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# Creation of wear resistant boride layers on selected steel grades in electric arc remelting process

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**Abstract**

This article deals with possibilities of an application of controlled diffusion processes in remelting of steel surface layers with an electric arc of non-consumable electrode, in the environment enriched by boron, with the aim to achieve an improved wear resistance. In the design of experiment, there was formulated an assumption that the dissociation and ionisation of environment can be achieved, allowing the initiation of diffusion processes in the surface layer of the steel remelted. Conditions for creation of hard and stable structures with required properties should be obtained by enrichment of surface layers. The steel grades 16MnCr5 and X8CrNiTi1810 were used in experiments. Values of hardness and relative abrasive wear resistance were measured on samples after remelting. The metallographic analysis of remelted samples was performed as well. A significant increase in values of studied parameters was observed when remelting in the boron containing environment. The dependence applies to the effect of the environment on the change of properties and boron content in the remelting environment.

Key words: electric arc remelting, diffusion processes, abrasive wear, boron

## 1. Introduction

The wear degradation of materials results in a significant economic loss. Conditions and intensity of wear processes are an integral part of the lifetime and reliability of tribological systems [1]. That is why there is a permanent effort to eliminate wear and its effects to the lowest extent.

The development of new materials with required properties is expensive. An appropriate alternative is the change of properties of existing materials by a technological process resulting in a targeted change of chemical composition and microstructure.

Functional surfaces of parts are the most exposed in material application in the environment inducing wear degradation. Therefore, the modifications mentioned above are related mainly to surface layers of materials only. There are various technologies applicable to the targeted change of the chemical composition and properties of surface layers, particularly wear resistance [2].

The application of processes based on a diffusion mechanism can be used as a method to achieve the changes mentioned. It is the targeted change, induced by the effect of the surrounding environment, causing an increase in the concentration of elements in a saturating environment or enrichment of the standard saturating environment with a specific element [3–6]. These methods are highly demanding regarding technology and time. One of the technologies is creating layers with higher boron content (boriding). In boriding, diffused boron forms a very hard layer with iron characterised by an extraordinary high resistance to abrasive wear as well as high oxidation and thermal resistance.

Besides solid solution, the borides FeB and $Fe_2B$ are formed in the reaction of boron with iron. Boron creates borides with other alloying elements (e.g., V, Cr, Ni, etc.) in iron alloys, eventually borocarbides with carbon ($M_x(B,C)_y$) [7–10]. One-phase ($Fe_2B$ only) or two-phase layers (FeB on the surface, $Fe_2B$ inside) can be formed in dependence on the boriding

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Table 1. Chemical composition of examined steels

| Steel | Chemical composition (wt.%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | Cr | Ni | Ti | P | S | Al min |
| 16MnCr5 | 0.14–0.19 | 1.10–1.40 | 0.17–0.37 | 0.80–1.10 | – | – | max. 0.035 | max. 0.035 | – |
| X8CrNiTi1810 | max. 0.12 | max. 2.00 | max. 1.00 | 17.0–20.0 | 8.0–11.0 | min. 5 x (% C – 0.03) | max. 0.045 | max. 0.030 | – |
| RFe100 | 0.06 | 0.45 | 0.15 | – | – | – | 0.020 | 0.020 | 0.020 |

environment, temperature regime and boriding time. The one-phase ($Fe_2B$ only) layer shows more favourable properties because of $Fe_2B$ being tougher along with only a bit lower hardness than FeB [11–13].

The contemporary intense research of procedures and technologies of creating diffusion layers is oriented towards improvement of their properties. It can be achieved by changing the parameters of common technologies using diffusion mechanisms [6, 14–18], or by a mutual combination of more technologies, e.g., by a subsequent remelting of layers in electric arc, laser, etc. [4, 5, 19–22].

The idea of remelting environment enrichment with a selected element when remelting in electric arc seems to be original in this context. The generation of necessary partial pressure of the given element, causing its diffusive penetration into material surface layer, is the principle of this method. This article deals with possibilities of an application of controlled diffusion processes in remelting of steel surface layers with an electric arc of non-consumable electrode, in the environment enriched by boron, with the aim to achieve an improved wear resistance in the remelted surface layer. In the design of experiment, there was formulated an assumption that the dissociation and ionisation of environment can be achieved, allowing the initiation of diffusion processes in the surface layer of the steel remelted. Conditions for creation of hard and stable structures with required properties should be achieved by surface layer enrichment.

## 2. Material and methods

### *2.1. Selection of remelted materials and preparation of samples*

Steels with chromium alloy were used as base materials for remelting (see Table 1).

