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EFFECT OF HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 30MnB5 BORON STEEL

VPLIV TOPLOTNE OBDELAVE NA MIKROSTRUKTURO IN MEHANSKE LASTNOSTI JEKLA 30MnB5 Z BOROM

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Boron-alloyed quenched and tempered steels are widely used in hot stamping in the automotive industry. Because of their lower carbon content, they are perfectly suited for the manufacturing of steels with good wear resistance and strength. In this study, the effect of heat-treatment parameters on the microstructure and mechanical behavior of the 30MnB5 boron steel are evaluated. The specimens were quenched after three different dwell times of (5, 15 and 30) min to define the optimum dwell time and then heat treated within the temperature range from 800 °C to 900 °C at the optimum dwell time. Tensile and hardness tests were performed at room temperature. Light and scanning electron microscopies were used to follow the microstructural changes, identify the fracture surfaces of the specimens exposed to the tensile test and their relation to the mechanical properties. The results showed that the heat-treatment parameters can substantially improve the mechanical properties of 30MnB5. The dwell time of 15 min at 850 °C and quenching were determined as the optimum process parameters for the 30MnB5 steel.

Keywords: SEM, heat treatment, light microscopy, boron steels, mechanical properties

Z borom legirana kaljena in popuščana jekla se uporabljajo pri vročem stiskanju v avtomobilski industriji. Zaradi nižje vsebnosti ogljika so primerna za obdelavo jekel z višjo trdnostjo in dobro odpornostjo proti obrabi. V raziskavi je bil ocenjen vpliv parametrov toplotne obdelave na mikrostrukturo in mehanske lastnosti borovega jekla 30MnB5. Vzorci so bili kaljeni po treh časih avstenitizacije (5, 15 in 30) min za opredelitev optimalnega časa zadržanja in nato toplotno obdelani v temperaturnem področju od 800 °C do 900 °C pri optimalnem času zadrževanja. Natezni preizkusi in trdota so bili izvršeni pri sobni temperaturi. Svetlobni in vrstični elektronski mikroskop sta bila uporabljena za spremljanje mikrostrukturnih sprememb in opazovanje površine preloma na nateznih preizkušancih v povezavi z mehanskimi lastnostmi. Rezultati so pokazali, da parametri toplotne obdelave močno vplivajo na mehanske lastnosti jekla 30MnB5. Optimalni parametri za jeklo 30MnB5 so 15 min avstenitizacije pri 850 °C, ki ji sledi kaljenje.

Ključne besede: SEM, toplotna obdelava, svetlobna mikroskopija, jekla z borom, mehanske lastnosti

1 INTRODUCTION

The survey shows that an addition of a small amount of boron ($10–30 \cdot 10^{-6}$) greatly increases the hardenability of low-alloy steels.[1–3] This effect is characterized by the grain-boundary segregation of boron, which retards the nucleation of ferrite by reducing the grain-boundary energy and does not affect the growth rates.[3] Several investigations have been conducted to control the segregation and precipitation, which usually depend on the total boron amount in steel and the processing parameters such as the austenitizing temperature, cooling rate and heat-treating temperature.[4,5] Deva et al.[4] studied the effect of boron on the mechanical properties of low-carbon Al-killed steel and reported that a boron addition increased the ductility and the *n*-value. Mun et al.[5] investigated the effect of the cooling rate, austenitizing temperature and austenite deformation on the transformation behavior of high-strength boron steel. Other alloying elements, such as Mn and Cr, are known to have only a small influence on the strength after quenching.[6] The most commonly used ultra-high-strength boron steels are 22MnB5, 27MnCrB5, 30MnB5 and 37MnB4.

Nowadays, hot-stamping steel such as 30MnB5 cannot be used as widely in automotive bodies as the 22MnB5 hot-stamping steel.[7–12] However, good mechanical properties obtained after suitable heat-treatment processes make it appropriate for automotive structural parts. The 30MnB5 steel belongs to the product category of quenched and tempered steels and it features outstanding forming properties and high strength after heat treatment.[13]

Güler[7] studied the hot stamping of boron steel using a water-cooled prototype mould and the microstructure and mechanical properties of the steel were researched after hot stamping. Bardelcik et al.[8] studied the effect of the cooling rate on the high-strain-rate behavior of hardened boron steel. In another study, the strains, transformation temperatures, microstructure, and microhardness of the micro-alloyed boron and aluminum-precoated steel were examined at a temperature between 873 K and 1223 K, using a fixed strain rate of 0.08 s^{-1}.[9]

Güler et al.[10] researched the high temperature ductility behaviour of Al-Si-coated 22MnB5 steel and found that the material exhibited a ductility loss at 700 °C.

