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The analysis of phase transformation of undercooled austenite and selected mechanical properties of low-alloy steel with boron addition

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ABSTRACT

The paper presents continuous cooling transformation (CCT) diagram of selected low-alloy boron steel with high resistance to abrasion. Tests were performed on samples with dimensions of Ø 3 mm × 10 mm. Samples were prepared from examined material in as – delivery conditions, then were austenitized at 930 °C for 20 min, and then cooled with the rates of $V_{800-500}$ = 0.17, 0.33, 1, 5, 10, 25 and 47 °C/s. During the dilatometric research, the critical temperatures were defined as well as the critical points specified for different cooling rates were designated. In addition, metallographic documentation of received microstructures after dilatometric investigations was prepared and hardness measurement was performed. Moreover, examinations of the basic parameters of strength, impact test and abrasion resistance test were performed and a tendency to brittle fracture was analyzed. The studies show big differences of the analyzed parameters depending on the applied heat treatment, which should provide guidance to users to specific applications of this type of steel.

1. Introduction

Working conditions of machines elements exposed to abrasive wear require use of materials with high strength and high resistance to abrasive wear. Traditionally unalloyed steels which contain from 0.40% to 0.65% of carbon are used. They obtain sufficient strength and toughness due to quenching and tempering at high temperatures, but they are not sufficiently resistant to abrasion. In case of performing tempering at low temperature after quenching these steels are resistant to abrasion but often break after contact with hard materials during their work. The solution to this problem may be to replace them by modern structural materials such as low-alloy boron steel with high resistance to abrasive wear.

In the 1930s it was already observed that the addition of boron significantly increases the hardenability of low and medium carbon steel. As a result of this research, the group of

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weldable bainitic steels with tensile strength to 1200 MPa were obtained. Production of boron steels with high resistance to abrasive wear began in the mid 1950s. At that time, Japanese ironworks JFE Steel Corporation began manufacturing of JFE EVERHARD steel plates, which were recommended for use in machine components exposed to abrasive wear [1]. In Europe, this type of steel was produced for the first time in 1970 by the Swedish steel company SAAB – Oxelösund [2]. Today low-alloy steels with boron achieve high resistance to abrasive wear and high strength. These features are obtained by using advanced technology of manufacturing. This makes boron steels increasingly popular and their application more diverse. Application of these steels can extend the lifetime of very expensive machine construction in many industries such as mining, the automotive, and agriculture industries. An interesting subgroup of these materials is steel with boron intended for heat treatment. These steels are supplied by the manufacturer after cold or hot rolling so that it is possible for them to be heat treated in a suitable manner by the purchaser for its specific application. Manufacturers inform that to obtain high resistance to abrasive wear typical heat treatment of these materials is quenching or quenching and tempering at low temperature. In the material cards the manufacturer presents only the basic mechanical properties of the product, but more knowledge about these steels would be desirable by the customer for an accurate selection of heat treatment. By selecting the parameters of heat treatment of these steels, the desired microstructure and mechanical properties suitable for the particular machine elements can be reached. This would allow them to extend their range of applications. However, the different microstructures, which cause different properties, require careful decision-making to define the application of these steels in various states of heat treatment. With this state of knowledge it is necessary to create CCT diagrams and analyze mechanical properties of low-alloy boron steels with high resistance to abrasive wear and to investigate the effect of cooling rate on their microstructure. This allows the building of a foundation for rational statements about the possible application of this type of steel in the future and planning for the next steps of heat treatment.

2. Methods of study

For the tests, the material from a group of low-alloy boron steels with high resistance to abrasive wear was selected. It was produced by a leading metallurgical company using advanced technology methods. The performed tests included chemical analysis, hardness measurements, dilatometric researches, tensile strength test, impact strength measurements, wear resistance research and metallographic studies using light and scanning electron microscopes.

Microstructure in delivery condition of investigated steel was presented in Fig. 1. Microstructure characterizes pearlite colonies (a quasi-eutectoid) surrounded by ferrite grains. Cementite in pearlite is lamellar and partially coagulated (Fig. 1b).

Chemical composition of investigated steel is summarized in Table 1. This composition is selected not only because of the need to obtain relatively high mechanical properties, but also to ensure its weldability and reduced price applied universality. Chemical composition analysis of the investigated steel was performed with the gravimetric method and with the spectral method. Aluminum and titanium are used as microalloying elements for the binding of nitrogen.

Dilatometric researches were performed using the dilatometer Linseis L78 R.I.T.A. The Ø 3 mm × 10 mm samples were obtained from examined material in as delivered condition. Samples were heated up to a temperature of 930 °C at a rate of 5 °C/s. Holding time at austenitization temperature was 20 min. Then samples were cooled with rates of: $V_{800\text{-}500} = 0.17$, 1, 5, 10, 25 and 47 °C/s, the change in extension of samples depending on temperature was recorded. Digital recording of dilatograms allows its subsequent differentiation to precisely define the temperature of subsequent phase transformations. Based on characteristic points read from the differential curves, CCT phase diagram for austenitizing temperature of 930 °C was created.