The presence of electric arc is a condition for generating the ionised and dissociated environment in the surroundings of the material processed. The welding technology with non-consumable tungsten electrode in the inert shielding atmosphere (TIG) is a convenient and available method allowing the generation of electric arc without additional material. The SMARTY TX 160 Aluwelding inverter was used for remelting. The remelting process was performed in the Ar shielding atmosphere with gas flow rate 10 l min$^{-1}$ and welding current 110 A.

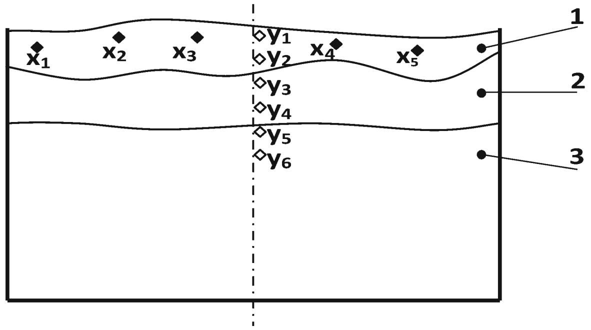

Fig. 1. Hardness measurement spots in the longitudinal cross-section of remelted sample: 1. remelted zone, 2. heat-affected zone, 3. base material.

The source of boron for melting boriding was boron carbide ($B_4C$) in a powder form, with boron content 74 wt.%. The powder was moisturised with a deionised water to prevent blowing it away from the surface of remelted samples by shielding gas flow. After that, it was manually applied to the surface of samples in the layer with thickness 2 mm and manually remelted by torch movement so the speed of torch motion was not defined. The sample was of a cylindrical shape with diameter ⌀ = 20 mm and length 30 mm. The whole round cross-section surface was remelted. Remelting in the Ar shielding atmosphere with no boron was performed to enable the evaluation of boron effect on resulting properties of examined materials. Samples with no heat treatment were used as a standard for comparison. Standards and borided samples were examined using the same method.

### *2.2. Measuring of properties*

The hardness of samples was measured according to the Vickers method (HPO 250 device) at load 98.1 N. Hardness measurements were performed on the normal cross-section of remelted layer according to the scheme in Fig. 1. Hardness changes with depth inside the material were measured in addition

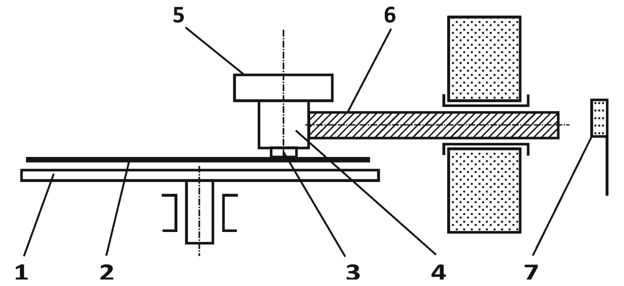

Fig. 2. Scheme of the test device for abrasive wear tests on abrasive cloth: 1. rotating round plate, 2. abrasive cloth, 3. test sample, 4. clamping head, 5. load, 6. moving screw allowing radial sample feed, 7. end switch.

to hardness values of the remelted zone to determine the depth of remelting as well as the width of heat-affected zone induced by remelting. Regarding the similar nature of remelting at all samples, the hardness-depth dependences were measured on only one sample for each environment.

To determine the resistance of remelted layers to abrasive wear, the test of relative wear resistance of materials on abrasive cloth (pin-on-disc) was used. The scheme of the test device is shown in Fig. 2.

The abrasive cloth is of a circle shape with diameter 480 mm, with test sample movement in spiral so that the contact surface is in contact with unused abrasive cloth. The friction trajectory length was 50 m at feed per revolution 5 mm. The test sample speed was 0.5 m s$^{-1}$. Relative load used in the test was 0.32 N mm$^{-2}$. Relative wear resistance is calculated using Eq. (1):

$$\Psi_{\mathrm{abr}} = \frac{W_{\mathrm{hpz}}}{W_{\mathrm{pz}}} = \frac{W_{\mathrm{opz}}}{W_{\mathrm{oz}}} \cdot \frac{\rho_{\mathrm{z}}}{\rho_{\mathrm{pz}}}, \qquad (1)$$

where $\Psi_{\mathrm{abr}}$ is abrasive wear resistance (–), $W_{\mathrm{opz}}$ is average volume reduction of reference test samples (mm$^3$), $W_{\mathrm{oz}}$ is average volume reduction of test samples (mm$^3$), $W_{\mathrm{hpz}}$ is average weight reduction of reference test samples (g), $W_{\mathrm{pz}}$ is average weight reduction of test samples (g), $\rho_{\mathrm{pz}}$ is specific weight of reference material (g cm$^{-3}$), and $\rho_{\mathrm{z}}$ is specific weight of tested material (g cm$^{-3}$).

