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Effects of Plastic Deformation and Heat Treatment on Microstructure and Properties of High Boron Cast Steel

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High boron cast steel is brittle owing to the network of boride which limits its applications. In order to improve its toughness, the high boron cast steel was treated with combined processes of plastic deformation and heat treatment as will be discussed in this article. The prepared samples were analyzed using scanning electron microscope (SEM), transmission electron microscopy (TEM), and x-ray diffraction (XRD). The results show that plastic deformation breaks up boride network and uniformly distributes broken boride particles in the matrix. During subsequent heat treatment, spheroidized borides are obtained. Compared with undeformed samples after heat treatment, the hardness of the deformed samples after heat treatment increases marginally (from 51.4 to 54.7 HRC) while the toughness increases considerably (from 5 to 107 J/cm^2). Fracture surface changes from brittle morphology to dimple morphology.

Keywords boride, forging, heat treatment, high boron cast steel, plastic deformation

1. Introduction

High boron cast steel (0.4-2.0 wt.% B) is used at present as wear-resistant materials (Ref 1-3) and raw materials for nuclear power generation (Ref 4). It has a number of good service properties such as wear resistance, heat resistance, large neutron capture cross section, etc. However, there exists a continuous boride network in the solidified structure of high boron cast steel, which destroys the continuity of matrix and reduces the toughness. Thus, the application of high boron cast steel is restricted in some severe conditions such as cyclical and impact loading. In order to enlarge its application, it is necessary to increase the toughness of high boron cast steel. Alloying (Ref 5, 6), heat treatment (Ref 7, 8) and rare earth (RE) modification (Ref 9-12) are the most common methods used to improve the toughness of high boron cast steel. However, these methods have little effect on improvement of toughness. Plastic deformation (Ref 13-15) or heat treatment (Ref 16, 17) is the most effective method used to improve the toughness of white cast iron through breaking up carbide network. Boride network in high boron cast steel is similar to that in white cast iron. Therefore, plastic deformation is also used to break up boride network. Accordingly, spheroidized boride is obtained through the process of combined plastic deformation and heat treatment in this study.

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The purpose of the present research is to study the effect of plastic deformation and heat treatment on the microstructural transformations, hardness, and toughness variations; to confirm the feasibility of applying hot deformation and spheroidizing processes of high boron cast steel; and to understand the boride deformation and spheroidizing mechanism.

2. Experimental Procedure

2.1 Smelting and Casting of High Boron Cast Steel

The high boron cast steel was melted in a 10-kg medium-frequency induction furnace with SiO_2 furnace lining, with charge materials of steel scrap, ferroboron, ferrosilicon, ferromanganese, ferrochromium, and ferromolybdenum ferroalloys. The liquid metal was superheated at 1550-1560 °C and then deoxidised with 0.1 wt.% aluminium. Subsequently, the liquid metal was poured into a sand mould at 1480 °C to obtain ∅ 50 mm × 120 mm ingots. Riser and bottom of the ingots were cut. Then, the ingots were machined into ∅ 44 mm × 80 mm. The chemical composition of high boron cast steel is given in Table 1.

2.2 Forging Process and Heat Treatment Method

Before forging, the samples were first annealed at 1050 °C for 4 h to homogenize the chemical composition and improve hot plasticity in high boron cast steel. Process of forging is used repeatedly to break up boride network. Forging temperature of high boron cast steel according to Fe-B phase diagram (Ref 18) (Fig. 1) changes from 900 to 1100 °C. The forging formability was very good, and no macrocracks were observed in the samples using such a forging process (Table 2).

According to Fe-B diagram (Fig. 1), heat treatment temperature is above the transformation temperature (910 °C) and below the eutectic temperature (1149 °C). Considering the free

Table 1 **Chemical composition of high boron cast steel (wt.%)**

C	B	Si	Mn	Cr	Mo	P	S
0.35-0.40	0.38-0.42	0.50-0.60	0.70-0.80	1.80-2.0	0.45-0.50	≤0.02	≤0.02

Table 2 **Forging process**

Holding temperature, °C	Holding time, min	Initial forging temperature, °C	Final forging temperature, °C	Forging ratio Y	Cooling method
1050	40	1050	900	4 and 8	Air cooling

