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The influence of heat treatment on microstructure and crack resistance of boron microalloyed steel plates

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Materials

ABSTRACT

Purpose: The work presents results of investigation of heat treatment conditions influence on microstructure and crack resistance of C-Mn constructional steels with microaddition of boron assigned to be used in production of high strength steel plates.
Design/methodology/approach: Metallographic observations, heat treatment, hardness measurements, impact strength examinations, fractographic analyses of fracture surfaces of test pieces have been performed.
Findings: Dispersive particles of interstitial phases formed on dislocations during the plastic deformation, limiting grain growth of austenite, create the possibility to obtain metallurgical products with fine-grained microstructure giving them high strength and guaranteed crack resistance, also at low temperature.
Research limitations/implications: Further research of microstructure in transmission electron microscope as well as complementary impact resistance tests at the temperature lower than -60°C are foreseen to be performed.
Practical implications: Obtained results of examinations, especially detailed fractographic analysis of fracture surfaces of test pieces together with chemical composition analysis of revealed non-metallic inclusions and precipitations of secondary phases will make contribution to better understanding of cracking mechanisms in the group of high-strength steels.
Originality/value: Performed research revealed that investigated steels present high crack resistance also at low temperature. It can be achieved through proper selection of chemical composition and adequate conditions of heat treatment and plastic working. The presence of microadditions of transition metals deriving from IVb and Vb group of periodic classification of the elements with high chemical affinity to nitrogen and carbon allows producing rolled products with high exploitation properties.
Keywords: Metallic alloys; Heat treatment; Microalloyed steels; Heavy plates; Crack resistance

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1. Introduction

High-strength steel plates with desired crack resistance are used for construction of highly loaded welded constructions, particularly wheeled cranes and road machines, heavy transport vehicles, high load capacity overhead travelling cranes, machines and devices for extractive industry and others. Initially, this type of plates with $YS_{0.2}$ ranging from 550 to 960 MPa and $KV_{-40^{o}C}$ >

27 J was made of heat-treatable steels containing ≤ 0.2% C, ≤ 1.6% Mn, ≤ 0.8% Si, ≤ 1% Cr, ≤ 2% Ni, ≤ 0.6% Mo and ≤ 0.1% V. High value of the C_E carbon equivalent of these steels equal from 0.72 to 0.82% created the necessity of preliminary heating of components connected through welding to the temperature even higher than 200°C [1-5].

Introduction of B in the amount of ≤0.005%, increasing hardenability, ≤0.04% Ti, ≤0.04% Nb and ≤0.08%V forming MX (M - Nb, Ti; X - N, C) interstitial phases that make possible production of products with fine-grained microstructure, permitted to reduce concentration of C ≤ 0.17%, Cr ≤0.8%, Mo ≤0.5% and C_E ≤0.56 and to produce toughened steel plates with $YS_{0.2}$ from 700 to 1100 MPa and $KV_{-40^oC} \geq 40$ J, and also to decrease the temperature of initial heating of welded parts to ≤ 150°C. Steels with Nb, Ti and B microadditions used for production of these plates require limitation of P ≤ 0.015% and S ≤ 0.005% concentration as well as modification of non-metallic inclusions which have an essential influence on decrease of nil ductility transition temperature and limitation of anisotropy of plastic properties of steel plates, i.e. obtaining the ratio of energy absorbed during fracture of transverse Charpy V-notch test pieces to longitudinal ones close to unity [6-8].

Boron microaddition which leads to an increase of hardenability of fine-grained steels exerts an effective influence only in the state as dissolved in a solid solution and causes a decrease of energy of these lattice defects, delay of nucleation during $\gamma \rightarrow \alpha$ transformation and a decrease of the critical cooling rate while segregating on austenite grain boundaries [9]. A desired effect can be achieved solely in case of steels with high metallurgical purity, considering that this element, due to its high chemical affinity to oxygen and nitrogen, forms B_2O_3 oxide in liquid metal transiting into slag, and bonds in a stable BN nitride in a solid state of steel. Although BN nitride dissolves in a solid solution, it requires application of high austenitizing temperatures; such temperatures lead also to dissolution of AlN and of a part of MX phases of microadditions introduced into steel. It's usually a cause of disadvantageous grain growth and deterioration of ductility. Therefore, formation of BN boron nitride is prevented by introduction of Ti in the amount necessary to fix nitrogen in TiN [10]. During cooling, boron forms $M_{23}(C, B)_6$ borides which dissolve in austenite at the temperature slightly higher than A_{c3} [11-13].

Steel plates, apart from having high strength, must be characterized with guaranteed crack resistance, also at low temperature.

