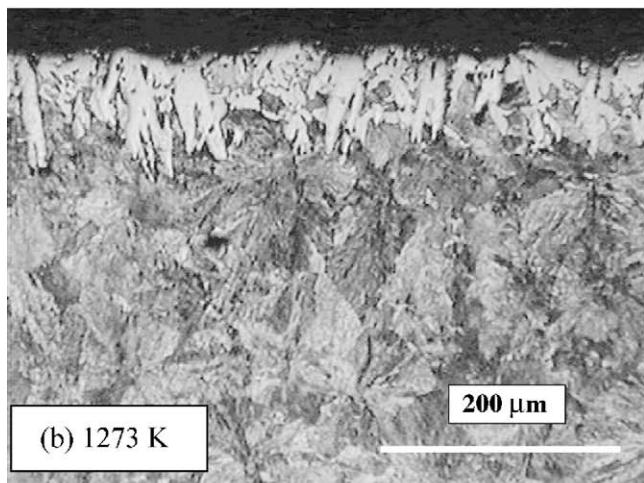
sawtooth morphology, which is typical in boronized steels, and that the borax content of the mixture had a notorious influence on the thickness of the boronized layer. By using M1 and M3 mixtures, the boride layer was relatively thin, but by using M2 mixture, the layer thickness was maximum.

As boronizing is a thermochemical diffusional process, the boride layer thickness must increase with both temperature and

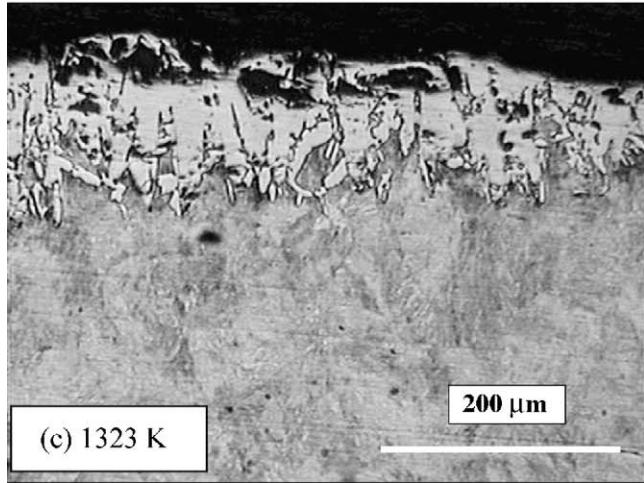
time. This is shown in Figs. 2 and 3, respectively, for the 1020 steel boronized in M2 mixture. At 1223 K (see Fig. 2a), the boride layer was relatively thin. By increasing the temperature, the boride layer thickness increased, but at 1323 K, the layer was porous (see Fig. 2c). On the other hand, by increasing the boronizing duration, the boride layer thickness also increased. By boronizing at 1273 K for 8 h, the boride layer thickness