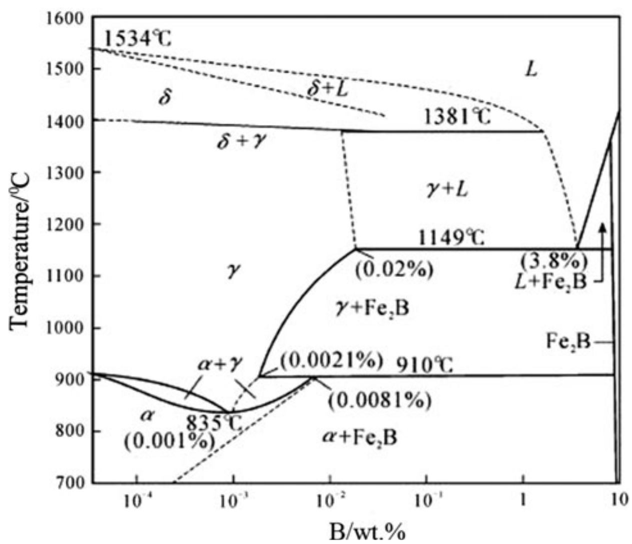

Fig. 1 Fe-B phase diagram

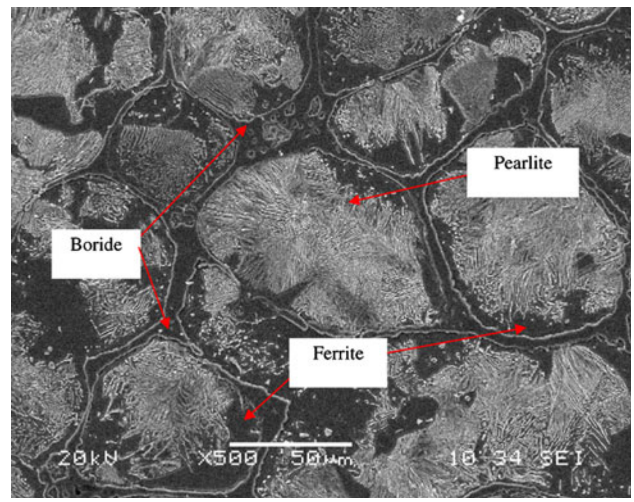

Fig. 2 Solidification structures of high boron cast steel after annealing

energy of boride, high temperature is helpful for its spheroidization. However, high temperature will lead to grain growth, decarbonization and deboronization. Therefore, 1050 °C is appropriate heat treatment temperature. All the samples were heated at 1050 °C for 1.5 h, followed by quenching in water. Subsequently, the samples were tempered at 200 °C for 4 h.

2.3 Microstructure Examination

The microstructures of all samples were analyzed using optical microscope (OM), x-ray diffraction (XRD), scanning electron microscope (SEM), and transmission electron microscopy (TEM). The fracture morphology of the samples after impact tests was observed using scanning electron microscope (SEM). All the samples were etched in 4% natal solution, and viewed under an optical microscope model Neophot 21. The scanning electron microscope used was a JEOL JSM-6360LV. The samples were examined in a JEOL JEM 200 CX TEM at an operating voltage of 200 kV. XRD was carried on a D/MAX-2400 diffractometer with Cu Kα radiation at 40 kV and 100 mA as an x-ray source. The specimens were scanned in the 2θ range of 20-85° in a step-scan mode (0.02° per step).

2.4 Mechanical Properties' Tests

Impact tests were done using a JB-300B Charpy impact testing device at room temperature. Charpy impact specimens with no notch were machined and their sizes were 10 mm × 10 mm × 55 mm. The average value of impact toughness was also obtained from three tests. The hardness was measured on an HRS-150 Rockwell-hardness tester. The average hardness value was also obtained from five measurements.

3. Results

3.1 Solidification Microstructure of High Boron Cast Steel

Figure 2 shows that the solidification microstructure of high boron cast steel after annealing consists of eutectic structure and metallic matrix. According to XRD analysis, the boride of eutectic structure is identified as Fe_2B (Fig. 3). The metallic matrix is composed of ferrite and pearlite. Moreover, netlike distribution of Fe_2B has been observed as shown in Fig. 2.