Charpy impact test was used to measure impact strength. The measurement was carried out at temperature 20, 0, −20 and −40 °C. The measurement was performed for selected

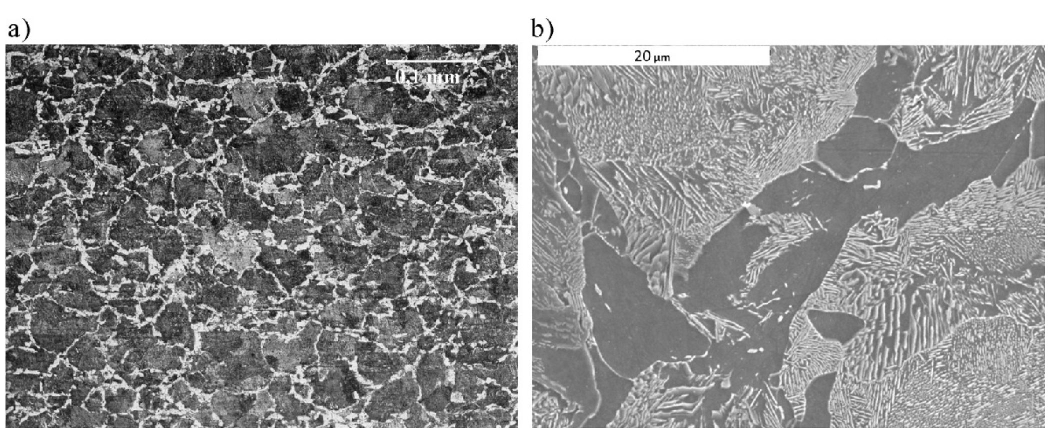

Fig. 1 – Microstructure of investigated low-alloy boron steel with high resistance to abrasive wear in as delivered condition: (a) light microscopy, etched state 5% HNO_3; (b) scanning electron microscopy; etched with 5% HNO_3.

Table 1 – Chemical composition of investigated steel.

Element		Content of elements		
		Spectral method	Gravimetric method	Manufacturer's data [3]
C	wt.%	0.240	0.220	0.250–0.300
Mn	wt.%	1.200	1.150	1.100–1.300
Si	wt.%	0.290	0.200	0.150–0.350
P	wt.%	0.012	0.020	0.030
S	wt.%	0.011	0.020	0.030
Ni	wt.%	0.130	0.150	No data
Cr	wt.%	0.460	0.350	0.200–0.500
V	wt.%	0.012	No data	No data
W	wt.%	0.007	No data	No data
Cu	wt.%	0.150	No data	No data
Al	wt.%	0.010	No data	0.020–0.050
Ti	wt.%	0.040	No data	0.030–0.050
Co	wt.%	0.030	No data	No data
Nb	wt.%	0.107	No data	No data
B	wt.%	0.003	No data	0.0015–0.004
Mo	wt.%	0.030	No data	No data

states that were obtained after cooling from temperature of 930 °C with rates of $V_{800\text{-}500}$ = 0.17, 1 and 25 °C/s. Actual type of fracture was evaluated using scanning electron microscope.

Measurement of basic parameters of the strength $R_{0,2}$, R_m and as well A_5 was carried out at room temperature for states that were obtained after cooling with selected rates of $V_{800\text{-}500}$ = 0.17, 1 and 25 °C/s.

The study of abrasion resistance was performed using the tester T-07 in accordance with the requirements of GOST 23.208-79. Steel grade 45 in normalized condition was used as a reference sample. The aim of this study was to determine the rate of wear resistance, K_b, compared to standard sample. The measurement were performed for selected states that occurred after cooling with rates of $V_{800\text{-}500}$ = 0.17, 1 and 25 °C/s.

3. Results and discussion

3.1. *Phase transformation diagram*

Fig. 2 shows the chosen dilatometric curves with the corresponding differential curves of cooling the samples with cooling rates 25 (Fig. 2a) and 5 °C/s (Fig. 2b) in the dilatometer with marked critical temperatures. Cooling rate is provided at a constant set point speed. The heat of phase transformations is compensated by dilatometer power. Therefore the cooling curves on the CCT diagram are with no disorders associated with the heat of phase transformations. To create a CCT diagram six dilatometric cycles at different cooling rates were made.

CCT diagram of investigated steel is shown in Fig. 3. In addition, Fig. 4 shows the microstructures obtained after cooling with different rates marked on the CCT diagram.