The interest in brittle cracking of steel is directly connected with unexpected break-downs of first welded constructions. The significance of the mechanisms and conditions of brittle cracking increased considerably after dissemination of welding technologies in shipbuilding industry, hoisting equipment, nuclear power engineering, means of heavy transportation and other applications made of high-strength steels. Brittle cracking is frequently the final stage of destruction of constructions, initiated by the course of fatigue process, stress corrosion or simultaneous influence of several phenomena, but since occurring unexpectedly, always creates serious danger for the surrounding.

Analyses of temperature changes of KV absorbed energy allow determining ITT impact transition temperature, representing ductile to brittle behaviour change, connected with intense decrease of plastic properties and crack resistance in a very narrow range of temperature, at simultaneous change of ductile (fibrous) fracture into brittle (distributive) fracture. As indicated in the reference [14], the KV absorbed energy at ITT temperature decreases practically to zero at low concentration of C and N and decreases mildly to zero value at higher concentration of these elements in the whole temperature range. Considering that only constructional alloys with guaranteed crack resistance are technically useful, the ITT impact transition temperature is conventionally set to T_{27J}, which responds to KV energy absorbed during fracture of Charpy V-notch test pieces equal 27 J. An alternative to this is the FATT (Fracture Appearance Transition Temperature); at such temperature the fracture surface of Charpy V-notch test pieces contains specific portion of brittle fracture, usually of 50% [15,16].

The scope of the work was to investigate the influence of heat treatment on microstructure and crack resistance of boron microalloyed steel plates.

2. Experimental procedure

The research was performed on two grades of constructional microalloyed steels with boron (Table 1), assigned to be used in production of steel plates. The material for testing was obtained from the Huta Stalowa Wola steel mill - Huta Stali Jakościowych S.A., in a form of 15 mm thick heat treated steel plates.

Table 1
Chemical composition of the investigated steels

Material	Mass contents, %				
Steel A	C	Mn	Si	Cr	Ni
	0.30	1.10	0.25	0.76	1.05
	Mo	V	Cu	Al	B
	0.23	0.05	0.16	0.03	0.002
Steel B	C	Mn	Si	Cr	Ni
	0.20	0.80	0.20	0.50	1.30
	Mo	V	Cu	Al	B
	0.35	0.10	0.17	0.03	0.003

The plate made of the A steel was subjected to austenitizing at the temperature of 880°C for 15 minutes with successive water quenching and tempering at the temperature of 180°C for 90 minutes with successive air-cooling. While the B steel plate was water quenched from the temperature of 910°C after austenitizing for 15 minutes and successively tempered under the same conditions as the A steel plate.

Within the framework of research metallographic observations of samples in as-delivered state, heat treatment of specimens, microscopic observations of heat treated samples, hardness measurements, impact test, fractographic analyses of fracture surfaces of test pieces and the attempt to evaluate the brittle fracture appearance transition temperature have been carried out. Metallographic specimens were prepared in order to investigate microstructure of steel in as-delivered and in heat treated state. The specimens were ground on abrasive papers with granulation of 400 to 1200 with successive mechanical polishing on polishing wheels dampened with diamond slurry. In order to reveal the real microstructure, samples were etched in three

percent solution of nitric acid and ethanol (Nital). Metallographic observations of specimens were carried out in Leica MEF 4A light microscope applying magnification ranging from 100 to 1000x.

With the purpose of determining the influence of heat treatment on microstructure and properties of steels, samples were taken from delivered plates and subjected to full annealing, normalizing annealing, hardening, hardening and medium-temperature tempering and toughening. The heat treatment of specimens was conducted in FURNACE F6000 electric chamber furnace supplied by Thermolyne with the accuracy of temperature adjustment equal ±1°C. Detailed parameters of performed heat treatment of samples are presented in Table 2.

Table 2.
Parameters of performed heat treatment of samples

Material	Sample	Heat treatment		
		Annealing	Quenching	Tempering
Steel A	1	880°C/15min/furn.	x	x
	2	880°C/15min/air	x	x
	3	x	880°C/15min/water	x
	4	x	880°C/15min/water	350°C/90min/air
	5	x	880°C/15min/water	600°C/90min/air
Steel B	6	910°C/15min/furn.	x	x
	7	910°C/15min/air	x	x
	8	x	910°C/15min/water	x
	9	x	910°C/15min/water	350°C/90min/air
	10	x	910°C/15min/water	600°C/90min/air

In order to determine the influence of heat treatment on hardness of investigated steels, Rockwell hardness tests were carried out.

Impact energy tests in the temperature range from +20 °C to -60 °C were conducted with the aim of studying the influence of heat treatment on crack resistance. The examination was done on Charpy impact testing machine with initial energy equal 300J. The test was done on V-notched 10x10 mm cross-section test pieces. In case of low temperature impact testing, the samples were cooled up to desired temperature in liquid nitrogen with the addition of ethanol.