The steel grade RFe100 (STN 412014) was used for reference test samples (chemical composition is presented in Table 1).

### *2.3. Microstructural and phase analysis of remelted layers*

The microstructural analysis of remelted layers was performed as well. Samples were etched in a 2 % nital solution. Observations were performed using the Olympus GX51 microscope.

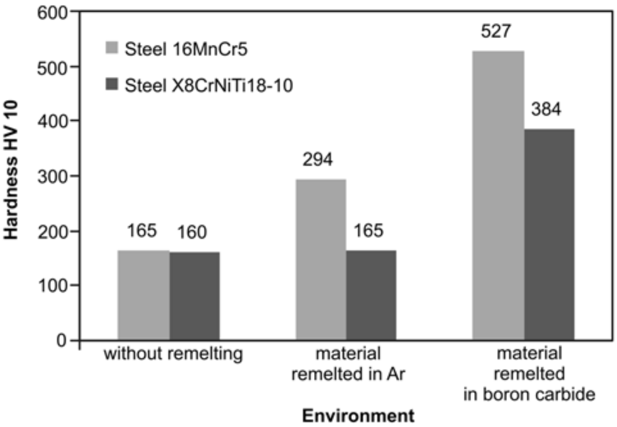

Fig. 3. Values of hardness HV10 for 16MnCr5 and X8CrNiTi18-10 depending on the remelting method.

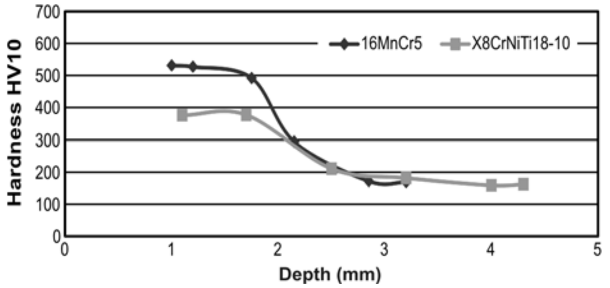

Fig. 4. Hardness HV10 values of 16MnCr5 and X8CrNiTi18-10 remelted in boron carbide vs. distance from the sample surface.

The chemical and structural composition of samples was analysed using the Jeol JSM 7000F scanning electron microscope with the Oxford Instruments EDX analytical unit with an auto-emission nozzle and INCA Energy 250 microanalysis unit, allowing the element analysis from atomic number 5 with energy 10 keV. Measurements were performed in immediate proximity to the surface and at the points on normal lines inside the sample material. This allows observing the depth of remelting as well as material mixing. The analyses performed using EDXS are semi-quantitative only and analyses of results of the phases present in borided layers are therefore informative only.

## 3. Results

### *3.1. Remelting effects on hardness*

The average hardness values HV10 of test samples with no remelting, with remelting in Ar and with remelting in the environment containing boron (remelting boriding) for the two tested steels are presented in Fig. 3.

The graphical representation of the dependence of hardness on distance from the sample surface is depicted in Fig. 4 for particular materials. Increased hardness is preserved to a depth of approximately 1.9–2 mm for the steel 16MnCr5. This is the remelted zone depth.

The heat-affected zone is characterised by a continuous decrease of hardness to the base material hardness value. A significant hardness fall to values of the base material (in the depth of 2–2.8 mm under the sample surface) is evident in the heat-affected zone created in the boron carbide remelting process.

An increase of hardness values up to 400 HV10 occurred in the remelted zone while remelting the steel X8CrNiTi18-10. This increased hardness is preserved to depth 1.6 mm. In the depth of 2.5 mm, rather a rapid hardness fall to 200 HV10 occurs in the heat-affected zone. Then, a gradual hardness decrease to the base material hardness level is observed in the heat-affected zone. This level was reached in the depth of 4 mm.

The results obtained indicate that for the steel 16MnCr5 remelted in the Ar shielding atmosphere, hardness increased by 129 HV10 (i.e., 78 %) as compared to the material not remelted. The total average hardness growth of remelting boriding compared to that of the steel remelted in pure Ar was 233 HV10 (i.e., 79.3 %). The increase of total average hardness in remelting boriding was 362 HV10 (i.e., almost 220 %) compared to steel with no remelting.