As can be seen from the CCT diagram of investigated steel (Fig. 3), the temperature of the $\alpha \rightarrow \gamma$ transformation is 815 °C. The start temperature of $(\alpha + Fe_3C) \rightarrow \gamma$ transformation is about 720 °C while the finish temperature is 735 °C. During cooling the start of martensitic transformation M_s occurs at 390 °C. Critical quenching rate is about 20 °C/s, but even after cooling with rate 47 °C/s homogeneous martensitic microstructure cannot be occurred. This was confirmed with the observation of the samples microstructure (Fig. 4a). Characteristic for this diagram is open bainite field. With decreasing of cooling rate start temperature of bainitic transformation changes from 390 °C to 570 °C along with decrease of the cooling rate. Finish temperature of bainitic transformation decreases slightly about 20 °C. Boundary temperature between upper and lower bainite according to literature data is 350 °C [5]. However, some studies can be found [6] where the lower bainite is formed even higher than 400 °C. According to the steel microstructures investigations it was detected that the upper bainite was present in the microstructure (Fig. 4c) after cooling with rates smaller than 10 °C/s. Nevertheless high start temperature of bainitic transformation generates a risk that with decrease of the cooling rate upper bainite microstructure can be obtained. Ferrite range occurs with upper bainite. Hardness of investigated steel decreases and after cooling with 5 °C/s is 301 HV10. The presence of ferrite has already been noted in the microstructure of the sample cooled with rate 10 °C/s (Fig. 4c). Ferrite grains can weaken the mechanical properties of this steel. In case of cooling with rate close to 15 °C/s there is a risk of obtaining grains of ferrite in the microstructure.

The ferrite–perlite microstructure occurs after cooling with rate 1 °C/s (Fig. 4e). However, it is non-equilibrium cooling and volume fraction of pearlite in the microstructure is higher than it was expected according to carbon content in examined steel. Characteristic for the presented diagram is a displacement of the diffusion processes to longer time as compared to the CCT diagram of steel that has similar chemical composition but does not contain boron [7]. Similar displacement to longer time was also noted for bainitic range. This indicates that boron has strong impact to increase bainitic hardenability. Efficiency of boron depends on the position of ferrite, bainite, and pearlite curves. Boron primarily inhibits transformation of ferrite while affects the increase of bainitic hardenability when curves of ferritic and pearlitic transformation are displaced to longer times [8]. This situation takes place in the case of the analyzed steel.

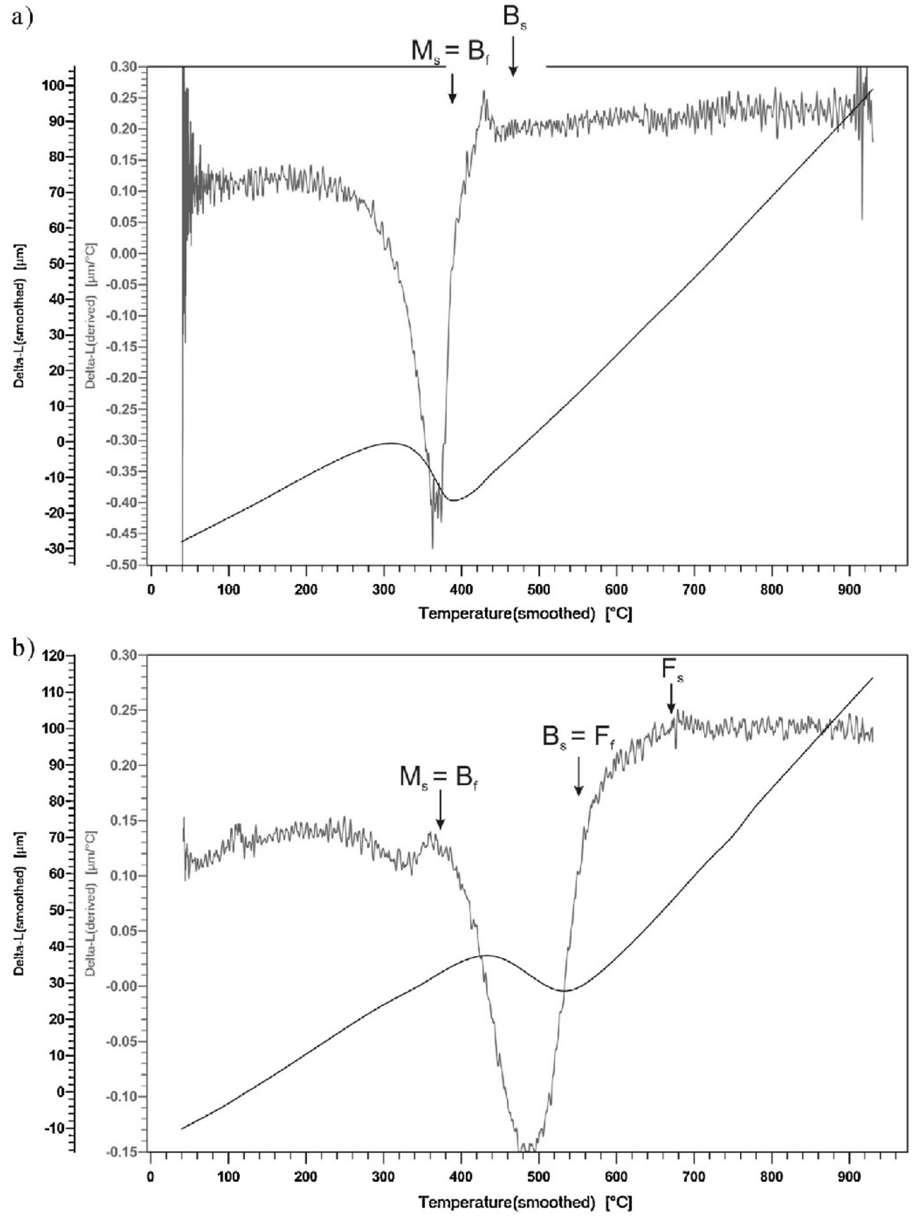

Fig. 2 – The dilatometric curves with the corresponding differential curves of cooling the samples with cooling rate (a) 25 and (b) 5 °C/s.