(a) 1223 K

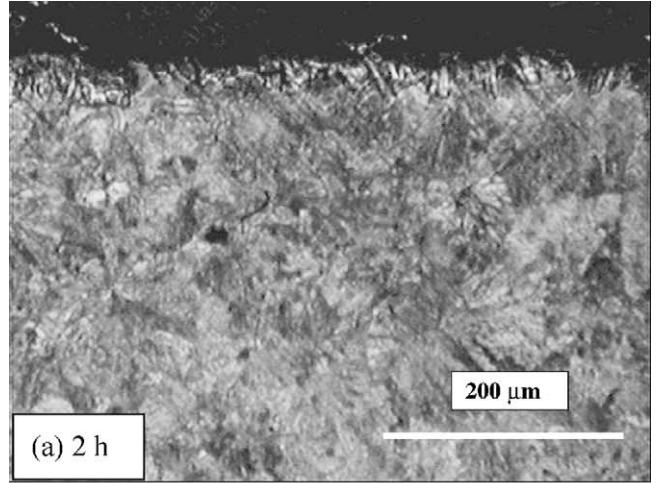


(b) 1273 K

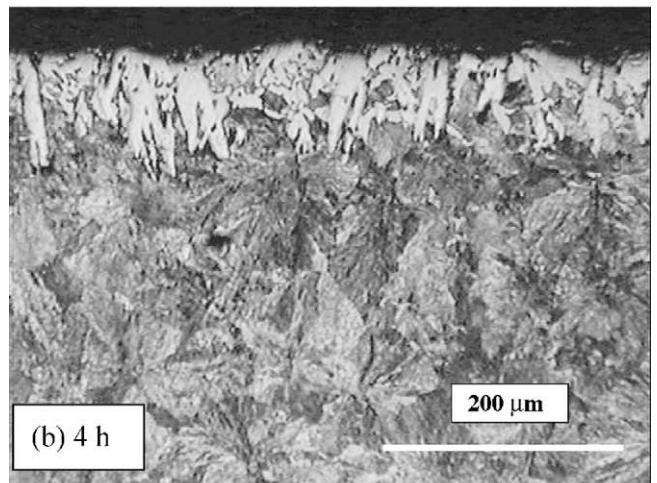


(c) 1323 K

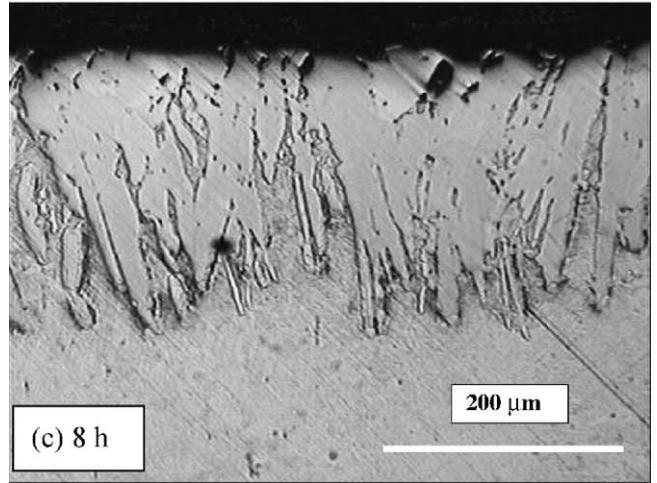
Fig. 2. Optical micrographs of 1020 steel boronized in M2 mixture during 4 h at different temperatures.



(a) 2 h



(b) 4 h



(c) 8 h

Fig. 3. Optical micrographs of 1020 steel boronized at 1273 K in M2 mixture during different times.

attained a value greater than 200 μm (see Fig. 3c). The increasing of the boronizing duration also explains the microstructural variation of the substrate: as expected, due to the duration increase, the grain size increased.

Due to the composition of the tested steels (see Table 1), the influence of C, Cr and Ni on the boride layer thickness can be analyzed: this influence is shown in Figs. 3c and 4(a–c). In