The hardness growth was significantly lower in case of the steel X8CrNiTi18-10, practically with no effect of remelting in Ar atmosphere. The boron introduction led to more than a double hardness increase in the layer created as compared to the steel remelted in pure Ar, reaching value 384 HV10. The hardness increase compared to steel with no remelting represented 224 HV10 (i.e., 140 %).

### 3.2. Remelting effects on abrasive wear resistance

Values of relative abrasive wear resistance $\Psi_{\mathrm{abr}}$ of particular test samples were calculated using Eq. (1). These values are depicted in Fig. 5. It is clear that the steel 16MnCr5 in 100 % Ar atmosphere remelting did not cause almost any increase of relative abrasive wear resistance as compared to material with no remelting. Relative abrasive wear resistance growth 0.6454 (i.e., 60 %) after remelting in boron carbide was found compared to the same steel with no remelting.

Remelting of the steel X8CrNiTi18-10 in the 100 % Ar atmosphere resulted in a minimal growth of relative abrasive wear resistance compared to material with no remelting (see Fig. 5), similarly to the steel 16MnCr5. The increased value was 0.0198 (i.e., 1.7 %) only.

The relative wear resistance improvement found after remelting in the boron carbide powder was 0.3706 (i.e., 31.4 %).

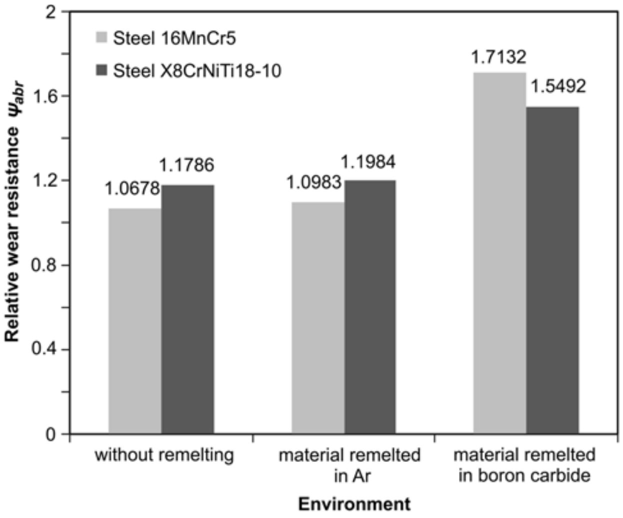

Fig. 5. Relative abrasive wear resistance values of 16MnCr5 and X8CrNiTi18-10 remelted in particular environments.

It can be concluded that remelting the steels 16MnCr5 and X8CrNiTi18-10 in boron carbide has caused a statistically significant improvement of relative abrasive wear resistance.

### 3.3. Remelting effects on structural composition

The differences in the structure of particular parts of 16MnCr5 after remelting are evident from the pictures obtained by light microscopy (LM, Fig. 6). The microstructure of thermally not affected base material consists of bainite-ferrite mixture (Fig. 6a). Ferrite forms polyedric grains, constituting approximately 50 % of structure. It is upper bainite in the bainitic phase. The presence of secondary cementite and $M_7C_3$ carbide particles can be expected in microstructure.

Thermal treatment results in a significant change of phase ratio and microstructure (Fig. 6b). After re-austenitising, resulting in the solution of secondary phases and consecutive rapid cooling, the ferritic phase is suppressed with a growth of the bainitic phase.

A complete change of structure has occurred in the heat-affected zone after boriding (Fig. 6c). Martensite with a very low ferrite portion constitutes the basis. The presence of martensite in structure can be attributed to the hardenability growth caused by higher carbon and boron content in the solid solution. The source material and remelting parameters led to very fine martensite formation.

Figure 7 documents the spots of the surface layer after remelting boriding where the EDX analysis of phases was performed.