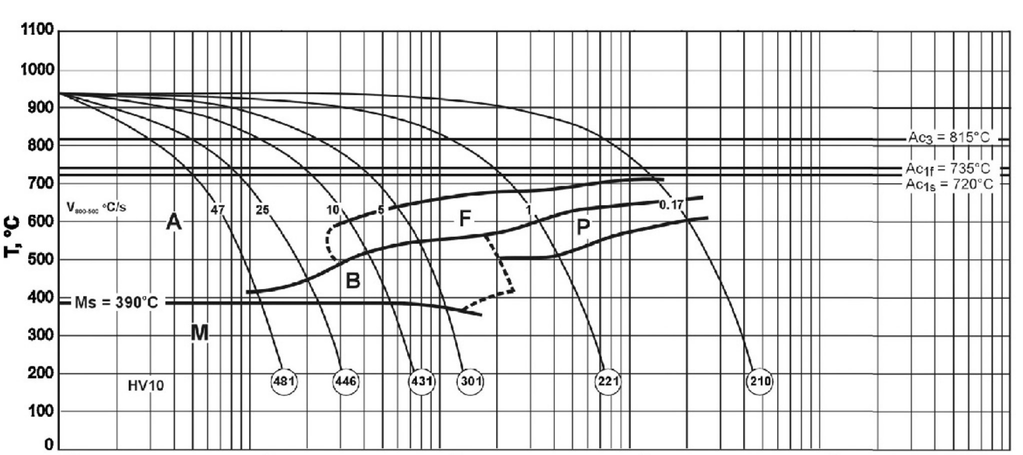

Fig. 3 – CCT diagram for investigated low-alloy boron steel after austenitization at 930 °C/20 min.