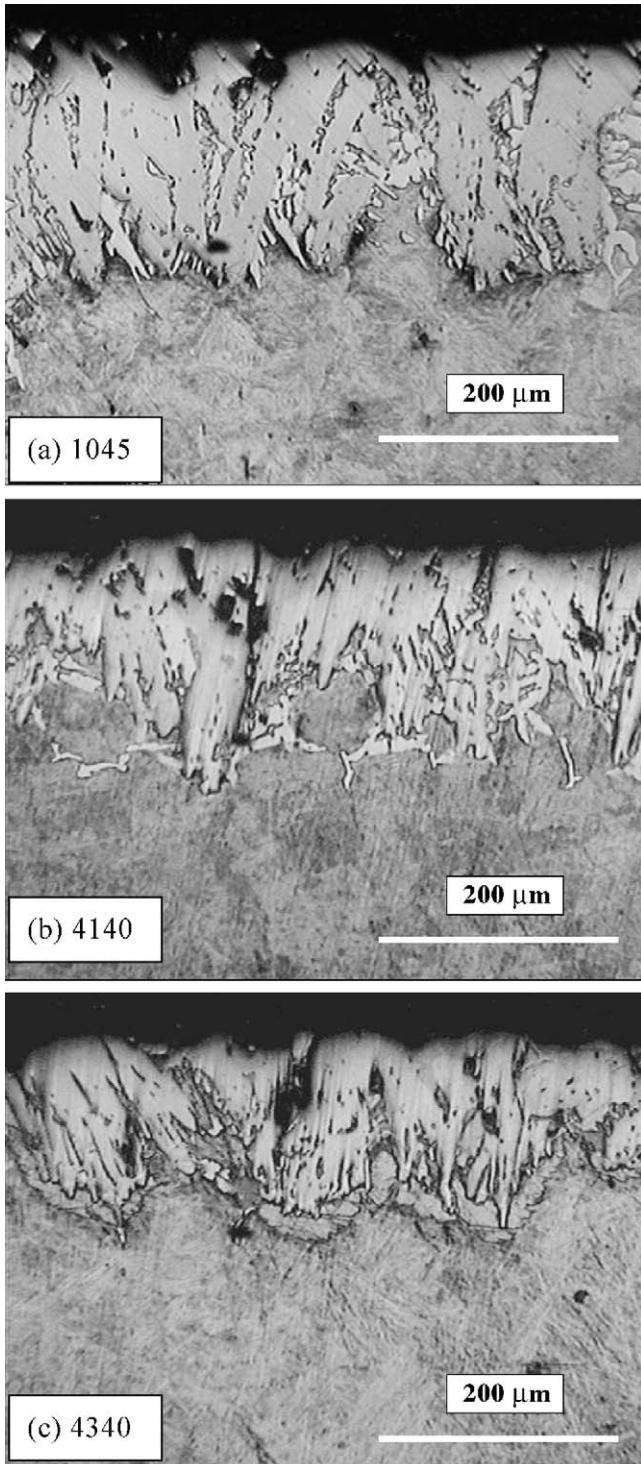


Fig. 4. Optical micrographs of different steels boronized at 1273 K during 8 h in M2 mixture.

general, the greatest thickness was obtained for the 1020 steel (Fig. 3c); which is a low carbon steel, without alloy elements. With the increasing of carbon (1045 steel), the layer thickness decreased (Fig. 4a). This decrease is attributed to the low solubility of carbon in the boride layer. Consequently, carbon is forced to move inwards, accumulating below the boride layer and forming a polyphase zone rich in carbides and borocarbides [5]. In 4140 steel (Fig. 4b), although B has a higher affinity for Cr than for Fe [3], the boride layer thickness was similar to that of 1045 steel. Carbon content is probably the factor that limits the layer thickness for these two steels. In the case of the 4340 steel (Fig. 4c), as this steel also contains Ni, and B has a higher affinity for Fe than for Ni [3], C and Ni are forced to move inwards, resulting in a relatively thin boride layer.

3.2. XRD analysis

In Fig. 5(a–d), the X-ray diffraction pattern of each steel boronized in M2 mixture at 1273 K during 8 h, is shown. In all patterns, the peaks are those of the Fe_2B phase only. Consequently, by using borax, the FeB phase did not form.

3.3. Boride layer hardness

The maximum microhardness values of the boride layer of samples boronized in the M2 mixture, measured at 25 and 50 μm depth, are shown in Fig. 6(a and b). They show that in all boronized steels, the maximum surface microhardness could be slightly over 2000 $\text{HV}_{0.1}$. They also show that this high microhardness was not obtained in all steels by using the same boronizing conditions: for example, the 1020 steel required a greater temperature than the others. At 1273 K, the maximum microhardness in the boride layer of the 1020 steel was about 1500 $\text{HV}_{0.1}$, while the maximum microhardness in the other steels was greater.

The average values of the boride layer microhardness of samples boronized at 1273 K during 4 h in M2 and M3 mixtures are shown in Fig. 7(a–d). For the 1020 and 4140 steels, the boride layer microhardness was greater with the M3 mixture than with the M2 mixture.

3.4. Abrasion tests

Mass loss values, as a function of sliding distance, for steels boronized in M2 mixture are shown in Fig. 8(a–d). In those figures it is observed that the samples boronized at 1223 K presented a relatively high mass loss which can be attributed to the fact that at such temperature the boride layers were relatively thin (see Fig. 2a). Accordingly, as boride layer thickness increases with temperature and duration of the boronizing process mass loss of samples treated at 1273 K during 8 h was relatively low (see Fig. 8c). Although at those boronizing conditions 1020 steel presented the lowest hardness (see Fig. 6) its mass loss was the lowest among all steels considered.

