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Microstructure and Mechanical Properties of a Low Alloyed MnB Cast Steel

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The microstructure and mechanical properties of a low alloyed MnB cast steel designed for coupler castings of trucks were studied. The results show that the microstructure of the MnB cast steel after water quenching is lath martensite and a small amount of massive islands in the matrix of lath martensite. The average size of the martensite packets is about 10 μm in length. Carbides precipitated dispersively at the tempering temperature of 450 °C. The carbides are slender and fibrous, of which the microstructure was θ-phase (Fe, Mn)$_3$C characterized by TEM. The MnB cast steel has good hardenability and tempering stability. Excellent combination of strength, ductility and low-temperature toughness were obtained after water-quenching and 450 °C tempering: *Rm* = 960-1040 MPa, *ReL* = 880-900 MPa, *A* = 19-21%, *Z* = 56-58%. Especially, the impact energy of the Charpy V-Notch (CVN) specimens reached 70-88 J at −40 °C. The fracture mechanism is transcrystalline fracture both for ambient temperature uniaxial tensile test specimens and for CVN impact test specimens broken at −40 °C, where the whole surfaces were manifested as voids and dimples.

Keywords hardenability, lath martensite, low alloyed MnB cast steel, strength and low-temperature toughness

1. Introduction

Cast steels are widely used in civilian industry such as lining board, toothed plate, hammer and other complex shape structural parts which require high strength and high toughness. Especially, low-temperature toughness is required when they are employed as a structure subjected to heavy load at low temperature. Demands for producing higher strength steel castings with good toughness and repair weldability have encouraged some researchers to focus on the microalloyed or low alloyed cast steels (Ref 1-4). Low alloyed cast steels are basically low to medium carbon steels with manganese level in the range of 0.6-1.5 wt.%, and additions of conventional alloying elements such as nickel, chromium, molybdenum, titanium, niobium and vanadium. Most of these low alloyed steels, with good combination of strength and toughness by tempering the quenched martensite at high temperature, have found many applications in manufacturing industrial parts (Ref 5, 6). With the shortage of natural resources and the demand for sustainable development, researching and production of high strength and high toughness cast steels without expensive elements such as nickel, chromium and molybdenum are required. But the elimination of nickel, chromium and molybdenum limits the hardenability of the cast steels, because of the difficulty to obtain martensite when the castings are large in diameter. In the case of steel castings, there is no process of deformation (such as forging, rolling, etc.). The mechanical properties of steel castings depend mainly on the alloying scheme and heat treatment. So, appropriate alloying scheme and heat treatment are of importance to obtain good hardenability and combination of strength and toughness.

In the present work, a low alloyed MnB cast steel free from alloying agents of nickel, chromium and molybdenum was designed for producing coupler castings of trucks subjected to heavy load at low temperature. In order to ensure repair weldability and strength, the content of carbon in the low alloyed MnB cast steel was lower than 0.30 wt.%. Manganese, the main alloying agent in the low alloyed MnB cast steel, was used to retard the pearlitic transformation and stabilize austenite during cooling, thus allowing a lower critical cooling rate to obtain good hardenability (Ref 7-10). Also, manganese solution strengthened the matrix in the microstructure. A proper amount of silicon was used for solid-solution hardening. Boron was used to improve the hardenability. Aluminum, titanium, and rare earth (Ce) were used to purify and refine the cast steel. The microstructure and mechanical properties of the low alloyed MnB cast steel by water quenching and tempering were characterized and the fracture mechanism of both uniaxial tensile test specimens at ambient temperature and Charpy V-Notch (CVN) impact test specimens at low temperature were investigated.

2. Experimental Procedure

In this study, the low alloyed cast steel was manufactured by vacuum induction melting and cast into standard keel blocks (shown in Fig. 1). Aluminum, titanium, and rare earth (Ce)

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were used to purify and refine the cast steel. The chemical composition of the tested steel is 0.28-0.30% C, 2.0-3.0% Mn and a little B. The heat treatment of the keel block samples was simple normalizing, water quenching and tempering. Before water-quenching, the keel block samples were normalized (900 °C for 40 min, air-cooled). In the quench-tempering treatment, the keel block samples were first heated to 650 °C holding for 50 min, then austenitized at 900 °C for 40 min followed by water cooling, and then tempered at different temperature.

The microstructure was characterized by scanning electronic microscopy (SEM) and transmission electronic microscopy (TEM). Ambient temperature uniaxial tensile properties were determined using 60 mm gage length cylindrical tensile bars in accordance with ISO 6892:1998 standards. The hardenability of the cast steel was tested in accordance with ISO 642:1999 standards, where the austenization temperature was 900 °C. Impact energy was determined using standard sized CVN specimens, in accordance with ISO 148:1983 standards, broken in a pendulum-type impact machine of hammer velocity 3.3 m/s, where the specimens were cooled to −40 °C. The fracture surfaces of tensile test specimens and CVN impact test specimens were analyzed by SEM to determine the fracture mechanism.