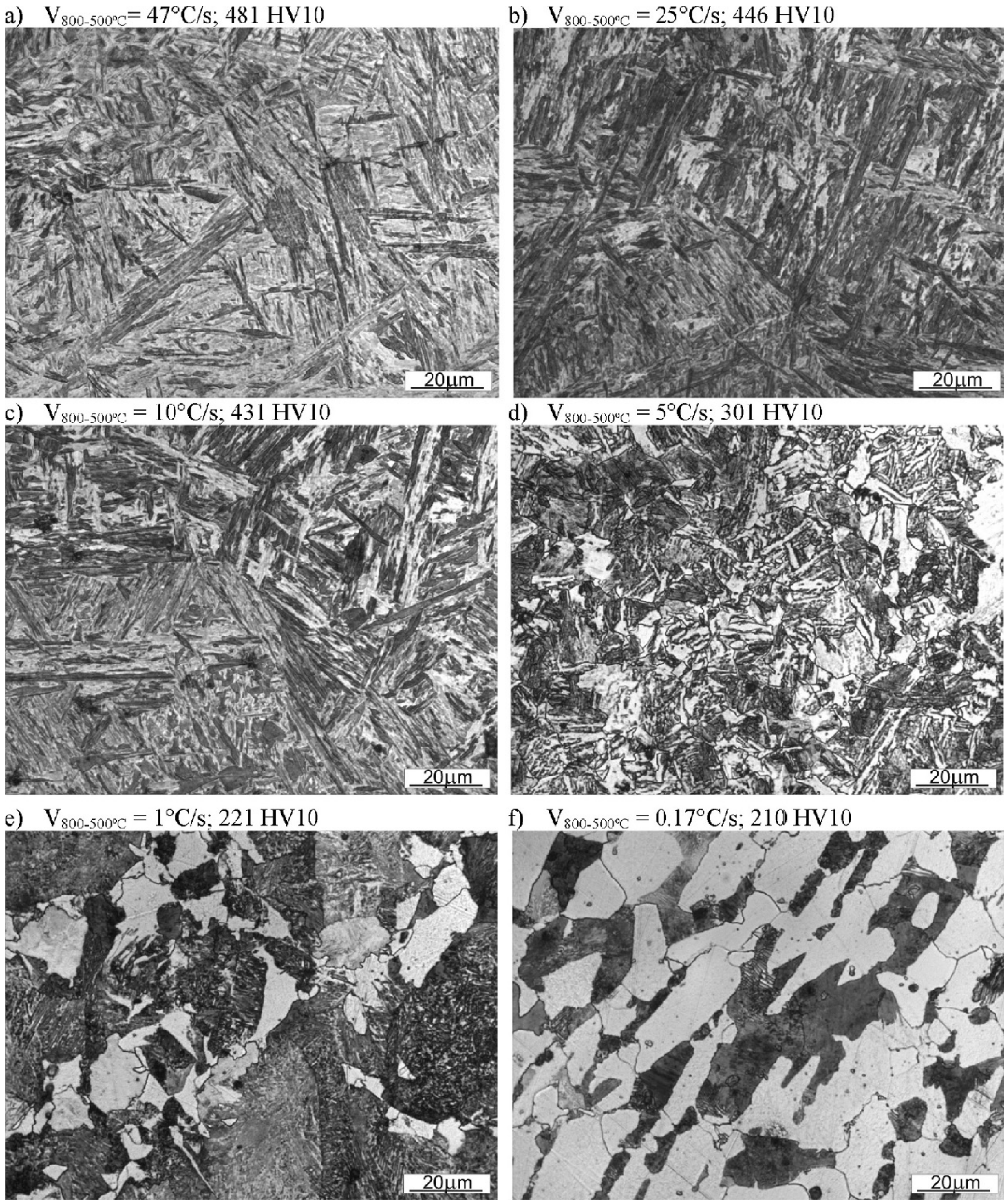

Fig. 4 – Microstructure and results of hardness measurement obtained after cooling with different rates from temperature of 930 °C: (a) low-carbon martensite and bainite; (b) low-carbon martensite and bainite; (c) low-carbon martensite, bainite and grains of ferrite; (d) low-carbon martensite, bainite and grains of ferrite; (e) ferrite and perlite; (f) ferrite and perlite. Etched with 5% HNO_3, light microscopy.

Other alloying elements presented in the investigated steel could have influence on the effectiveness of boron. For example, niobium and molybdenum increase the stability of supercooled austenite. Chromium, molybdenum and manganese retard the growth of ferrite nucleus. Aluminum and titanium, prevent a formation of boron nitride and reduce the austenite grain size. Dissolved boron increases the hardenability of steel. Time and temperature of the austenitization have an effect on the amount of dissolved boron in the austenite. For the specified boron and other alloying element contents, there is an austenitization temperature at which the addition of boron most effectively raises hardenability.

For further tests of mechanical properties there were selected the specimens after cooling with rates of $V_{800-500}$ = 0.17, 1 and 25 °C/s.

3.2. *Tensile strength results*

The results of tensile test depending on the cooling rates are shown in Table 2. Samples were taken in the longitudinal direction to the rolling direction.

Table 2 – Results of tensile test.

Cooling rate [°C/s]	$R_{m,av}$ [MPa]	$R_{p0,2,av}$ [MPa]	$A_{5,av}$ [%]
25	1728	1236	11
1	600	363	27
0.17	532	360	27

The highest tensile strength of the steel occurs after cooling with rate 25 °C/s, in this state the average value is 1728 MPa. The parameter R_m decreases with decreasing of cooling rate and shows value of 600 MPa for specimens cooled with rate 1 °C/s. A similar, relatively low value of R_m (532 MPa) is characterized by the steel after cooling with rate 0.17 °C/s. The average value of the yield point for tested steel after cooling with rate 25 °C/s is equal to 1236 MPa. Decreasing of cooling rate significantly reduced value of this parameter. Average yield strength values for analyzed steel after cooling with rates 1 °C/s and 0.17 °C/s are much smaller and are equal to 363 and 360 MPa, respectively. It should be noted that for these states elongation values are highest and equal to 27% while after cooling with rate 25 °C/s average elongation value is 11%. Elongation of 11% is acceptable for this type of steel.

3.3. *Impact strength results*

The measurement results for steel cooled with different rates are summarized in Table 3. Samples were taken in the longitudinal direction to the rolling direction. Macroscopic view of fractures was presented in Fig. 5. Fig. 6 shows microscopic views of central zones and areas under mechanical notch of selected fractures obtained after Charpy test at room temperature and −40 °C.

Table 3 – Results of impact test at temperature range from 20 to −40 °C.

Cooling rate [°C/s]	KCV_{av} [J/cm^2]			
	20 °C	0 °C	−20 °C	−40 °C
25	43	38	38	31
1	66	34	17	6
0.17	110	57	23	16

Taking the criterion of minimum impact strength equal to 35 J/cm^2, which is adopted for construction materials in many applications [9], tested steel meets this criterion in all analyzed states of heat treatment at 20 °C. However, already at lower temperatures impact strength values for two of the three selected states are smaller. The criterion is not met for specimens cooling with rate 1 °C/s even at 0 °C, and their impact strength is further lowered at sub-zero temperatures. Tested steel cooled with rates 1 and 0.17 °C/s shows the impact strength at −40 °C equal to 6 and 16 J/cm^2, respectively. Whereas after cooling with rate 25 C/s impact strength of tested steel at temperature −20 °C equals to 38 J/cm^2 and meets the criterion