This apparently contradictory behaviour would be explained by both a greater boride layer thickness (see Figs. 3c and 4) and a lower brittleness of this layer, in comparison with the other

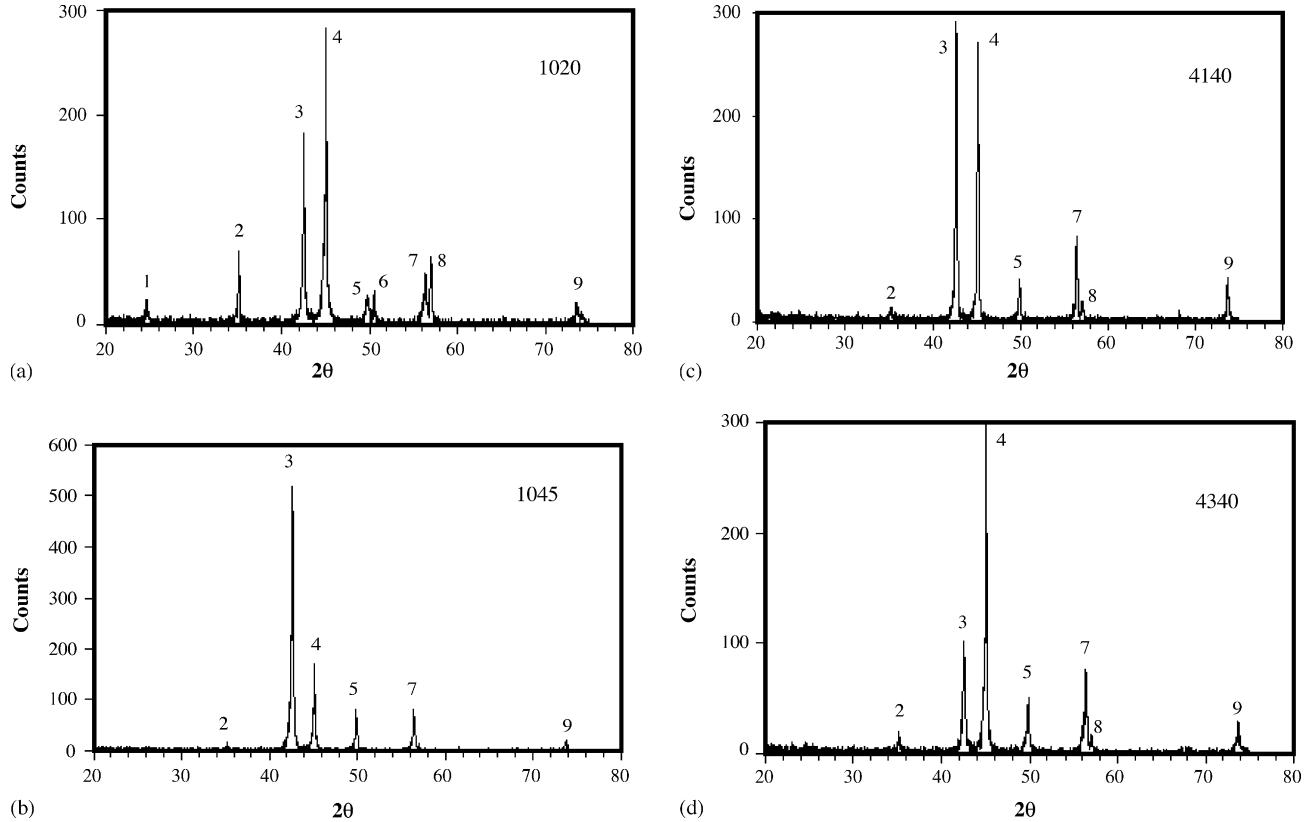


Fig. 5. X-ray diffraction patterns of samples boronized at 1273 K during 8 h in M2 mixture. (1): Fe_2B (1 0 1), (2): Fe_2B (0 2 0), (3): Fe_2B (0 0 2), (4): Fe, (5): Fe_2B (1 1 2), (6): Fe_2B (2 2 0), (7): Fe_2B (0 2 2), (8): Fe_2B (2 0 2) and (9): Fe_2B (1 3 2).

steels. The lower brittleness would be confirmed by the cracks observed on the surface of the boronized 1045, 4140 and 4340 steels after they were abrasion tested (see Fig. 9).

As shown in Fig. 8c, the initial dependency of mass loss with sliding distance was linear for all steels treated at 1273 K during 8 h. For 1020 steel, the linear dependency was up to 3500 m, presenting within that range a wear rate of 25 $\mu\text{g}/\text{m}$. Instead, for the other steels considered linear dependency was only maintained up to 2200–2500 m, after which the mass loss rate increased. It must be noted that such a mass loss rate increase does not necessarily mean that the boride layer was completely worn out.

Rather, that change must be related to the formation, by localized wear, of grooves at zones where the corresponding boride layer was thinner, as shown in Fig. 9.