Naderi et al.[11] investigated the compression behavior of the 22MnB5 boron steel at a temperature between 600 °C and 900 °C and for the strain rates of (0.1, 1.0 and 10.0) s^{-1}. Güler and Özcan[12] studied the hot and cold forming simulations of a prototype model with Usibor 1500 steel by Dynaform FEA software and stated that the hot stamping process was safer thereby not allowing an undesirable deformation.

Bardelcik et al.[13] investigated Usibor 1500. sheet metal blanks 1.2 mm were austenized and quenched at five different cooling rates ranging from 14 °C/s to 50 °C/s and the as-quenched microstructures ranging from bainite to martensite were obtained. Güler et al.[14] studied the effect of heat-treatment parameters on the microstructure and mechanical properties of the 22MnB5 steel, as well as the temperature and cooling-rate parameters.

Junye et al.[15] investigated the 30MnB5 hot-stamping steel, quenched and tempered at 200–600 °C for 2 min. The orientation relationship (OR) with the parent phase and the misorientation evolution of martensite variants were characterized with an electron backscatter diffraction analysis (EBSD). The hot-ductility behavior of a 30MnB5 boron-steel sheet was investigated by Güler et al.[16] to better understand the ductility and plasticity during hot-deformation processing and characterize the fracture surfaces and fracture mechanisms associated with the hot-ductility process. The studies on steel 30MnB5 generally focused on wear properties and weldability.[17–19] Yazıcı[17] investigated the effects of gaseous carbonitriding processes on the wear characteristics of the 30MnB5 steel. Nalbant and Palalı[18] investigated the wearing behavior of the coating layers on the plowshares used in soil tillage. Yazıcı[19] studied the effects of the hot-stamping process and different hard-facing techniques involving the 30MnB5 steel, such as shielded metal arc welding (SMAW) and gas metal arc welding (GMAW), on the abrasive wear of ploughshares.

On the other hand, heat treatment of steels can improve toughness and hardness, and it usually consists of austenitizing and quenching, followed by multiple tempering.[20] Bílek et al.[21] studied the austenitizing and oil-quenching of the Vanadis 6 PM Cr-V ledeburitic steel. Balcar et al.[22] showed the influence of the quenching temperature on the mechanical properties and microstructure of the A 694-F60 steel. Serák et al.[23] investigated the hardness behavior of the P/M tool steel under various heat-treatment conditions with the aim of finding the maximum hardness while the heat treatment consisted of soft annealing, austenitizing, hardening and tempering.

The objective of this paper is to present the correlation between the microstructure and mechanical behavior of the 30MnB5 boron sheet metal, heat treated at different temperatures and dwell times.

Table 1: Chemical composition of the investigated 30MnB5 steel in mass fraction (*w*/%)

Tabela 1: Kemijska sestava preiskovanega jekla 30MnB5 v masnih deležih (*w*/%)

Material	C	Si	Mn	P	S	Cr	Ti	B	Ni
30MnB5	0.27	0.22	1.29	0.008	0.007	0.3	0.04	0.003	0.03

Table 2: Mechanical properties of the investigated 30MnB5 steel

Tabela 2: Mehanske lastnosti preiskovanega jekla 30MnB5

Material	Tensile strength (MPa)	Yield strength (MPa)	Young's modulus (GPa)	Vickers hardness (HV1)
30MnB5	550	363	222	183

Table 3: Heat-treatment schedule for the 30MnB5 specimens

Tabela 3: Pregled toplotnih obdelav vzorcev iz jekla 30MnB5

Specimen	Heat-treatment temperature	Dwell time
W850-5m	850 °C	5 min
W850-15m	850 °C	15 min
W850-30m	850 °C	30 min
W800-15m	800 °C	15 min
W825-15m	825 °C	15 min
W840-15m	840 °C	15 min
W860-15m	860 °C	15 min
W875-15m	875 °C	15 min
W900-15m	900 °C	15 min

2 MATERIALS AND METHODS

2.1 Materials

The hot-rolled 30MnB5 with a thickness of 2.5 mm, with the chemical composition from **Table 1** and the mechanical properties from **Table 2** was investigated. The optical microstructure of the 30MnB5 steel consisted of ferrite and pearlite phases shown in **Figure 1**.