3.2 Microstructures of High Boron Cast Steel After Forging

Figure 4 shows the microstructures of high boron cast steel after forging from 1050 °C, followed by an air cooling. Plastic deformation breaks up the boride network and the metallic matrix becomes continuous phase (Fig. 4). Netlike boride becomes strips after forging. At the same time, secondary precipitates can be found in Fig. 4(b) and (d). According to the XRD result (Fig. 5), the secondary precipitates is $Fe_{23}(B,C)_6$. Under the increasing deformation, broken boride particles are uniformly distributed in the metallic matrix (compare Fig. 4a and c).

3.3 Microstructures of High Boron Cast Steel After Heat Treatment

Figures 6 and 7 show the undeformed and deformed microstructures of high boron cast steel after water quenching from 1050 °C, followed by tempering at 200 °C for 4 h. In each case, the metallic matrix transforms into tempered martensite. The boride network in undeformed high boron cast steel cannot be changed by heat treatment, which indicates its high thermal stability at high temperature (Fig. 6). Nevertheless, the strips and bulks boride in the deformed high boron cast steel becomes spheroidized boride particles after heat treatment (Fig. 7). This is because the boride network is broken up during

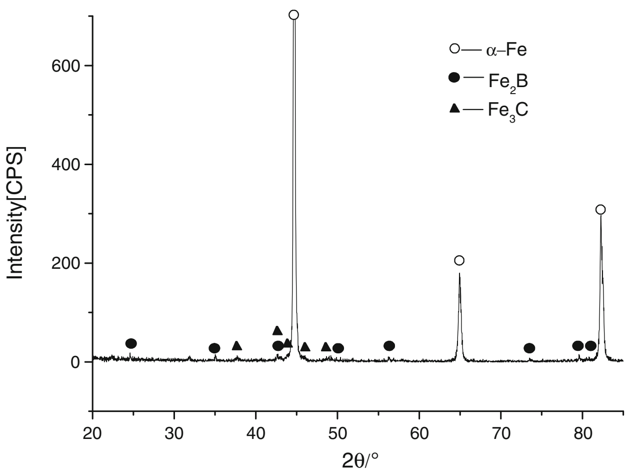

Fig. 3 X-ray diffraction pattern of high boron cast steel

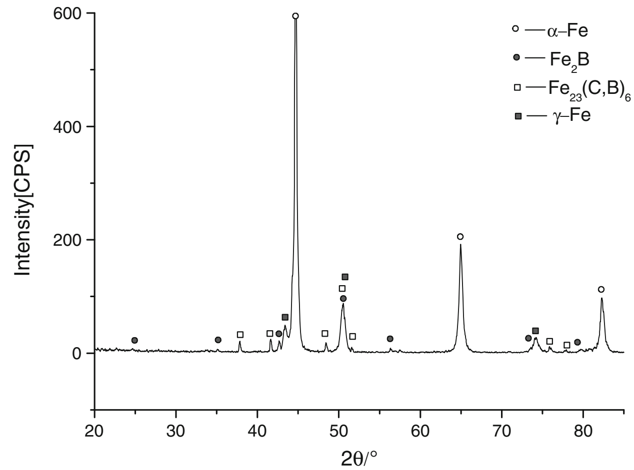

Fig. 5 X-ray diffraction pattern of high boron cast steel after forging

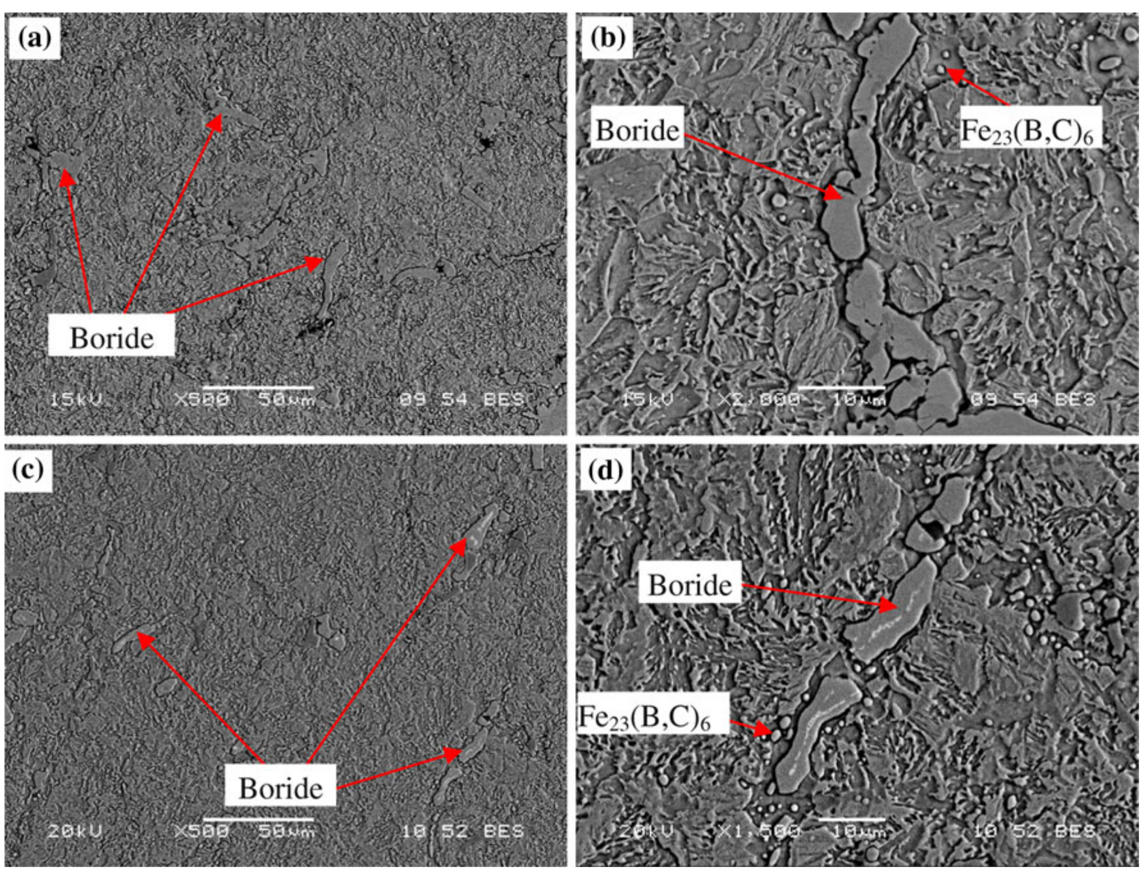

Fig. 4 Structure of deformed high boron cast steel: (a) low magnification of forging reduction ratio 4, (b) high magnification of forging reduction ratio 4, (c) low magnification of forging reduction ratio 8 and (d) high magnification of forging reduction ratio 8