Fractographic observations of fracture surfaces of test pieces were carried out in ZEISS/SUPRA 25 scanning electron microscope, applying the accelerating voltage 20kV. Identification of chemical constitution of revealed non-metallic inclusions and precipitations of secondary phases located on the fracture surfaces was conducted with the help of EDS (Energy - Dispersive Spectrometry) spectrometer equipped with EDAX detector.

There was an attempt to determine the ITT impact transition temperature of investigated steels on the basis of analysis of obtained KV absorbed energy values of samples examined in the temperature range from +20 to -60°C (27J criterion), and basing on the examination of fracture surfaces of these samples in scanning electron microscope (FATT criterion).

3. Results of investigations

Observations carried out in light microscope allowed to examine the microstructure of the A and B grade of steel in as-delivered state, i.e. after hardening and low-temperature tempering and after normalizing annealing, full annealing, hardening, hardening and medium-temperature tempering, as well as after toughening.

The A steel subjected to austenitizing at the temperature of 880°C for 15 minutes and successively slowly cooled along with cooling the furnace up to the ambient temperature demonstrated fine-grained ferritic-pearlitic microstructure (Fig. 1) with slightly higher participation of ferrite in relation to pearlite. While application of air-cooling of the steel after austenitizing under the same conditions leads to formation of fine-grained bainitic-ferritic microstructure, yet in this case the portion of ferrite is small and is equal approximately 20%. The microstructure of investigated steel in as-delivered state, i.e. after water hardening from the temperature of 880°C, after austenitizing for 15 minutes and low-temperature tempering at the temperature of 180°C for 90 minutes with successive air-cooling is shown in Fig. 2. The A steel heat treated under such conditions obtained microstructure of low-tempered martensite. Application of toughening, i.e. hardening and high-temperature tempering at the temperature of 650°C leads to formation of microstructure of high-tempered martensite (Fig. 3). The figure presents traces of grain boundaries of primary austenite with precipitated on them carbides of alloying elements.

The B steel subjected to full annealing, i.e. austenitizing at the temperature of 910°C for 15 minutes with successive cooling along with the furnace, reveals - in accordance with expectations - ferritic-pearlitic microstructure (Fig. 4). Revealed microstructure, in comparison with microstructure of the A steel after the same heat treatment (full annealing), is characterized with less fine-grained microstructure and - what is less obvious considering lower concentration of carbon - higher participation of α phase. Microstructure of tempered martensite obtained after water hardening of samples after their austenitizing at the temperature of 910°C for 15 minutes and tempering at the temperature of 180 and 650°C with successive air-cooling is presented in Fig. 5 and 6. Performed metallographic observations revealed that investigated steels have comparable microstructure after the heat treatment done under the same conditions. Application of optimal conditions of the heat treatment, especially recommended austenitizing temperature and the presence of carbide-forming elements in steel, precipitating on the boundaries of γ phase and significantly limiting their growth, decide that investigated steels show fine-grained microstructure of products of supercooled austenite transformations, what guarantees obtaining advantageous exploitation properties.

The measurements carried out on Rockwell hardness testing machine made possible to determine the hardness of both steels in as-delivered state and after applied heat treatment (Table 2). Detailed parameters of performed hardness test are set together in Table 3.

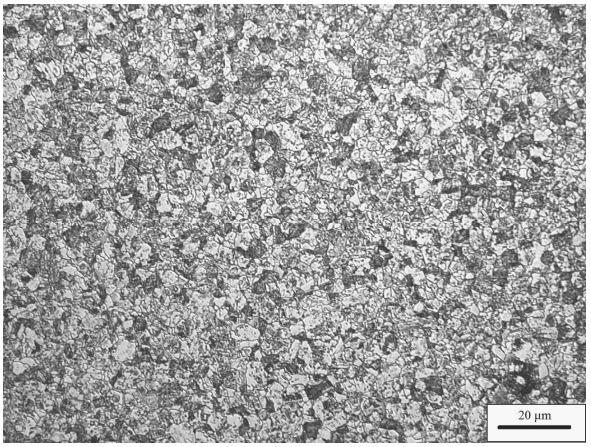


Fig. 1. Fine-grained ferritic-pearlitic microstructure of the A steel; full annealing at 880°C/15 minutes/furnace

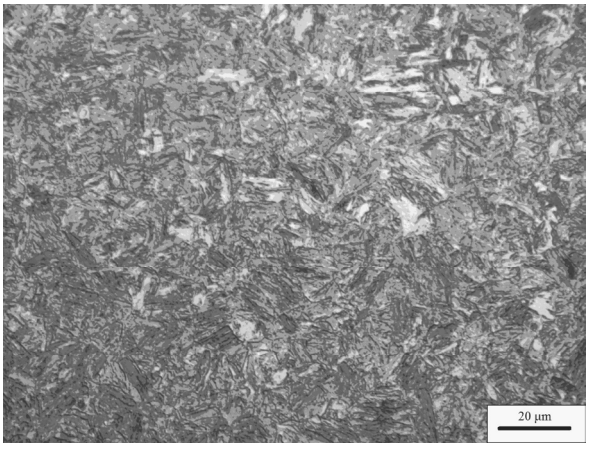


Fig. 2. Low-tempered martensite of the A steel; hardening at 880°C/15 minutes/water + tempering at 180°C/90 minutes/air