In Fig. 8d, mass loss as a function of sliding distance, for steels boronized in M3 mixture at 1273 K during 4 h is shown. It is possible to observe that when using the M3 mixture, 1020 steel mass loss was lesser than when the M2 mixture was used (see Fig. 8b). By using the M3 mixture, in the wear linear stage, the wear rate was 23 $\mu\text{g}/\text{m}$. This smaller loss can be explained by the greater hardness of the boride layer of 1020 steel when the M3 mixture is used (see Fig. 7a).

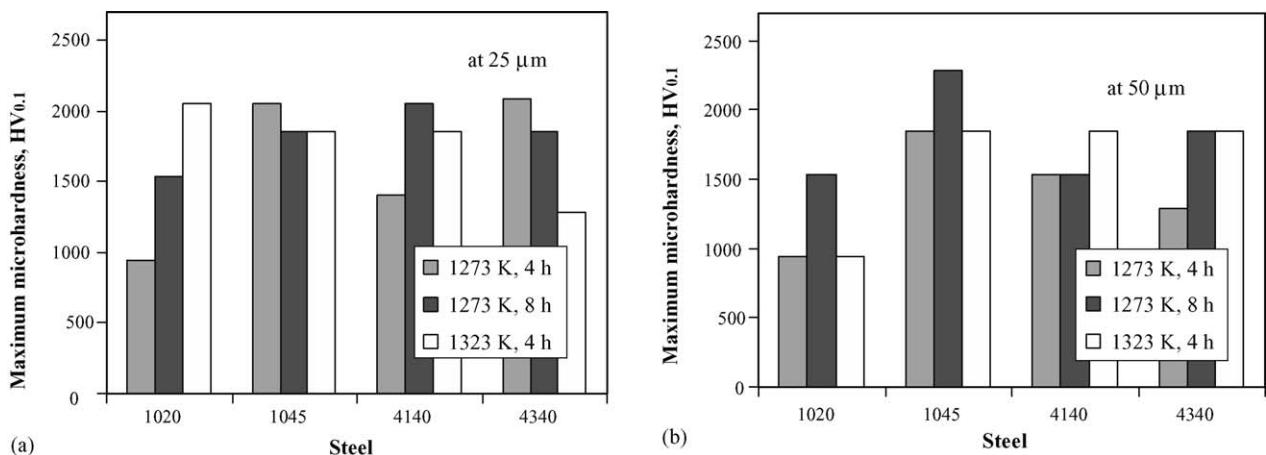


Fig. 6. Maximum microhardness of samples boronized in M2 mixture at 25 and 50 μm depth.