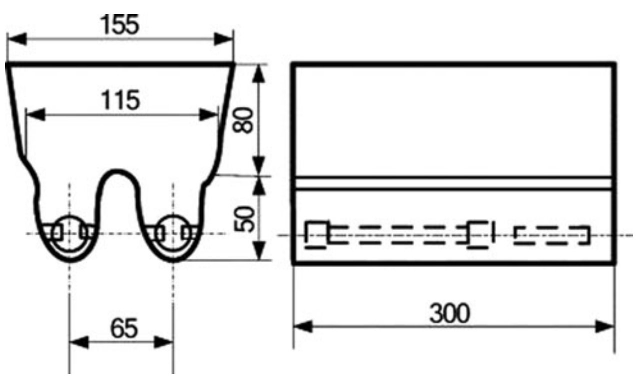

Fig. 1 Shape and dimension of Keel block

3. Results and Discussion

Microstructure of the MnB cast steel after 900 °C water quenching and 250 °C tempering is shown in Fig. 2. The characteristic microstructure is lath martensite and a small amount of massive islands in the matrix of lath martensite. The characteristic dimension of the microstructure is the equivalent diameter of the packet of martensite lath, which is approximately 10 μm in length. Very fine and dispersively distributed carbides precipitated from the matrix of lath martensite after 250 °C tempering. The microstructure of the water-quenched and 450 °C tempered sample is shown in Fig. 3. More dispersively distributed carbides precipitated from the lath martensite and the massive islands after 450 °C tempering. The TEM results show that the microstructure of the carbides was θ-phase (Fe, Mn)$_3$C (cementite), which is the stable phase of carbides in the MnB cast steel, as shown in Fig. 4.

The MnB cast steel has excellent hardenability which is superior to the commercial 30MnCrNiMo cast steel (with the composition of 0.27-0.33 C, 0.20-0.40 Si, 0.60-1.50 Mn, 0.35-0.65 Cr, 0.35-0.75 Ni, 0.15-0.25 Mo, wt.%). The Jominy curve of the investigated cast steel compared to that of 30CrNiMo steel is shown in Fig. 5. It can be observed that the hardness, 23 mm from the quenched end, can be maintained above 46 (HRC) for the MnB cast steel while the hardness of the 30MnCrNiMo cast steel decreased significantly with an increase in the distance from the quenched end.

The variation of hardness of the tempered samples is shown in Fig. 6. The hardness decreases slowly with an increase in the tempering temperature below 450 °C. When tempered at 450 °C for 1 h, the hardness of samples can be maintained at 36 (HRC). The hardness falls quickly after tempering above

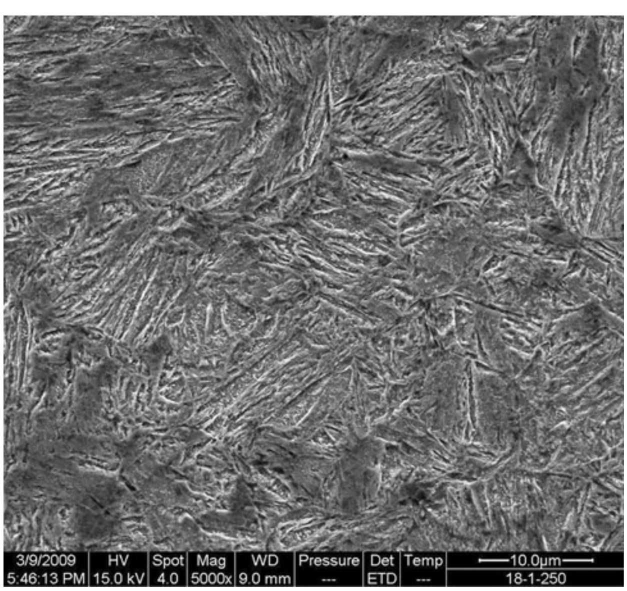

Fig. 2 SEM microstructure of the MnB cast steel (etchant 4% nital), water-quenched and 250 °C tempered