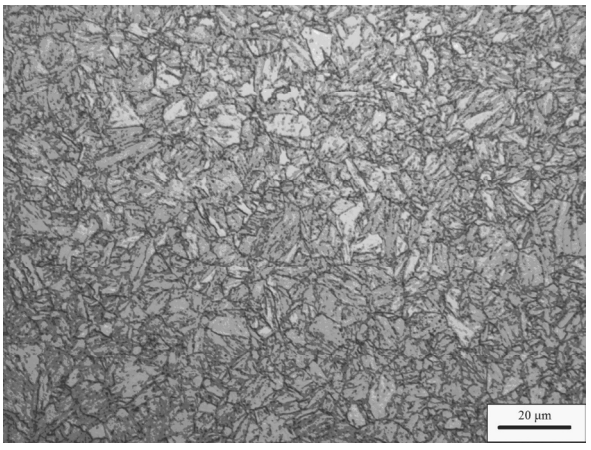


Fig. 3. High-tempered martensite of the A steel with traces of grain boundaries of primary austenite; hardening at 880°C/15 minutes/water + tempering at 650°C/90 minutes/air

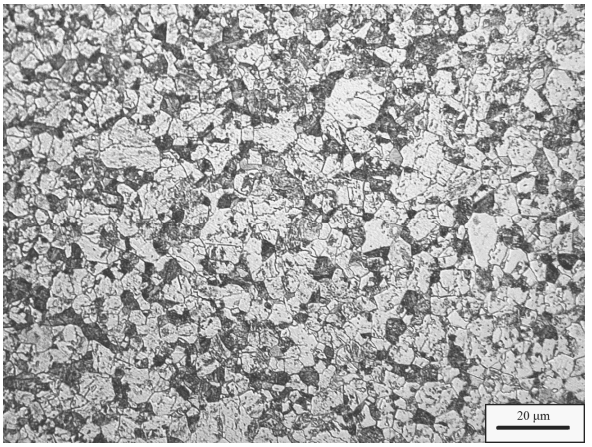


Fig. 4. Fine-grained ferritic-pearlitic microstructure of the B steel; full annealing at 910°C/15 minutes/furnace

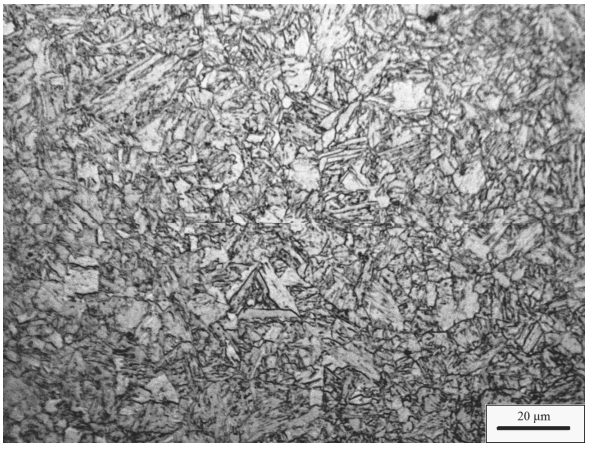


Fig. 5. Low-tempered martensite of the B steel; hardening at 910°C/15 minutes/water + tempering at 180°C/90 minutes/air

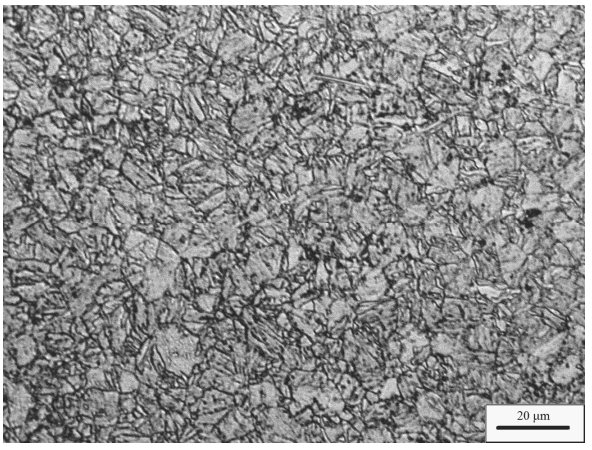


Fig. 6. High-tempered martensite of the B steel with traces of grain boundaries of primary austenite; hardening at 910°C/15 minutes/water + tempering at 650°C/90 minutes/air

It arises from conducted hardness measurements of the A steel that - in accordance with expectations - the highest hardness, i.e. 53HRC approx. was noted for the steel after hardening. Slightly lower hardness - equal about 52HRC - was noted for the steel examined in as-delivered state, i.e. after hardening and low-temperature tempering. The lowest hardness - equal about 37HRC - was noted for the A steel after full annealing, i.e. austenitizing at the temperature of 880°C for 15 minutes with successive slow cooling up to the ambient temperature along with the furnace. Hardness of the steel in the state after normalizing is worth pointing out - it's equal about 50HRC. High hardness of the A steel in this state is a result of fine-grained bainitic-ferritic microstructure.