2.2 Test procedure

The specimens were quenched from 850 °C after the dwell times of (5, 15 and 30) min. The optimum dwell time was determined to be 15 min. Then the quenching

Figure 1: Light micrograph of the investigated as-delivered 30MnB5 steel

Slika 1: Svetlobni posnetek mikrostrukture preiskovanega jekla 30MnB5 v dobavljenem stanju

Figure 2: Light micrographs of the samples quenched from 850 °C after the austenitization times of: a) 5 min, b) 15 min and c) 30 min
Slika 2: Svetlobni posnetki mikrostrukture vzorcev, kaljenih iz 850 °C, po času avstenitizacije: a) 5 min, b) 15 min in c) 30 min

temperatures of (800, 825, 860, 875 and 900) °C were tested. The heat-treatment schedules are outlined in **Table 3**. All the test specimens were placed in a box-type furnace held at a defined temperature.

The tensile and hardness tests and the microscopic analyses were performed on the heat-treated materials. The tensile tests were performed at room temperature on a UTEST universal tensile-testing machine 25 t and the average tensile strength for each heat-treatment parameter was determined as the average of five specimens. The hardness was measured using a Metkon Duroline Microvickers hardness tester with a 0.98 N (HV1) load. The average hardness was established from five measurements on the same axis in each region of interest.

The microstructures of the specimens were examined with a Nikon MA100 light microscope. These specimens were previously ground with 400, 800, 1000, 1200, 2000 SiC grinding papers, then polished using 1 μm and 0.3 μm alumina pastes and etched in a solution of 20 % Nital. The failure surface structures of the tensile-test specimens were examined with a scanning electron microscopy (SEM, CARL ZEISS EVO 40, UK).

3 RESULTS AND DISCUSSION

In the study, the heat treatment was carried out at the temperatures above the Ac_3 temperature followed by water cooling. The preliminary definition of the Ac_3 temperature for heating was deduced from the Hougardy[24] relation (1). According to this formula Ac_3 is 821 °C for 30MnB5 which is compatible with the value in[15]:

$$Ac_3\ (°C) = 902 - 255\ C - 11\ Mn + 19\ Si - 5\ Cr + 13\ Mo - 20\ Ni + 55\ V \qquad (1)$$

3.1 Effect of the heat-treatment time

The initial light microstructure of ferrite and pearlite is shown in **Figure 1** and the microstructures after the heat treatments of the 30MnB5 steel, shown in **Figure 2**, predominantly consisted of martensite. With an increase in the dwell time, martensite features became much longer and coarser (**Figures 2b** and **2c**).

The variations in the hardness and tensile strength of the specimens quenched after various austenitizing times are shown in **Figure 3**, where the specimens heated for 15 min show the best mechanical properties. The hardness and tensile strength for the specimens heat treated for 5 min were about 462 HV1 and 1078 MPa, respectively; after the heat treatment 15 min, the hardness and tensile strength increased by about 24.7 % and 60.2 %. It seems possible that the difference is due to an insufficient dwell time and, therefore, due to the inability to obtain homogeneous austenite. With a higher dwell time the hardness and tensile strength are higher at the same austenitization temperatures because the carbon homogeneity reached the equilibrium level. The specimens heat treated for 30 min exhibited a decline in the hardness and tensile-strength values, being about 506 HV1 and 1714 MPa, respectively. The effect of this dwell time is a coarser martensite (**Figure 2c**). These results indicate that the specimen heated for 15 min at 850 °C exhibits the best mechanical properties.