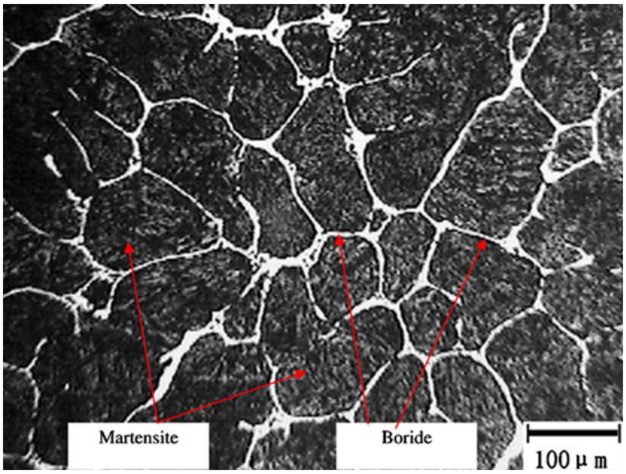

Fig. 6 Optical metallograph of undeformed sample after heat treatment

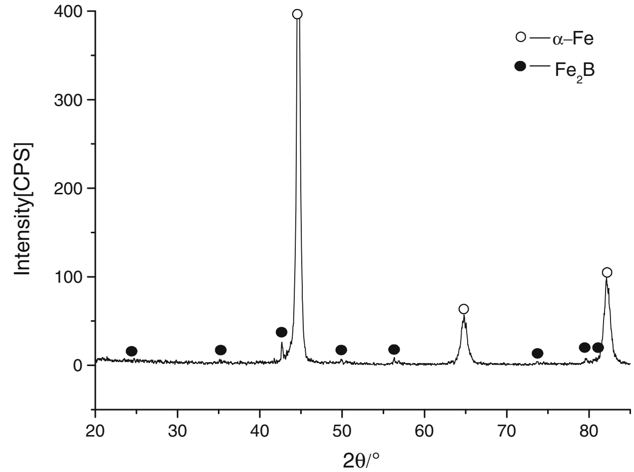

Fig. 8 X-ray diffraction pattern of high boron cast steel after heat treatment

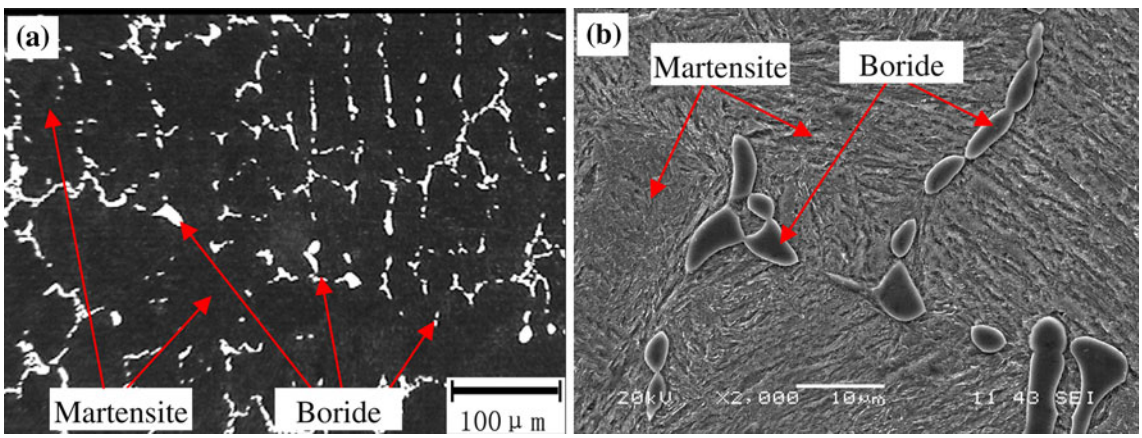

Fig. 7 Microstructure of deformed sample after heat treatment: (a) optical metallograph and (b) SEM image

plastic deformation, which is beneficial for boride to be developed into spheroidized morphology and become less continuous. Meanwhile, the secondary precipitates cannot be observed in Fig. 7. XRD analysis proved that it does not exist after heat treatment (Fig. 8).

3.4 Effects of Plastic Deformation and Heat Treatment on Mechanical Properties

The mechanical properties of high boron cast steel are listed in Table 3. Compared with undeformed samples after heat treatment, the hardness of deformed samples after heat treatment increases marginally (from 51.4 to 54.7 HRC) while the toughness increases considerably (from 5 to 107 J/cm^2).

4. Discussion

4.1 Mechanism of Hot Deformation in High Boron Cast Steel

In order to improve the plasticity during the hot deformation, the austenization of high boron cast steel was carried out at elevated temperature of 1050 °C. During the austenitizing, metallic matrix transforms to austenite while eutectic boride

Table 3 Mechanical properties of high boron cast steel after heat treatment (*Y* represents forging reduction ratio)

	Y = 0	*Y* = 4	*Y* = 8
Hardness, HRC	51.4	52.6	54.7
Impact toughness, J/cm^2	5	65	107

remains network. However, network of borides is partially broken, and then some borides are also marginally deformed under a flow stress generated by austenite at high temperature. With a forging reduction ratio 4, the structure differs from the cast condition; with a forging reduction ratio 8, the broken boride particles are uniformly distributed in the matrix with flow of austenite. At the same time, plastic deformation leads to dislocation density increasing in the matrix near the boride particles (Fig. 9a). As the temperature decreases, secondary precipitates are nucleated on dislocations (Fig. 9b). A more detailed study is done with the deformation of boride. In the process of hot plastic deformation, the dislocation density evidently increases in boride (Fig. 10a, b). Slipped dislocation (Fig. 10a) leads to deformation of boride. With the increasing deformation, slip results in dislocation pile-up in boride, which