Accomplished hardness tests of the B steel revealed that the highest hardness - of approx. 51HRC - was noted for this steel in as-quenched state, while the lowest - of approx. 36HRC - after full annealing. Investigated steels in as-delivered state, i.e. after hardening and low-temperature tempering, present the hardness of about 52 and 50 HRC - for the A and B steel, respectively. Conducted measurements showed that studied steels present comparable values of hardness after the heat treatment under similar conditions, however, slightly higher hardness was noted for the A steel. It's a result of more fine-grained microstructure of this steel and higher concentration of carbon. The results of hardness measurements remain in correlation with the results of metallographic observations in light microscope.

Table 3
The results of hardness measurements of investigated steels

Material	Sample	Hardnes HRC					
		1	2	3	4	5	**Average value**
Steel A	1	36.0	37.0	37.0	37.0	37.0	**36.8**
	2	49.0	50.0	49.0	50.0	50.0	**49.6**
	3	53.0	53.0	52.0	54.0	54.0	**53.2**
	AS	52.0	52.0	52.0	51.0	52.0	**51.8**
	4	48.0	49.0	49.0	49.0	49.0	**48.8**
	5	42.0	42.0	42.0	43.0	42.0	**42.2**
Steel B	6	35.0	36.0	36.0	36.0	35.0	**35.6**
	7	43.0	45.0	45.0	45.0	46.0	**44.8**
	8	52.0	51.0	51.0	51.0	52.0	**51.4**
	AS	49.0	49.0	50.0	50.0	50.0	**49.6**
	9	50.0	47.0	48.0	49.0	49.0	**48.6**
	10	45.0	45.0	45.0	45.0	44.0	**44.8**

AS - as-delivered state

Performed research in scanning electron microscope allowed to evaluate the topography of fracture surfaces of Charpy V-notch test specimens of the A and B steel after testing them in the temperature range from -60 to +20°C and to identify chemical composition of non-metallic precipitations and inclusions of secondary phases revealed on the fracture surfaces. Observation of fracture surfaces was carried out in unrefined state, i.e. directly after the impact test. In order to avoid dispersive particles of secondary phases and non-metallic inclusions to fall out from the fracture surface, the samples were not subjected to cleaning in ethanol in ultrasonic washer, purposefully. That is why in some cases the fracture surface of specimens is partially oxidized, however - it does not influence the quality of presented Figures.

Fracture surface topography of Charpy V-notch test pieces made of the A steel after performed impact test in the investigated range of temperature is presented in Fig. 7 and 8. The observations carried out in scanning electron microscope revealed that in the whole range of testing temperature applied, the A steel samples have ductile fracture with numerous craters and voids with different dimensions. In sparse cases, some fractures with small dimensions and pulls were revealed (Fig. 8).

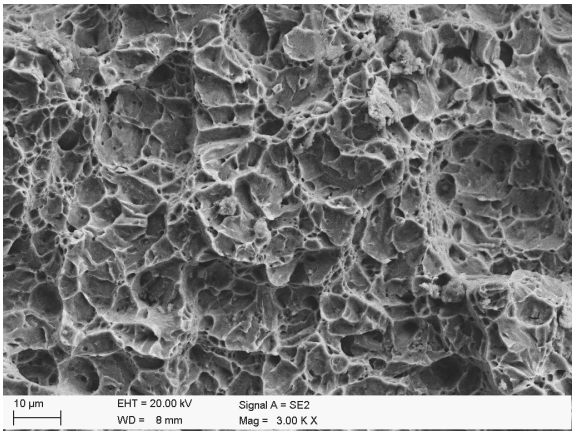


Fig. 7. Ductile fracture with numerous craters of the A steel after impact test at the temperature of -20 °C

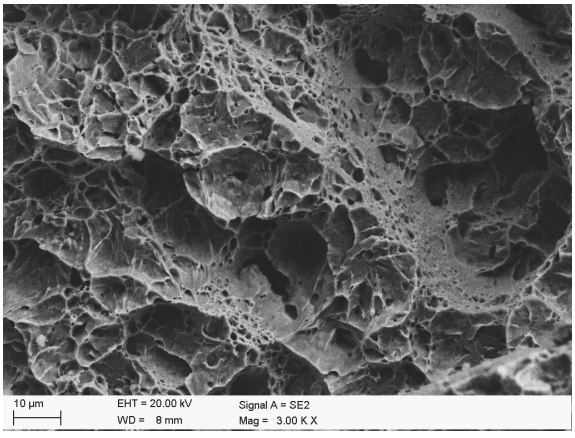


Fig. 8. Ductile fracture with numerous craters of the A steel after impact test at the temperature of -40°C