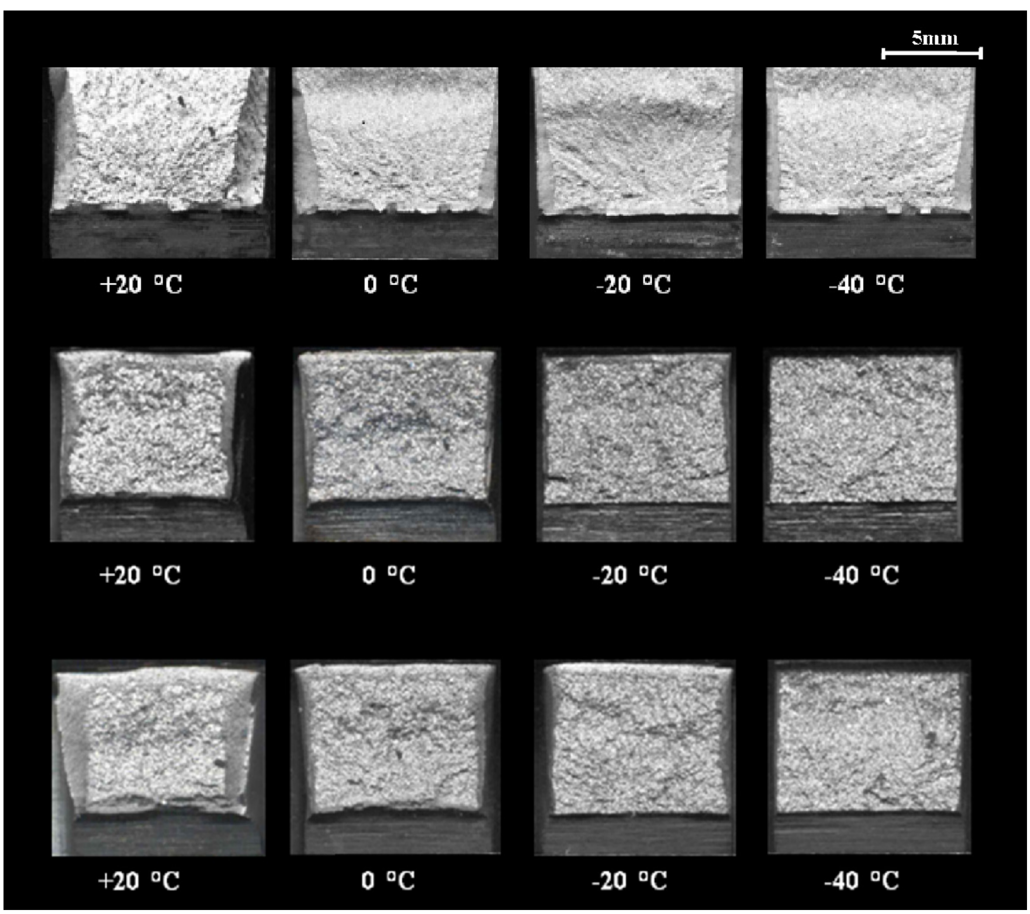

Fig. 5 – Macroscopic view of the fractures of specimens cooled with rates: (a) 25 °C/s, (b) 1 °C/s, (c) 0.17 °C/s. Test temperature 20 °C, 0 °C, −20 °C and −40 °C.