3.2 Effect of the heat-treatment temperature

From the references[2,5,8,14] it was concluded that quenching at various temperatures causes major microstructural changes in the initial ferrite-pearlite microstructure of the steel. In this study, the effects of the heat-treatment temperature on the mechanical properties of the 30MnB5 steel heat treated at (800, 825, 840, 850,

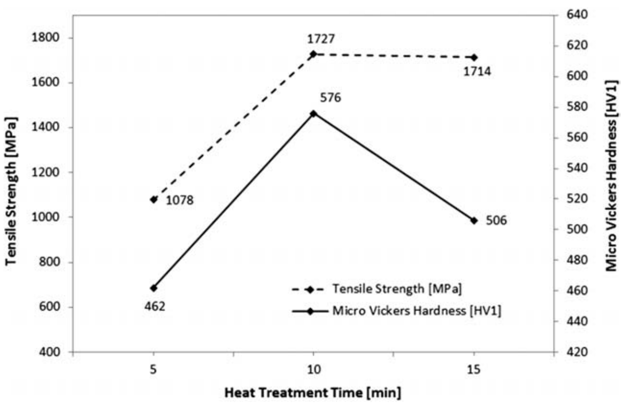

Figure 3: Hardness and tensile strength of the samples quenched from 850 °C after the austenitization times of 5 min, 15 min and 30 min
Slika 3: Trdota in natezna trdnost vzorcev, kaljenih iz 850 °C, po času avstenitizacije 5 min, 15 min in 30 min