A thin layer of Fe(B,C) was found at the sur-

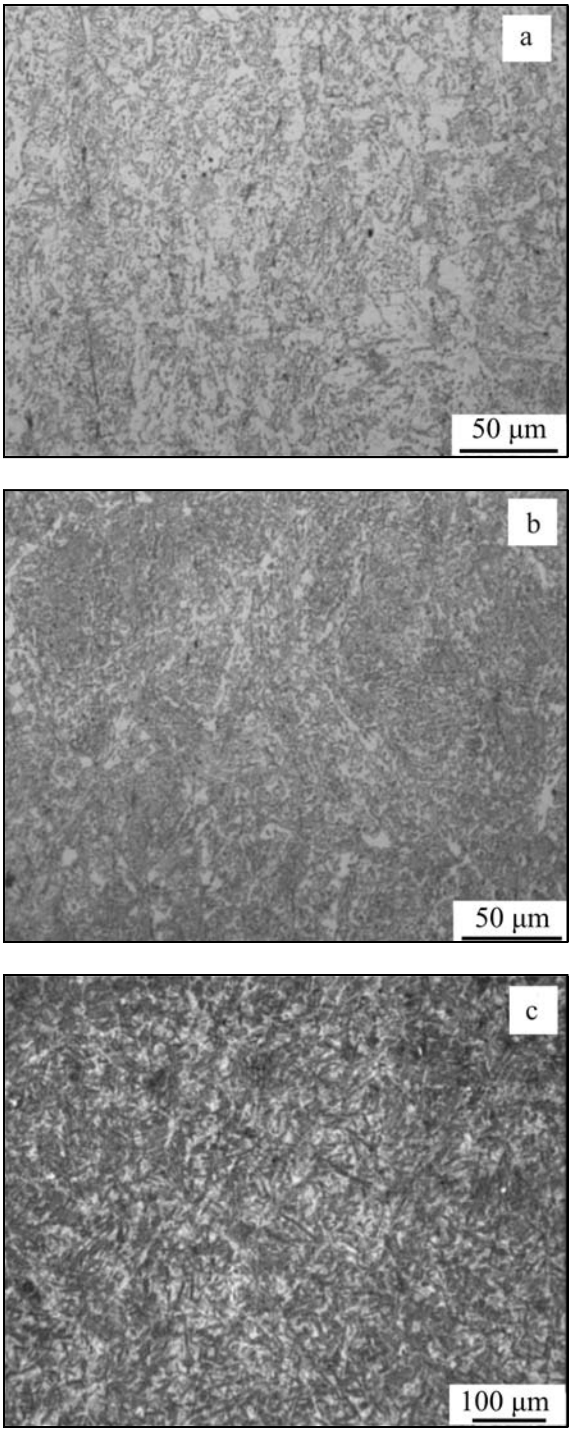

Fig. 6. Microstructure of 16 MnCr5 after remelting: a) zone not affected by heat formed by ferrite and upper bainite mixture, b) heat-affected zone after remelting, formed by upper bainite mainly, c) fine martensite in the heat-affected zone after remelting boriding.

face, with a Fe(B,C) and $Fe_3$(B,C) mixture under it. Borocarbide $Fe_3$(B,C) "cementite" is a stable phase in the Fe-B-C system [23]. The mixture of Fe(B,C) and $Fe_2$(B,C) in iron matrix enriched by B, Si and Al was found locally under the thin surface layer. The EDX spectra of boride FeB (a) and iron matrix enriched by carbon, silicon and aluminium (b) are shown in Fig. 8a,b. It can be stated that pure iron borides have not been found in the experimental material but iron carboborides were found instead, i.e., borides where a part of boron is replaced by carbon [7, 8].