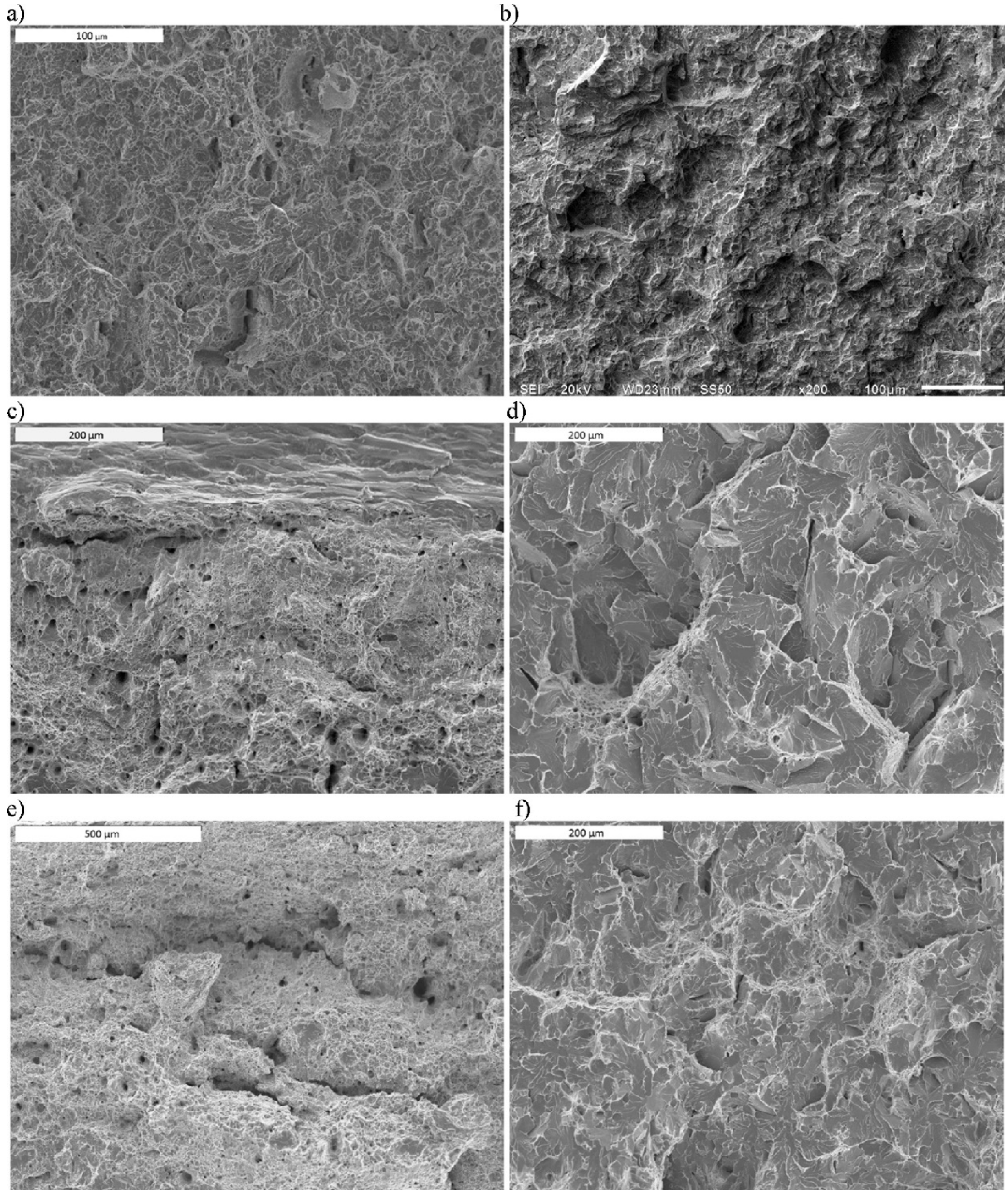

Fig. 6 – Microscopic view of fracture: (a) central zone, specimen cooled with rate 25 °C/s, test temperature 20 °C; (b) central zone, specimen cooled with rate 25 °C/s, test temperature −40 °C; (c) ductile narrow zone under mechanical notch, specimen cooled with rate 1 °C/s, test temperature 20 °C; (d) central zone, specimen cooled with rate 1 °C/s, test temperature 20 °C; (e) ductile narrow zone under mechanical notch, specimen cooled with rate 0.17 °C/s, test temperature 20 °C; (f) central zone, specimen cooled with rate 0.17 °C/s, test temperature 20 °C. Non-etched state, SEM.

cited. Impact strength at temperature of −40 °C is 31 J/cm^2 and is slightly smaller than 35 J/cm^2. It should be emphasized that the specimens cooled at the rate of 25 °C/s show the lowest sensitivity on the KCV values measured at different temperatures when the KCV values for the specimens with ferrite and perlite microstructure decrease in the meaningful way in the same conditions of Charpy test.

Another way to determine the temperature of ductile to brittle transition is a direct analysis of the fracture nature. It is assumed that the criterion of impact (35 J/cm^2) corresponds to the occurrence the mid-brittle and mid-ductile fracture. Analysis of the fractures shows the differences in the assessment of the fragility according to these two criteria. Impact strength at 20 °C, for tested steel in all states of heat treatment, is higher than the mentioned criteria. Participation of brittle fracture, however, far exceeds the value of 50% after cooling with rate 1 °C/s and at room temperature is 61% (Fig. 5b). At temperature of 0 °C, participation of brittle fracture exceeds 80% for this state (Fig. 5b).

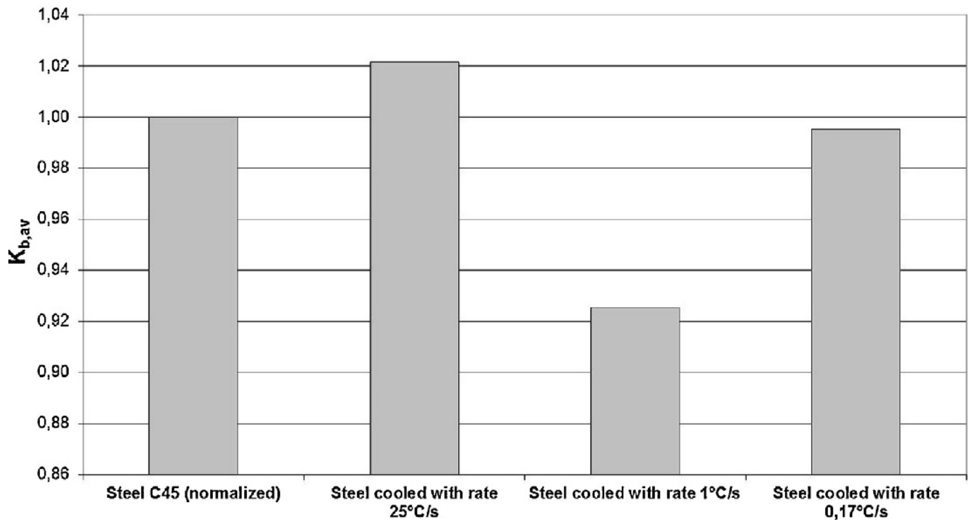

Fig. 7 – The rate of wear resistance, K_b, of tested steel after different states of heat treatment.