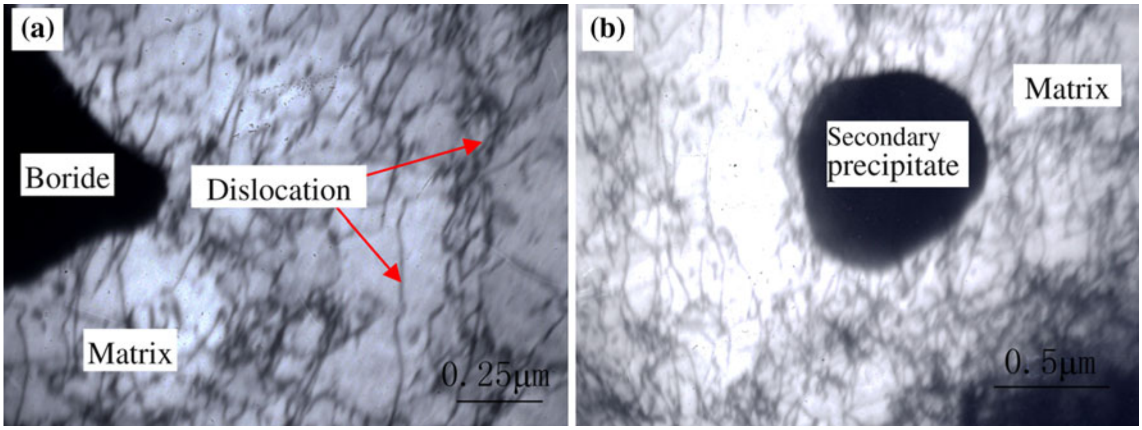

Fig. 9 Microstructure TEM micrographs after deformation: (a) dislocation density increasing in the matrix near the boride particles and (b) secondary precipitates of high boron cast steel

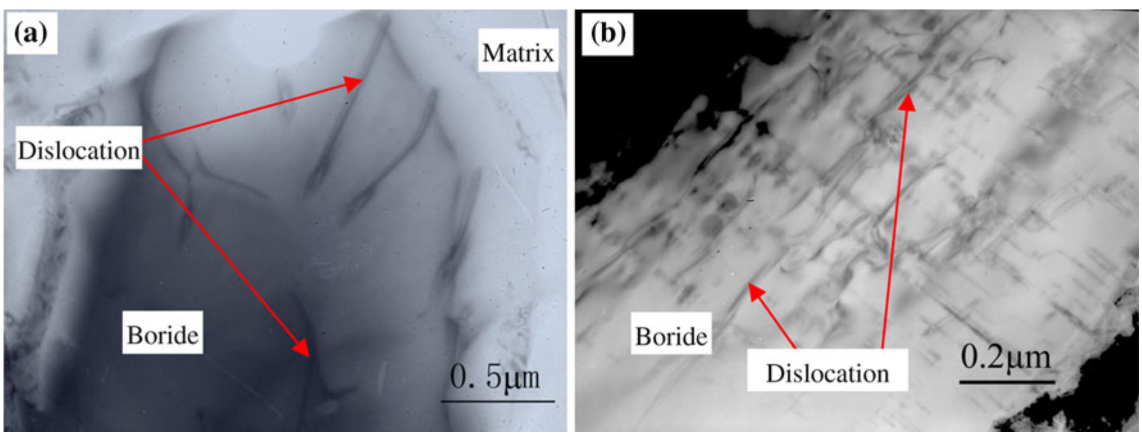

Fig. 10 Microstructure TEM micrographs after deformation: (a) dislocation in boride and (b) dislocation pile-up in boride