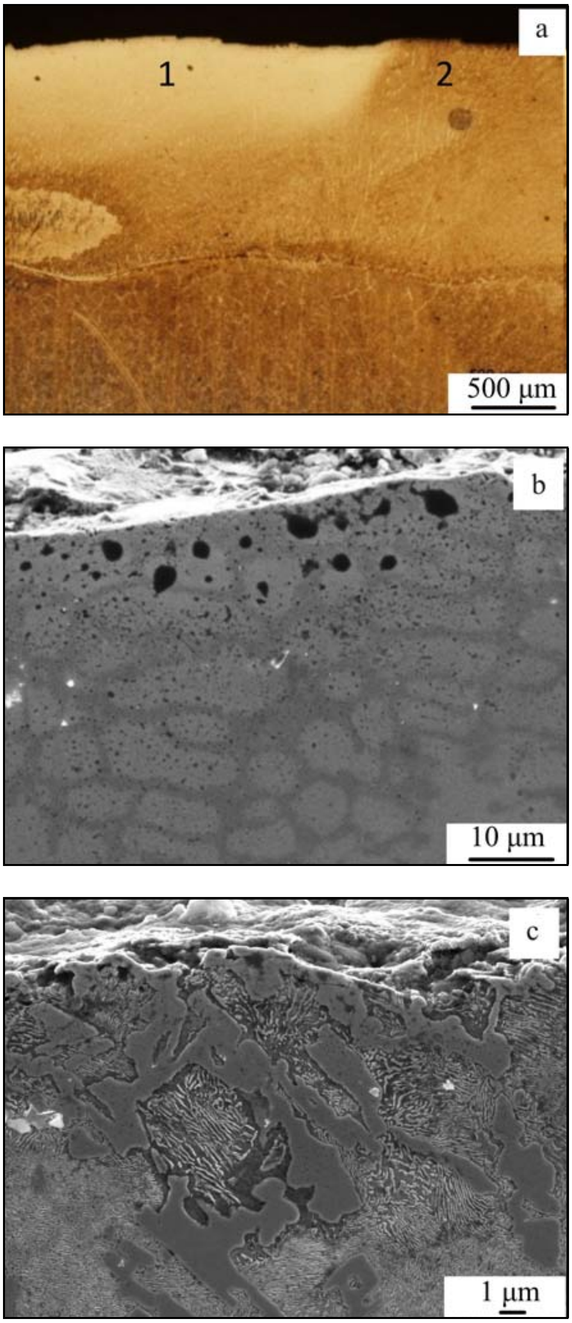

Fig. 7. LM microstructure of the surface layer of 16MnCr5 after remelting boriding: a) remelted surface, LM, b) detail of zone 1 at the surface, SEM, c) detail of zone 2 at the surface, SEM.

The spectrum of carboboride Fe(B,C) from the

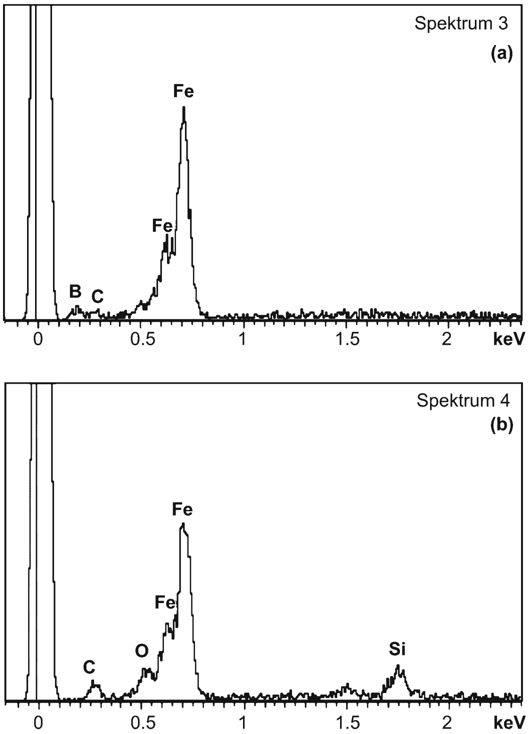

Fig. 8. EDX spectra (16MnCr5): a) Fe(B,C) layer at the surface, b) iron matrix.

very top part of the surface and iron matrix approx. 30 μm under that is presented in Fig. 8.

The microstructure of the base material not affected by heat for X8CrNiTi18-10 is formed by austenite, $\delta$ ferrite and carbidic phase rich in chromium, probably $Cr_{23}C_6$ and TiN (Fig. 9a).

A similar phase formation was observed after remelting. Austenite polyedric grains can be discerned clearly in structure (Fig. 9b). The austenite grain size did not change significantly in this area but grain size homogenisation happened.

Structure has a dendritic nature after fusion boriding (Fig. 9c). It was obtained after material melting and rapid solidifying after remelting.

The phase analysis at the surface, being more heterogeneous than ferritic steel (Fig. 10), showed the presence of a boron carbide $B_4C$ thin layer alloyed by Fe and Cr at the surface (Fig. 11a). The layer formed by $(Fe,Cr,Ni)_7(B,C)_3$ with the network of $B_4C$ and $(Fe,Cr,Ni)_4(C,B)$ type was found in one zone under the surface, and the iron matrix (austenite) with the $(B,Fe,Cr)_4C$ network was present elsewhere (Fig. 11b), generating the heterogeneity mentioned above. The network changes into $Fe_3C$ alloyed by Cr deeper inside the base material. The Fe matrix has the microstructure of steel base material enriched by a low content of Si and Al. When measuring from the surface towards inside, the B and C content decreases, Fe and Cr content increases, and Ni is stable.