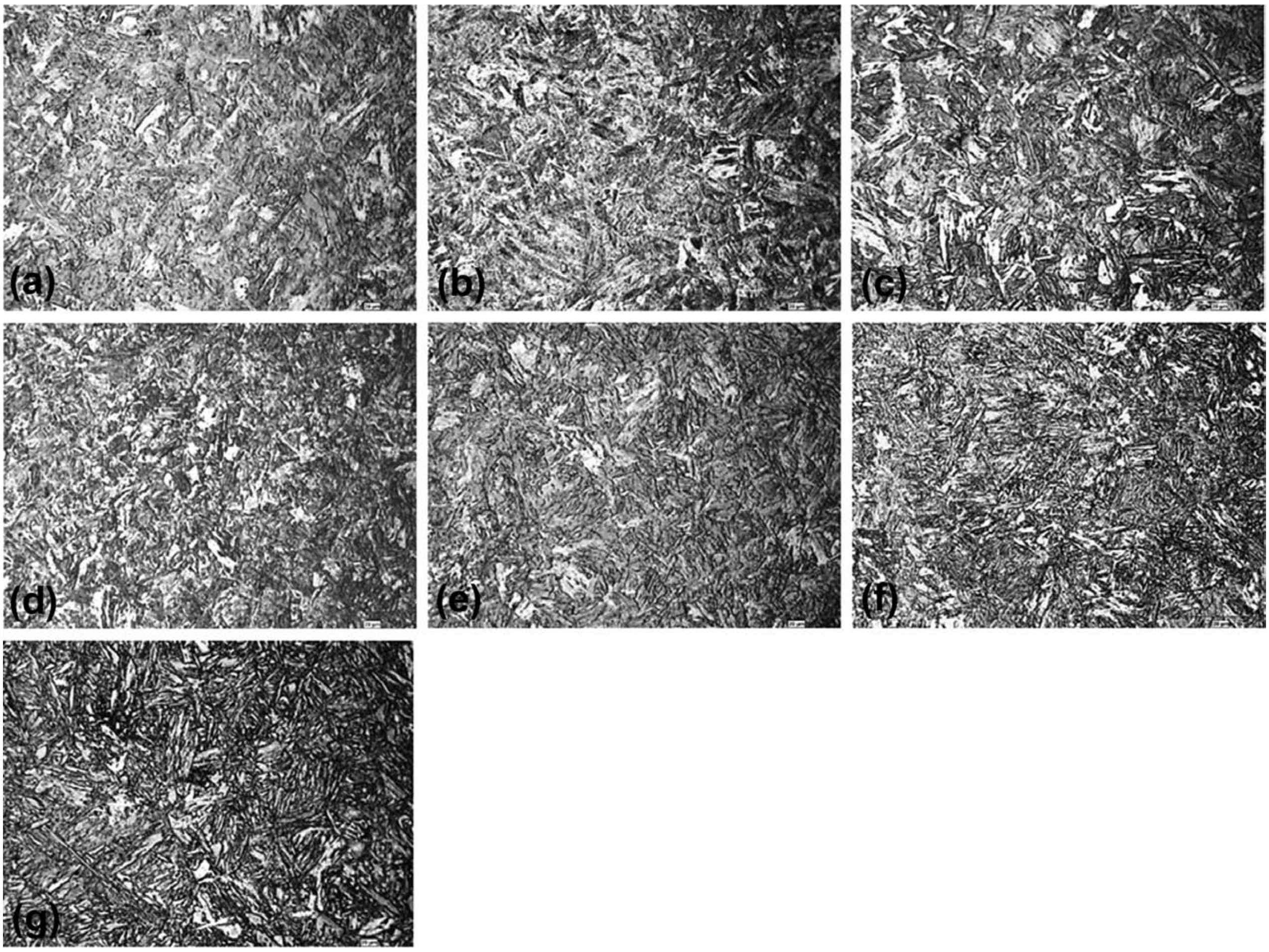

Figure 4: Light micrographs of the samples quenched from: a) 800 °C, b) 825 °C, c) 840 °C, d) 850 °C, e) 860 °C, f) 875 °C and g) 900 °C after an austenitization time of 15 min

Slika 4: Svetlobni posnetki mikrostrukture vzorcev, kaljenih iz: a) 800 °C, b) 825 °C, c) 840 °C, d) 850 °C, e) 860 °C, f) 875 °C in g) 900 °C, po 15 min avstenitizacije

860, 875 and 900) °C for 15 min are shown in **Figures 4a** to **4g**.

As seen in **Figure 4**, the microstructure mostly consists of martensite. **Figure 4a** shows that the microstructure of the steel heated at 800 °C for 15 min and then quenched consists of relatively fine martensite, bainite and ferrite. As shown with the micrographs of specimens W800 (**Figure 4a**), W825 (**Figure 4b**) and W840 (**Figure 4c**), white inserts of ferrite are embedded in the martensite matrix. The amount of ferrite decreased and the intensity of martensite increased with the increase in the quenching temperature, from 800 °C to 900 °C. The micrographs show that the increase in the quenching temperature increases the quantity of martensite and changes its morphology (**Figures 4f** and **4g**).

The lowest hardness value of approximately 567 HV1 was obtained for the specimens quenched from (800, 825 and 840) °C (**Figure 5**). It is clear from this figure that the hardness increases with the decreasing ferrite amount.

With an increase in the quenching temperature from 800 °C to 900 °C shown in **Figure 5** the strength first increases and then decreases. The amount of the ferrite in the quenching structure decreases gradually and its morphology changes as well. A higher strength was obtained by the specimen quenched when at 850 °C,

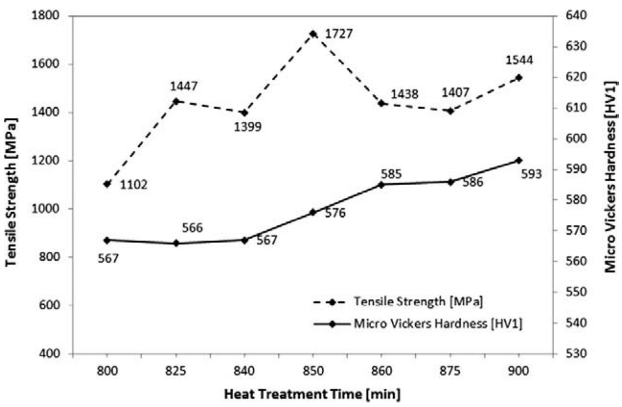

Figure 5: Hardness and tensile strength of the samples quenched from (800, 825, 840, 850, 860, 875 and 900) °C after an austenitization time of 15 min

Slika 5: Trdota in natezna trdnost vzorcev, kaljenih iz (800, 825, 840, 850, 860, 875 in 900) °C, po 15 min avstenitizacije