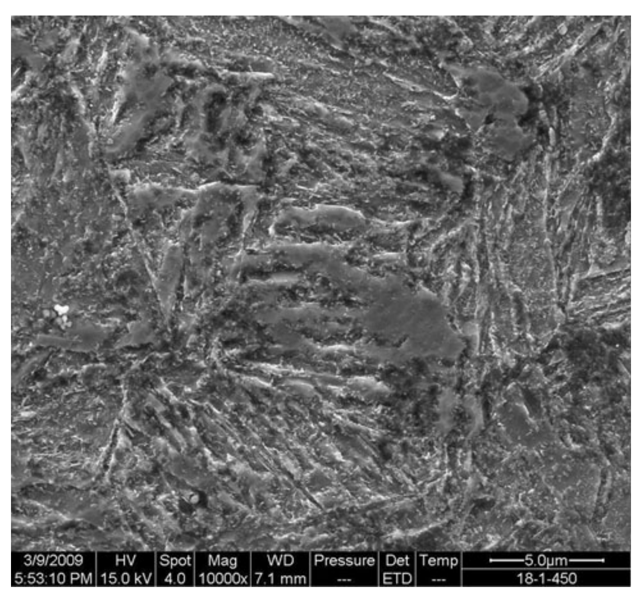

Fig. 3 SEM microstructure of the MnB cast steel (etchant 4% nital), water-quenched and 450 °C tempered

450 °C. So the MnB cast steel has a good tempering stability in the temperature range below 450 °C.

The results obtained from tensile and CVN tests are reported in Table 1. It can be seen that the MnB cast steel can obtain better combination of strength and low-temperature impact toughness than the commercial 30MnCrNiMo cast steel does. The MnB cast steel samples by 900 °C water quenching and 450 °C tempering have high yield strength above 880 MPa with good ductility (A = 19-21%, Z = 56-58%). The tensile engineering stress-engineering strain curves of MnB cast steel are shown in Fig. 7. The 900 °C water-quenched and 450 tempered samples of MnB cast steel exhibit an observable yield point phenomenon like that of the annealed samples. Especially, the impact energy can reach 80-90 J at 0 °C and 70-88 J at −40 °C, which is of importance for the steel castings for low-temperature service. By contrast, the commercial 30MnCrNiMo cast steel by 920 °C water quenching and 600 °C tempering has yield strength 660-680 MPa with impact energy 54-55 J at −40 °C.

The SEM micrographs of tensile fracture surface of the water-quenched and 450 °C tempered MnB cast steel samples are shown in Fig. 8. Examination of fracture surface revealed that the fracture surface was covered with a population of voids and deep dimples of wide range of sizes. The macro-fractographic appearances of fracture surface of CVN impact

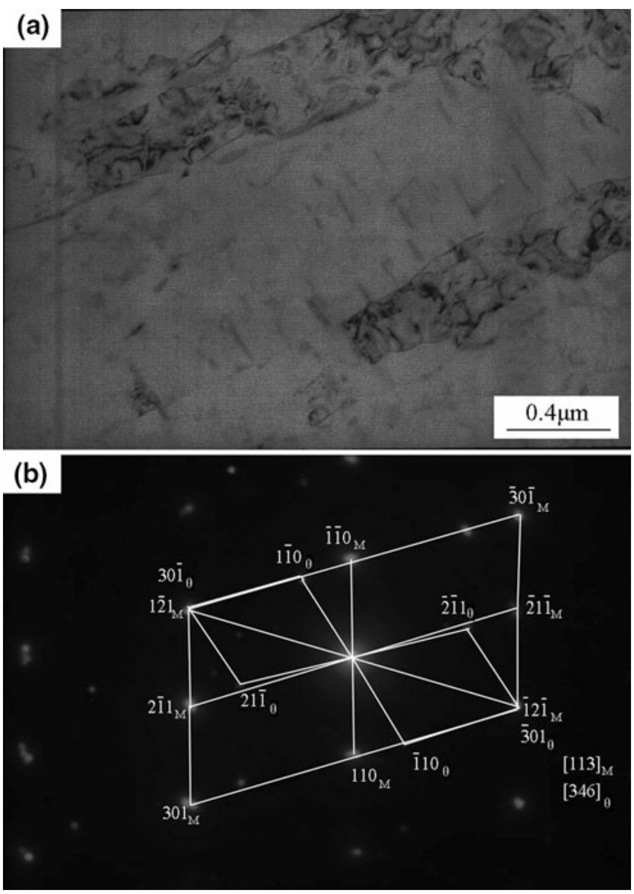

Fig. 4 TEM micrographs, water-quenched and 450 °C tempered: (a) bright field image and (b) reflection spots