Similar topography of the fracture surface is present in case of Charpy V-notch test pieces made of the B steel after the impact test (Fig. 9-12). Performed examinations pointed out that samples of investigated steel after impact resistance test carried out in the temperature range from -60 to +20°C have attributes of ductile fracture with numerous craters and voids with different dimensions. The flat areas (Fig. 10), speaking possibly about local course of brittle cracking, were revealed only in case of the sample after the impact test carried out at the temperature of -40°C.

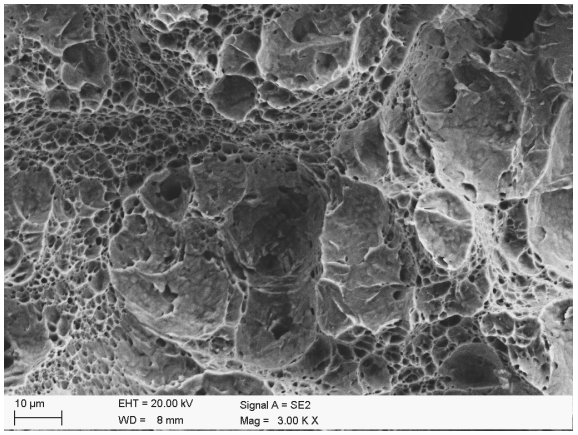


Fig. 9. Ductile fracture with locally revealed flat areas of the B steel after impact test at the temperature of -40°C

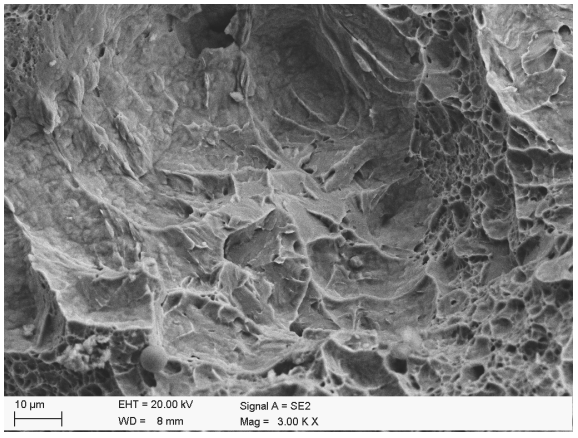
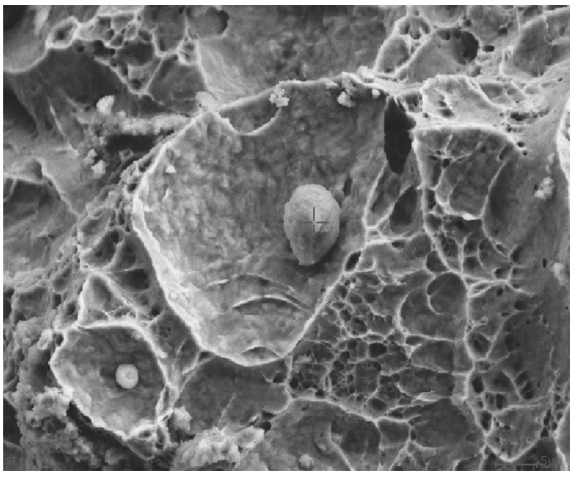


Fig. 10. Ductile fracture with locally revealed flat areas of the B steel after impact test at the temperature of -40°C

The presence of non-metallic inclusions, mainly in a form of globular (Ca, Mn)S and (Ca, Mg)S complex sulphides was revealed on the fracture surface of the A and B steel specimens (Fig. 11). Qualitative analysis of revealed non-metallic inclusions suggests that the non-metallic inclusions were modified with compounds of calcium during the ladle metallurgy process. It's confirmed in spectrograms of analyzed non-metallic inclusions, where apart from spectral lines deriving from S, O, Al, Mn, Mg and Fe there are also spectral lines coming from Ca. Taking into consideration that calcium is more active towards the oxygen than Al and also its higher chemical affinity to sulphur than it's noted for Mn, this element leads to displacement of Al from oxide inclusions and displacement of Mn from sulphuric inclusions.