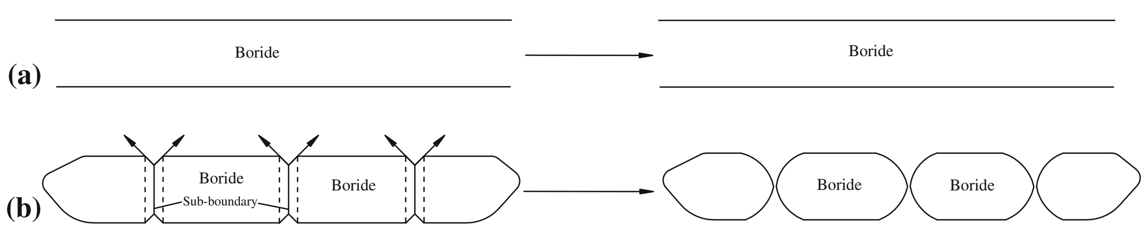

Fig. 11 Schematic representation of morphological changes during heat treatment: (a) undeformed borides and (b) deformed borides

leads to stress concentration (Fig. 10b). When stress concentration reaches a critical value, a lot of microcracks in boride occur. These microcracks result in breakup of boride. The presence of dislocation pile-up in boride during plastic deformation proves that boride in high boron cast steel has the capability of plastic deformation at high temperature.

4.2 Effect of Heat Treatment on Spheroidization of Boride

Carbide spheroidization of white cast iron has been previously studied in the literature (Ref 16, 19). It was observed that the dissolution of carbides developed everywhere at the carbide/matrix interfaces. Consequently, the carbide phases become smaller and thinner as the dissolution continued in situ observations of the dissolution process. However, spheroidized boride of high boron cast steel cannot be obtained by heat treatment. Diffusion of boron in high boron cast steel is difficult because boron solubility is very low in metal and alloys (Ref 18). As a result, boride in high boron cast steel appears to be so stable at high temperature. Schematic representation of morphological changes of undeformed borides during heat treatment is shown in Fig. 11(a).

Plastic deformation promotes appearance of sub-boundary in the boride of high boron cast steel (Fig. 12). During heat treatment, the boride in deformed high boron cast steel changes from strips morphology to spheroidized morphology. The thermodynamical driving force comes from the decrease of free energy between eutectic boride and matrix interface. The kinetic driving force is the diffusion of the boron atom on the boride/matrix interface. The boron concentration at the boride/matrix interface varies with the curvature radius of the interface, which is quantitatively described by the Gibbs-Thomson equation (Ref 20), as shown in the equation

$$\ln\frac{C_{\mathrm{r}}}{C_{\infty}} = \frac{2\gamma V_{\mathrm{m}}}{RTr} \quad \text{(Eq 1)}$$

where γ is the surface energy, V_{m} is the molar volume of boride, R is the gas constant, T is temperature, C_{∞} is the boron concentration of flat area, and C_{r} is the boron concentration of curvature radius r.

According to the Eq 1 mentioned above, the diffusion of boron at the sub-boundary is easier and faster than that of at plane joint mainly owing to the larger curvature radius of boride at sub-boundary. Meanwhile, boron atoms between sub-boundary and austenite/boride interfaces have higher diffusion activation energy. Moreover, the diffusion of boron atoms along these unstable sub-boundary results in part of the eutectic boride dissolving in the matrix and then precipitating on boride itself. Therefore, the spheroidized boride forms during high temperature heat treatment. Schematic representation of morphological changes of deformed borides during heat treatment is shown in Fig. 11(b).

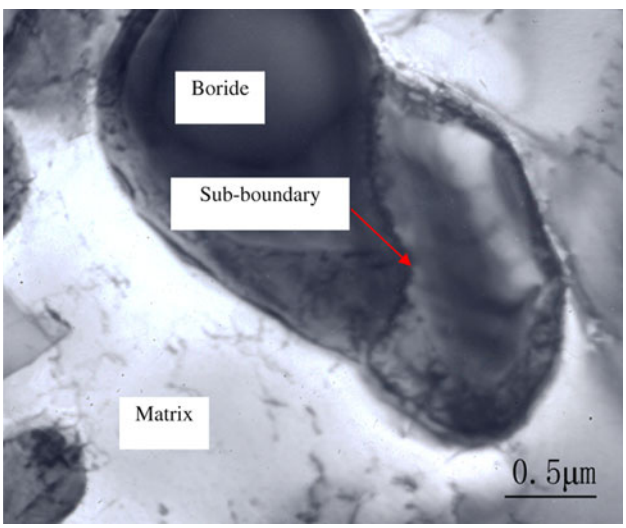

Fig. 12 Microstructure TEM micrographs after deformed: sub-boundary of boride in deformed sample