For specimens cooling with rate 0.17 °C/s, when the values of impact strength are higher, surfaces of brittle fracture exceed 40% at room temperature but at 0 °C exceed 75% (Fig. 5c). In this case, transition from ductile to brittle fracture takes place at room temperature or even higher than 20 °C. Ductile narrow zone under mechanical notch (Fig. 6c and e) provides a low resistance of steel to initiation of brittle fracture. Central zones of the fracture for these two states are typical brittle fracture (Fig. 6d and f).

Different fracture is provided in tested steel after cooling with rate 25 °C/s. Plastic zones under mechanical notch and in lateral areas are visible not only at 20 °C, but also in sub-zero temperatures up to the temperature of −40 °C (Fig. 5a). Kind of fracture in central zone is also different from previous states. Central zone contains many ductile areas. Microstructure of fine acicular martensite and bainite provides greater resistance to the development of fracture at all temperatures. This resistance is caused by the formation of the small facets, partially deformed plastically, in the central zone of sample (Fig. 6a and b). This type of fracture occurs also after test at temperature of −40 °C. Thus this microstructure exhibits more security against the occurrence of brittle fracture in comparison to previous microstructures composed with ferrite and perlite.

3.4. *Wear resistance*

Values of $K_{b,av}$ after different heat treatment are presented in Fig. 7. Analyzed steel exhibits the greatest resistance to abrasion after cooling with rate 25 °C/s. Steel cooled with rate 0.17 °C/s shows a similar resistance to the normalized steel C45. The lowest value of the wear resistance is present in tested steel cooled with rate 1 °C/s. However, steels with a martensitic-bainitic microstructure shows only a few percent advantage over the steels C45 after normalization but wear mechanism is more beneficial for hardened steel as it was evidenced by operational tests [10]. Micro-cutting and micro-ploughing are the predominant micro-mechanisms in material removal but the proportion of micro-ploughing increases by increasing matrix toughness [11]. Soft, plastic microstructures are abraded mainly due to micro-ploughing that causes rather plastic deformation of the material than material loss. However, in case of martensitic or martensitic-bainitic microstructures, the harder and more brittle, material loss is caused with micro-cutting that additionally causes smoothing of the surface.

4. Conclusions

(1) The prepared CCT diagram of investigated steel shows that temperature of the $\alpha \rightarrow \gamma$ transformation is 815 °C. The start temperature of $(\alpha + Fe_3C) \rightarrow \gamma$ transformation is about 720 °C while finish temperature is 735 °C. During cooling the start of martensitic transformation M_s occurs at 390 °C. Critical quenching rate is about 20 °C/s but after cooling with a rate of 25 °C/s homogeneous martensitic microstructure cannot occur.
(2) Beneficial effect of boron micro-addition is a delay of the diffusion processes and increase of bainitic hardenability. The ferrite starts to occur in microstructure during cooling with the rate about 10 °C/s.
(3) High start temperature of bainite transformation (580 °C) may generate a risk of receiving the upper bainite in the microstructure during cooling with a lower rate.
(4) As a result of cooling with the rates of 25 °C/s and 47 °C/s low-carbon martensite and lower bainite with hardness 446 HV10 were received. This type of structure is characterized by high strength properties combined with sufficient toughness. This eliminates the need of providing tempering at low temperature after quenching to the stress relaxation.
(5) Tested steel achieved high mechanical properties after cooling with rate of 25 °C. Greater toughness and less tendency to brittle fracture, in the operating temperature range of most devices from 20 °C to −40 °C, occurs in tested steel after cooling with rate 25 °C/s in comparison to this steel cooled with rates 1 °C/s and 0.17 °C/s. High basic strength parameters $R_{0,2}$ and R_m and greatest resistance to abrasion are also exhibited in steel cooled with rate 25 °C/s. Elongation value is also acceptable for hardened state.

(6) Low-alloy boron steel with high resistance to abrasive wear only with martensitic or martensitic-bainitic microstructure can be applied in exposed to abrasive wear machine components from which high tensile and impact strength are required. Prepared CCT diagram defines the cooling rate (min 20 °C/s) required to obtain a martensitic-bainitic microstructure.
(7) To achieve the most beneficial properties of the low-alloy boron steel it is recommended to perform the heat treatment combining by austenitization and quenching in water or oil. Based on prepared CCT diagram it was stated that austenitization temperature can be lower (depends on quenching medium) to 845 °C (water) or 865 °C (oil). Tempering after quenching is not necessary.

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