Only non-metallic inclusions correctly modified with calcium compounds in a globular form, hard to deform in the rolling process were identified in the investigated steels.

a)



b)

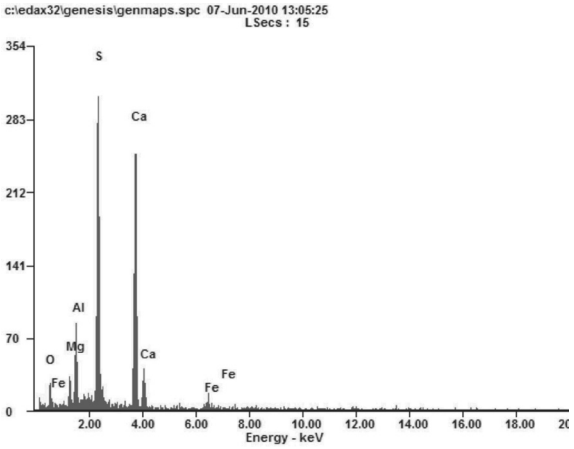


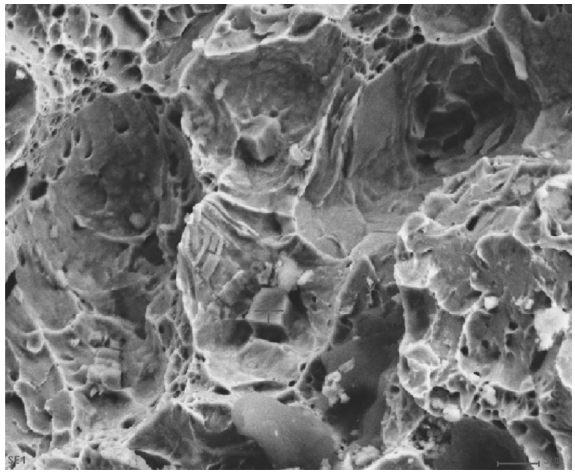
Fig. 11. (Ca, Mg)S complex sulphide with small portion of calcium aluminate on the fracture surface of the B steel specimen after impact test performed at the temperature of - 40°C: a - a view of the inclusion, b - spectrum of non-metallic inclusion

Non-metallic inclusions with such morphology will not have any impact on anisotropy of ductile properties of steel plates, usually expressed by a ratio of energy absorbed during fracture of Charpy V-notch test pieces transverse to the rolling direction and energy absorbed during fracture of Charpy V-notch samples cut according to this direction.

Moreover, the presence of MX (M - Nb, Ti, V; X - N, C) dispersive particles of interstitial phases with NaCl type cubic lattice was revealed on the fracture surface of Charpy V-notch test pieces made of the B steel. TiN titanium nitrides and Ti(C, N) titanium carbonitrides were mainly identified on the fracture surface of test pieces of this steel - (Fig. 12). Although the chemical composition of the B grade of steel supplied by the producer doesn't contain Ti, performed analysis of chemical composition of dispersive particles with the use of EDS spectrometer demonstrated unequivocally the presence of this

element in the steel. It can be noted when setting together the spectrograms of analyzed interstitial phases where apart from distinct spectral lines deriving from Ti, N and C, there are also some spectral lines coming from Fe. They derive from the steel matrix.

a)



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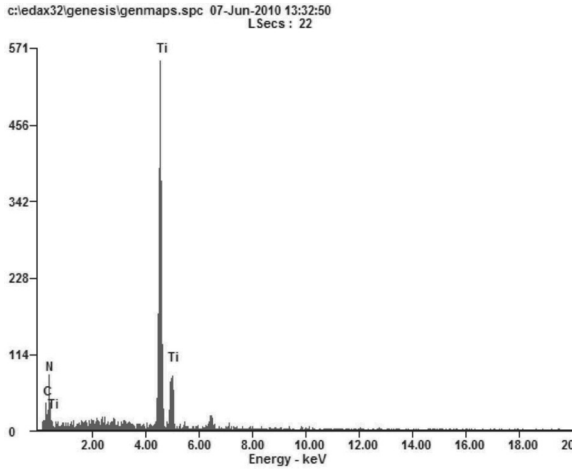

Fig. 12. Titanium carbonitride Ti(C, N) on the fracture surface of the B steel specimen after impact test performed at the temperature of -40°C: a – a view of the particle, b – spectrum of carbonitride

Revealed dispersive particles of interstitial phases formed on dislocations slow down the course of dynamic recovery and possibly also dynamic recrystallization during the plastic deformation and additionally decrease the rate of thermal recovery and static or metadynamic recrystallization and limit grain growth of recrystallized austenite in the intervals between successive rolling passes and after the end of hot-working. Dispersive particles of secondary phases limiting movements of austenite grains create the possibility to obtain metallurgical products with fine-grained microstructure giving them high strength and guaranteed crack resistance, also at low temperature.

Performed examinations of fracture surface topography of Charpy V-notch test pieces prepared of the A and B steel grades, demonstrated after the impact test that the samples are characterized with ductile fracture in the applied temperature range, i.e. from -60 to +20°C. Investigated surfaces of both steels do not reveal brittle fractures. It means that examined test pieces experienced ductile cracking, which is usually preceded by high plastic strain and occurs under influence of stress which considerably exceeds the yield stress.