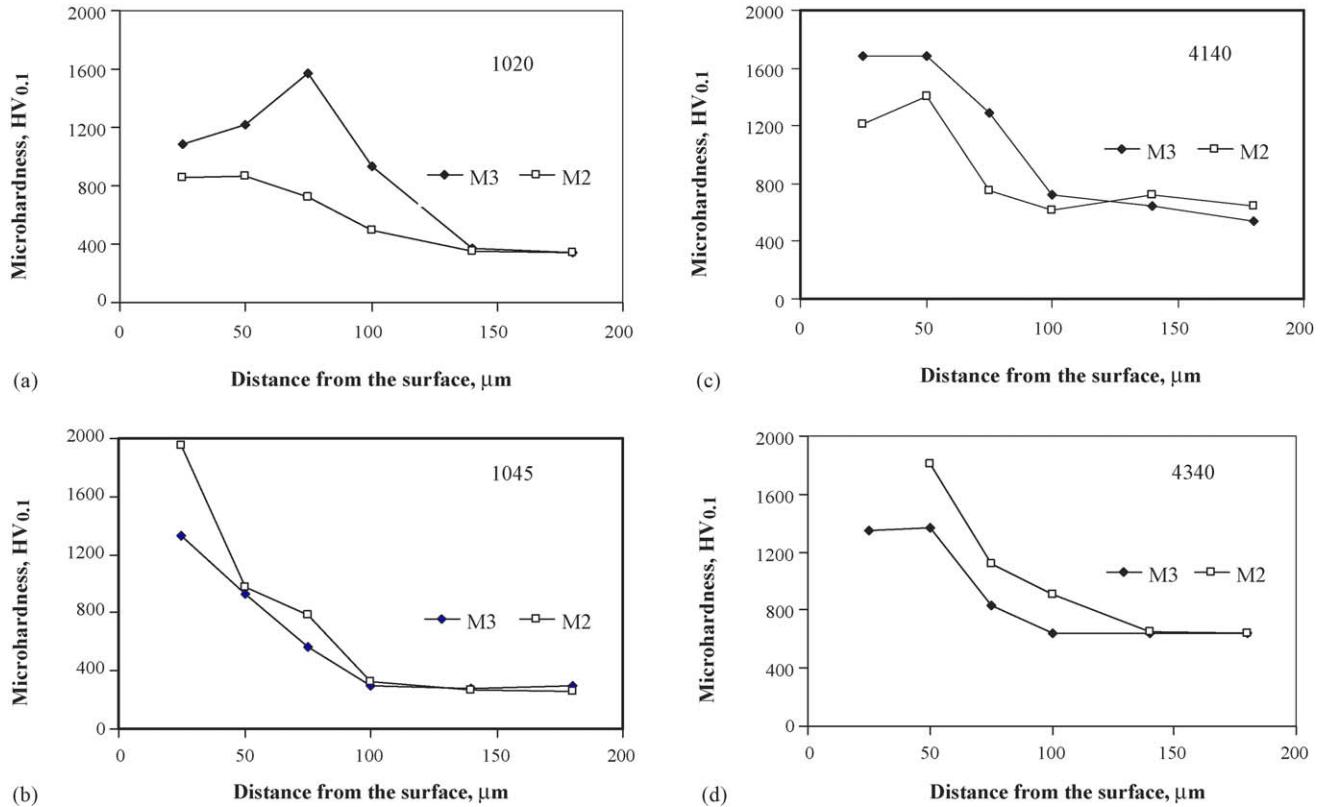


Fig. 7. Microhardness profiles of samples boronized at 1273 K during 4 h in M2 and M3 mixtures.