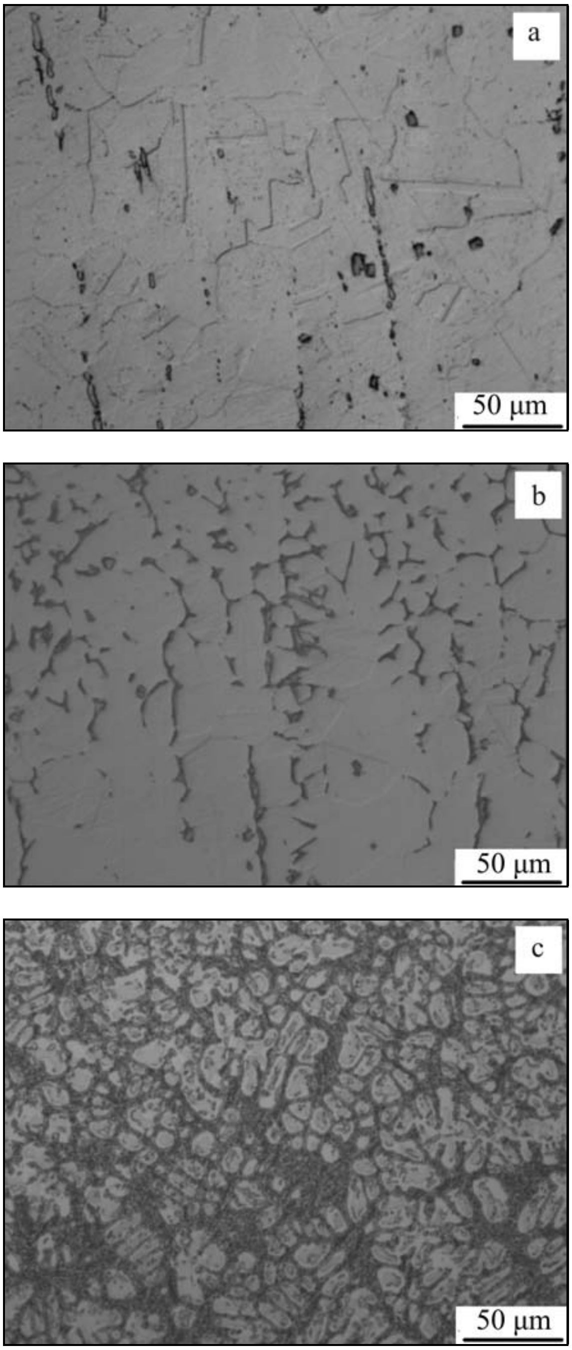

Fig. 9. Microstructure of X8CrNiTi18-10: a) material not affected by heat, b) heat-affected zone after remelting, c) zone after remelting boriding.

## 4. Discussion

The change of polyedric blended microstructure to mostly acicular bainitic one in the steel grade 16MnCr5 after remelting results in a relatively significant hardness increase from 165 to 294 HV10. In terms of abrasive wear resistance results, this structure did not achieve better results as compared to ini-

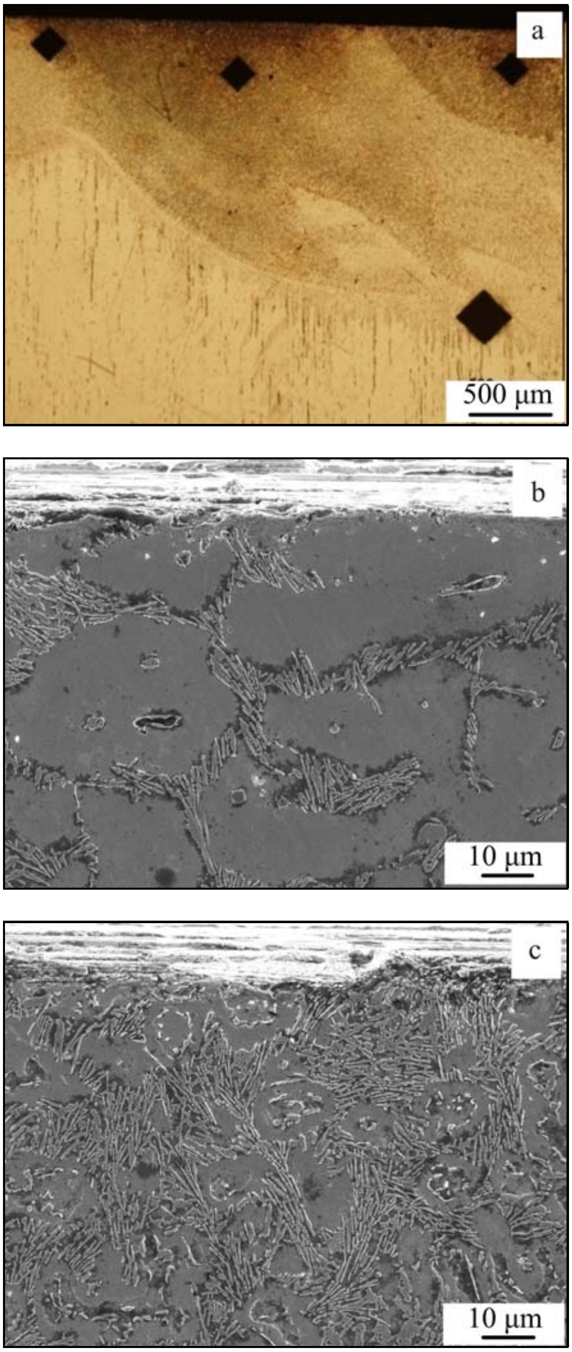

Fig. 10. Surface after remelting in $B_4C$ (X8CrNiTi18-10): a) LM; b, c) SEM.