Conducted examination of impact resistance of samples made of the A and B steel in as-delivered state allowed to determine crack resistance in the temperature range from -60 do +20°C. It arises from data presented in Fig. 13 that the B steel demonstrates higher crack resistance in the studied temperature range. In regards to similar microstructure, the difference between energy absorbed during fracture of Charpy V-notch test pieces at the same temperature (from 9J at the temperature equal -60°C to 18 J at the temperature of +20°C) is a result of different chemical composition of the A and B steel (Table 1). Higher values of KV energy absorbed during breakage of the B steel grade Charpy V-notch test piece in relation to the A steel grade test pieces is a result of lower concentration of carbon, 0.1% higher Mn/C ratio and lower concentration of Cr. An attempt to evaluate the ITT impact transition temperature for the A and B steel according to the values of KV energy absorbed during fracture of Charpy V-notch test pieces obtained during testing in the temperature range from -60 do +20°C has been undertaken.

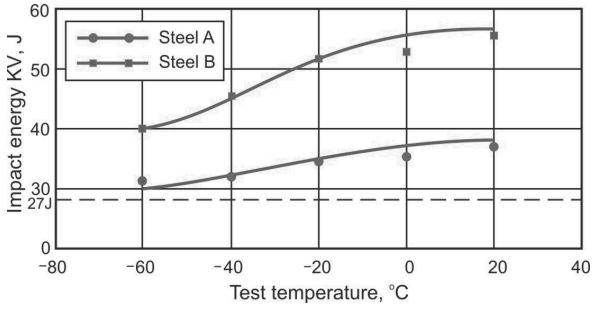

Fig. 13. The influence of testing temperature on the values of energy absorbed during fracture of the A and B Charpy V-notch test pieces

It results from data set together in Fig. 13 that the energy absorbed during breakage of Charpy V-notch test pieces at the lowest testing temperature, i.e. -60°C is equal approximately 31 and 40J - for the A and B steel grade, respectively. It indicates that the criterion for evaluation of the T_{27J} impact transition temperature, corresponding with KV absorbed energy equal 27J, has a limited application in the applied temperature range.

Conducted observations of surface fractures of the A and B steel test pieces indicated, that in the whole range of testing temperature, i.e. from -60°C to +20°C, they only have features of ductile fracture. Therefore, also application of the FATT criterion,

allowing to evaluate the ITT impact transition temperature basing on the observations of fracture surfaces is limited. Hence, the ITT impact transition temperature cannot be determined on the basis of data concerning KV energy absorbed during fracture of test pieces in the applied temperature range. It means that the nil ductility transition temperature for both A and B grade of steel is lower than -60°C. In order to determine the ITT impact transition temperature for the A and B steel, impact test at the temperature lower than -60°C must be performed. Summarizing, it can be stated that the chemical composition of investigated steels and heat treatment conditions have been selected in the optimal way, what guarantees high crack resistance also at low temperature.

4. Conclusions

Performed examinations of boron microalloyed constructional steels allowed drawing the following conclusions:

- conducted microscopic observations revealed that both steels, A and B, have fine-grained microstructure of products of supercooled austenite transformations, guaranteeing high exploitation properties,
- hardness of investigated steels in as-delivered state, i.e. after water hardening from the temperature of 880°C (910°C) and low-temperature tempering at the temperature of 180°C for 90 minutes with successive air-cooling is approximately equal 52 and 50 HRC – for the A and B steel, respectively,
- performed examinations of fracture surface topography of Charpy V-notch test pieces prepared of the A and B steel grade after the impact test demonstrated that in the applied temperature range, i.e. from -60 to +20°C, the samples are characterized with ductile fracture,
- the presence of non-metallic inclusions, mainly in a form of (Ca, Mn)S and (Ca, Mg)S globular complex sulphides was revealed on the fracture surface of both A and B steel grade specimens; non-metallic inclusions with such morphology will not influence the anisotropy of plastic properties of studied plates,
- dispersive particles of interstitial phases - mainly nitrides and titanium carbonitrides - limiting grain growth of austenite have been revealed during examinations in scanning electron microscope; it decides about the possibility to obtain metallurgical products with fine-grained microstructure giving them high strength and guaranteed crack resistance, also at low temperature.
- higher crack resistance (compared to the A steel) in the applied testing temperature range, i.e. -60 to +20°C, was noted for the B steel; the cause of such result is lower concentration of carbon and higher Mn to C ratio as well as lower concentration of Cr,
- the criteria put into use to evaluate the impact transition temperature for investigated steels (T_{27J} and FATT criteria) have limited application,
- the ITT impact transition temperature cannot be determined on the basis of data concerning changes of KV energy absorbed during fracture of Charpy V-notch test pieces in the applied temperature range; it means that the impact transition temperature of investigated steels is lower than -60°C.

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