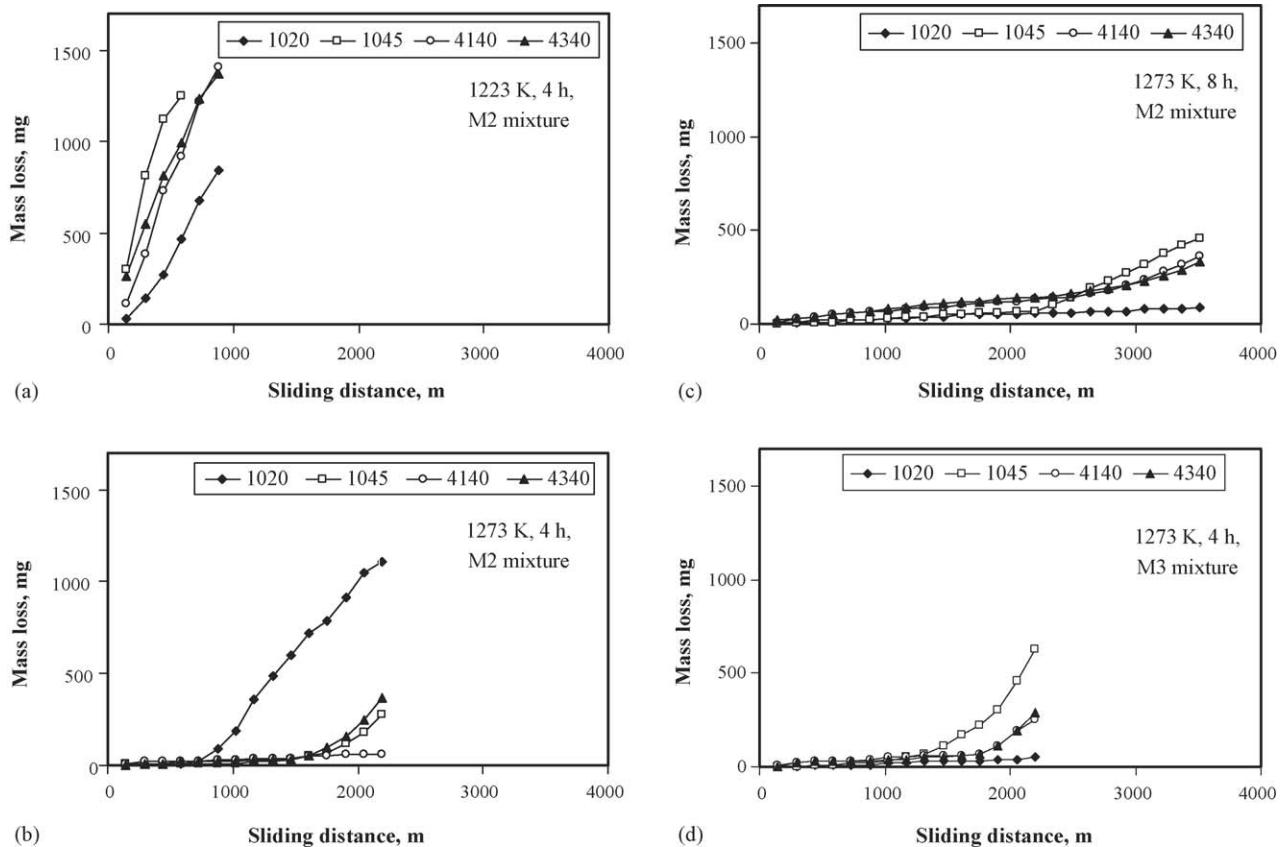


Fig. 8. Mass loss of boronized samples as a function of sliding distance, at the conditions stated on each figure.

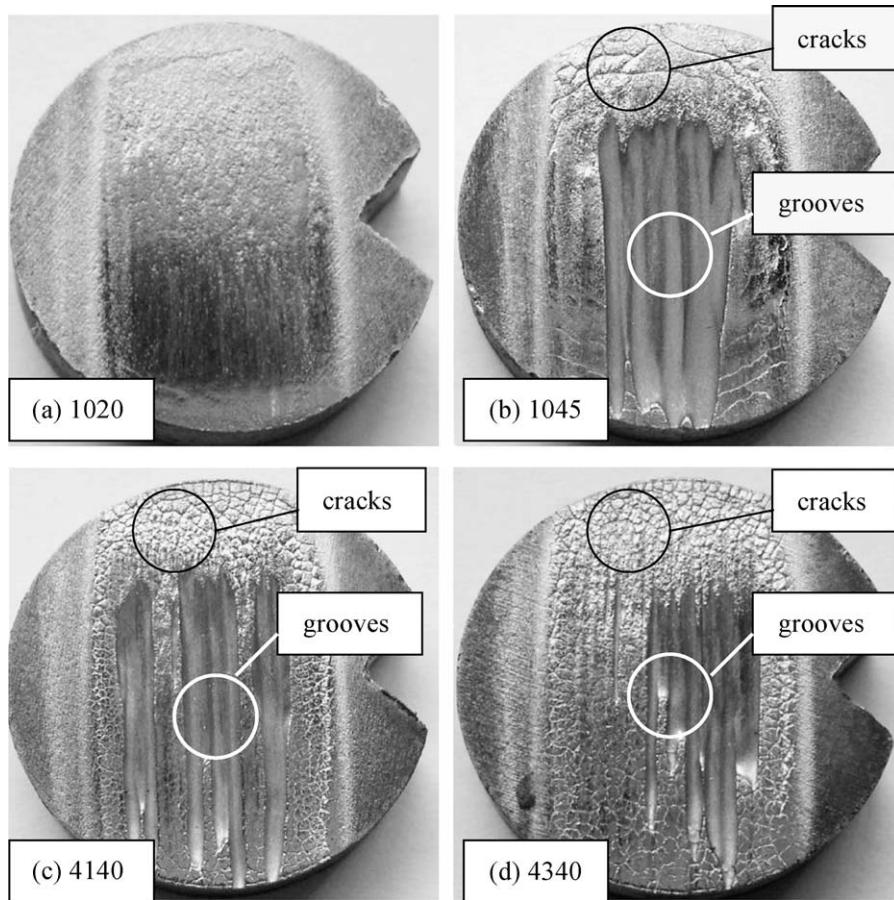


Fig. 9. Surfaces of samples boronized at 1273 K during 8 h in M2 mixture, after abrasive test.

4. Conclusions

The 1020, 1045, 4140 and 4340 steels can be satisfactorily boronized in a mixture of borax and SiC at 1273 K. The resulting boride layer is a Fe₂B single phase one. In the boride layer, the maximum microhardness value for all steels was greater than 2000 HV_{0.1}. Among all steels, the boronized 1020 showed the best abrasive wear resistance.

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