4.3 Improvement of Toughness in High Boron Cast Steel

Figure 13(a) and (b) show the impact fracture morphology of undeformed and deformed samples of high boron cast steel after heat treatment. Mechanism of brittle fracture is crack initiation and propagation (Ref 21). In the study of white cast iron, Frost (Ref 22) discovered that fracture initiated at porosity, inclusions, or carbides and propagated more easily through massive carbide/matrix interface than through martensitic matrix. The eutectic boride network in high boron cast steel is like that in white cast iron. The combined strength between the boride/matrix interfaces is relatively weak, which leads to crack that can easily initiate at the boride/matrix interfaces under the action of impact loading. The crack propagation along the grains will cause the cleavage fracture to appear. When the crack encounters the boride network, it surrounds the crystal grain and propagates along the boride network. The spreading rate of crack increases. Therefore, the toughness of high boron cast steel is relatively low. The fracture morphology of high boron cast steel after heat treatment is observed in Fig. 13(a).

By contrast, as shown in the previous studies, high boron cast steel made by the process of combined plastic deformation and heat treatment has more spheroidized and better distributed eutectic boride particles. The matrix of high boron cast steel becomes continuous phase after forging. Moreover, forging eliminates casting defects such as shrinkage cavity, porosity and crack. Therefore, the brittleness of the grain boundaries has decreased. So the cracks hardly propagate along the boundaries. The fracture surface exhibits dimple morphology, as shown in Fig. 13(b). Thus, the toughness of high boron cast steel by process of combined plastic deformation and heat treatment improves.

5. Conclusions

(1) Solidification microstructure of high boron cast steel consists of eutectic boride and metallic matrix. The eu-

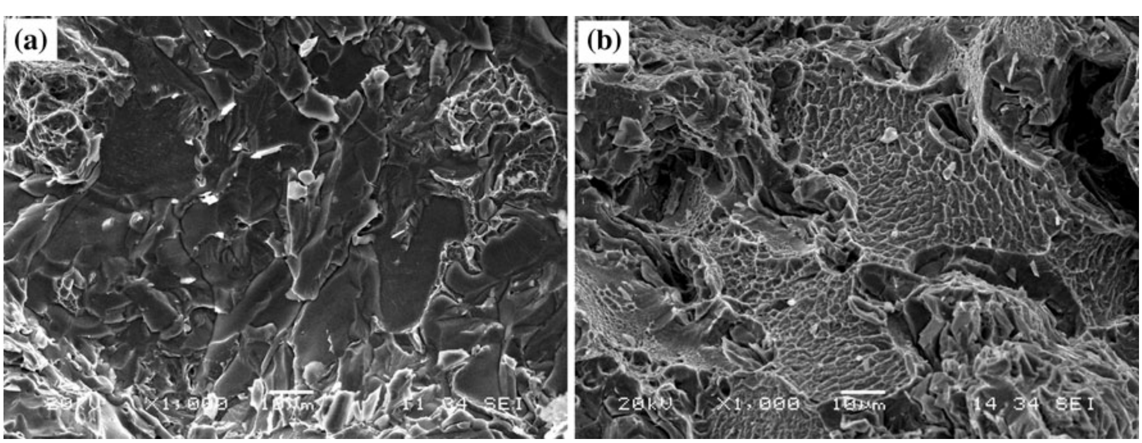

Fig. 13 Impact fracture surface of high boron cast steel after heat treatment: (a) undeformed sample and (b) deformed sample

tectic boride is Fe_2B and metallic matrix is composed of ferrite and pearlite.

(2) Plastic deformation breaks up boride network and promotes appearance of sub-boundary in the boride of high boron cast steel. Appearance of dislocation slip and dislocation pile-up in boride during plastic deformation proves that boride in high boron cast steel has the capability of plastic deformation at high temperature.

(3) After heat treatment, the matrix transforms to tempered martensite and the morphology of boride in the deformed high boron cast steel changes into a spheroidized structure.

(4) Compared with the undeformed samples after heat treatment, the hardness of the deformed samples after heat treatment increases marginally (from 51.4 to 54.7 HRC) while the toughness increases considerably (from 5 to 107 J/cm^2).

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