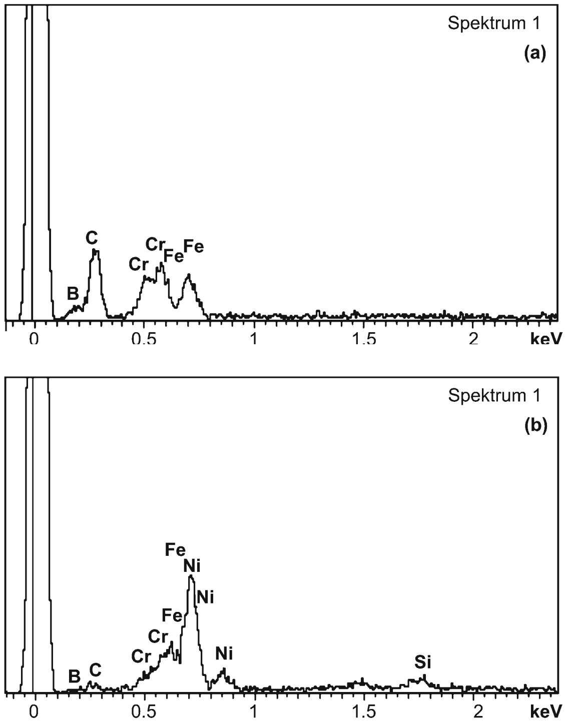

Fig. 11. EDX spectra (X8CrNiTi18-10): a) carbide of $B_4C$ type, b) Fe matrix.

tial condition before remelting. It can be explained by the absence of hard stable phases, which would bring this resistance in. The matrix is formed by fine martensite after boriding, with borides of FeB and $Fe_2B$ types precipitated and with a thin surface layer of FeB type. The presence of borides in the structure of remelted layers can be assumed based on similarity with experiments conducted by other researchers. Some authors obtained structures of iron borides when remelting steels in dusting containing boron, and chromium borides in steels with higher chromium content [3, 5]. More than a triple growth of hardness compared to initial values can be attributed to properties of such a structure. The wear resistance improvement is definitely caused by borides presence at the surface of samples after remelting. As shown by the microstructural analysis, the thickness of this surface layer is not homogeneous, with a potential effect on surface lifetime in the abrasive environment.

Wear resistance is not an inherent material property such as for instance some mechanical or physical properties. Relative wear resistance moves up with the growth of material hardness, along with wear being reduced and tool lifetime being extended. These observations have been proved in tests of weld deposits in laboratory and operational conditions [24, 25].

A little hardness increase of base material after X8CrNiTi18-10 remelting can be explained by a slight shrinkage of austenitic grain size. The fact that it is austenitic steel, thus no $\alpha/\gamma$ transformation is present, along with a short stay at high temperatures in remelting did not lead to so significant structure changes having hardness change as a result.

More than a double hardness increase after remelting boriding compared to not remelted condition is related to a significant microstructure change resulting from mixing with $B_4C$ added and longer carbon and boron diffusion in HAZ. The wear resistance improvement is very interesting, being significantly lower after test than in 16MnCr5. This fact can be explained by matrix properties having an effect on material wear resistance, along with phases composition at the surface.

## 5. Conclusions

Based on the study of surface layers properties after remelting and fusion deposition of $B_4C$ on one type of ferritic steel and one type of austenitic steel, the following conclusions can be formulated:

1. The boride of FeB type was created at the surface of ferritic steel, and matrix changed from ferrite-bainite mixture to fine martensite after remelting.

2. Remelting boriding conditions were not sufficient to change the applied boride to another one, more convenient for austenitic steels.

3. Newly-formed layers at both materials had a non-uniform thickness; the layer in case of austenitic steel was heterogeneous.

4. The hardness and wear resistance values of ferritic steel were higher after both technological processes applied.

5. The boron effect on abrasive wear resistance improvement was proved in case of both steels examined.

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