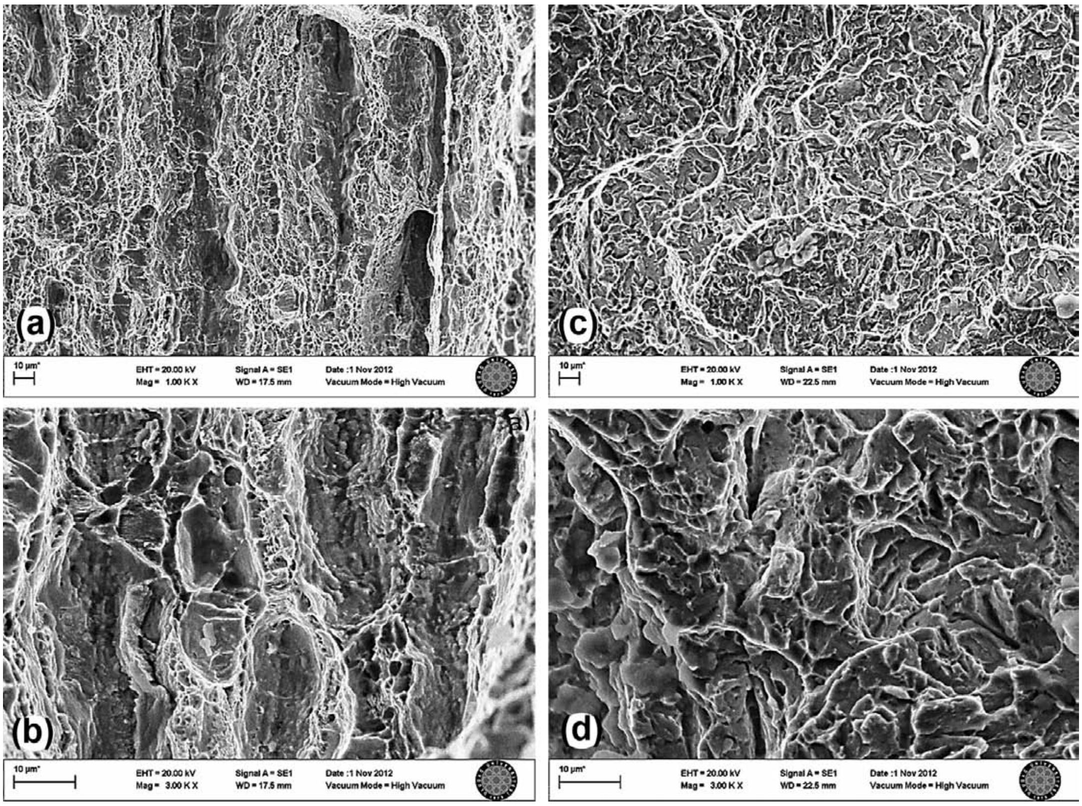

Figure 6: SEM images of the fracture surfaces of tensile tested specimens: a) low magnified untreated, b) high magnified untreated, c) low magnified heat treated at 850 °C for 15 min and then quenched and d) high magnified heat treated at 850 °C for 15 min and then quenched
Slika 6: SEM-posnetki prelomov nateznih preizkušancev: a) neobdelano, majhna povečava, b) neobdelano, velika povečava, c) kaljeno iz 850 °C po 15 min avstenitizacije, majhna povečava, d) kaljeno iz 850 °C po 15 min avstenitizacije, velika povečava

having a microstructure of martensite and bainite. The mechanical properties of this specimen were better than those of the fully martensitic specimens. In other samples (quenched from (860, 875 and 900) °C), which also had bainite-martensite microstructures, the tensile strength decreased above 850 °C. The amount of the hard phase (martensite) increased with the increasing temperature, while the hardness was decreased. As the transformation of austenite into martensite generated a considerable amount of dislocations in the microstructure, the tensile strength was decreased. The dislocations unlocked the plastic-deformation progress at the early stage of the tensile test.

The SEM images of the surfaces of the untreated specimen and the specimen quenched from 850 °C, fractured due to the tensile failure are shown in **Figure 6**. The fractured surface of the untreated specimen contains long and deep fibrous grooves, with the orientation parallel to the hot-rolling direction (**Figure 6a**). The specimen exhibited a ductile fracture behavior as evident from the fibrous fracture surface with dimple growth shown in the higher-magnification image of **Figure 6b**. For the specimen heated at 850 °C for 15 min and quenched, the fracture surface shown in **Figure 6c** has a homogenous microstructure. The fracture mechanism on the surface is a transgranular cleavage (**Figure 6d**), with small dimples on the intergranular surfaces (**Figure 6b**). The brittleness is characterized by transgranular facets.

4 CONCLUSIONS

The effects of heat treatments on the microstructure and mechanical properties of the 30MnB5 boron steel were investigated. The following conclusions can be drawn from the present study:

- The amount of martensite depends on the quenching temperature.
- The highest strength values were obtained for the samples quenched from 850 °C after a dwell time 15 min, with the highest tensile strength of 1727 MPa.
- With an increase in the heat-treatment temperature, the average size and form of the martensite structure changed. Above 850 °C, the hardness increased and the tensile strength decreased.
- The untreated 30MnB5 steel exhibited ductile fracture, while the specimen quenched from 850 °C after a dwell time 15 min exhibited brittle fracture.

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