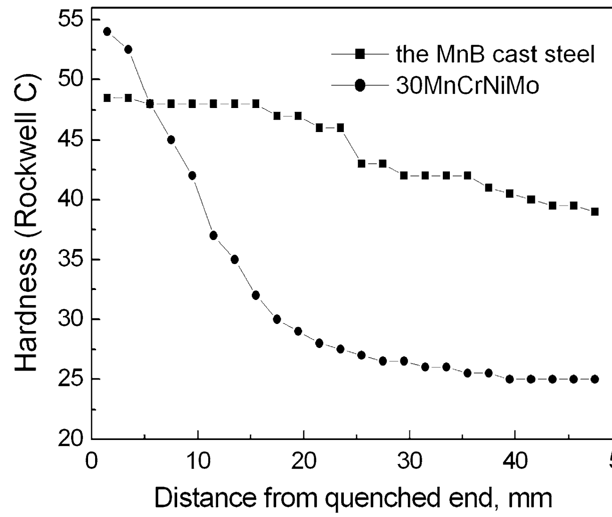

Fig. 5 Jominy curve of the investigated cast steel compared to that of 30CrNiMo steel

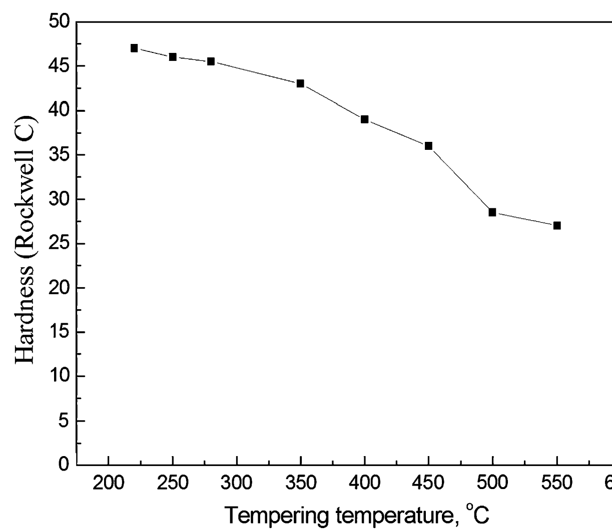

Fig. 6 Hardness of tested samples tempered at different temperatures

Table 1 Comparison of mechanical properties of MnB cast steel and 30MnCrNiMo cast steel

	***ReL*, MPa**	***Rm*, MPa**	***A*, %**	***Z*, %**	**A_{KV} (−40 °C), J**	**Heat treatment**
30MnCrNiMo cast steel	660-680	770-790	23-26	51-58	54-55	920 °C WQ and 600 °C T
MnB cast steel	880-900	960-1040	19-21	56-58	70-88	900 °C WQ and 450 °C T

WQ, water-quenched; T, tempered

test specimen, broken at −40 °C, are shown in Fig. 9. Fracture surface was essentially rough at the macroscopic level with large region of shear lip, shown in the position D. The SEM micrographs are shown in Fig. 10, which were taken from the corresponding positions in Fig. 9. The fracture surface was also covered with a population of voids and dimples.

4. Summary and Conclusion

The microstructure and mechanical properties of a low alloyed MnB cast steel designed for producing coupler of trucks subjected to heavy load at low temperature were studied. The following results can be concluded:

- The microstructure of MnB cast steel after water quenching was lath martensite and a small amount of massive islands in the matrix of lath martensite. The average size of martensite packets is about 10 μm in length. Carbides precipitated dispersively from the quenched matrix after tempering. The precipitated carbides at 450 °C were slender and fibrous and the TEM results showed that the microstructure of the carbides was θ-phase (Fe, Mn)$_3$C (cementite).
- The MnB cast steel had good hardenability and tempering stability below 450 °C.
- The fracture mechanism of water-quenched and 450 °C tempered samples was transcrystalline fracture both for ambient temperature uniaxial tensile test specimen and CVN impact test specimen at −40 °C. The whole surface was manifested as voids and dimples.

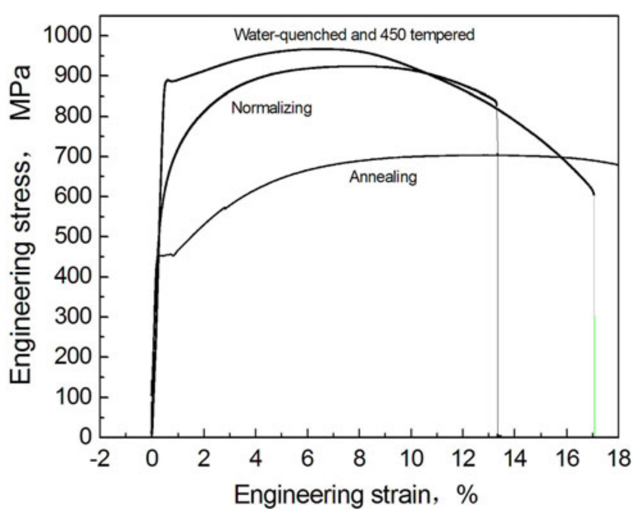

Fig. 7 Engineering stress-engineering strain curves

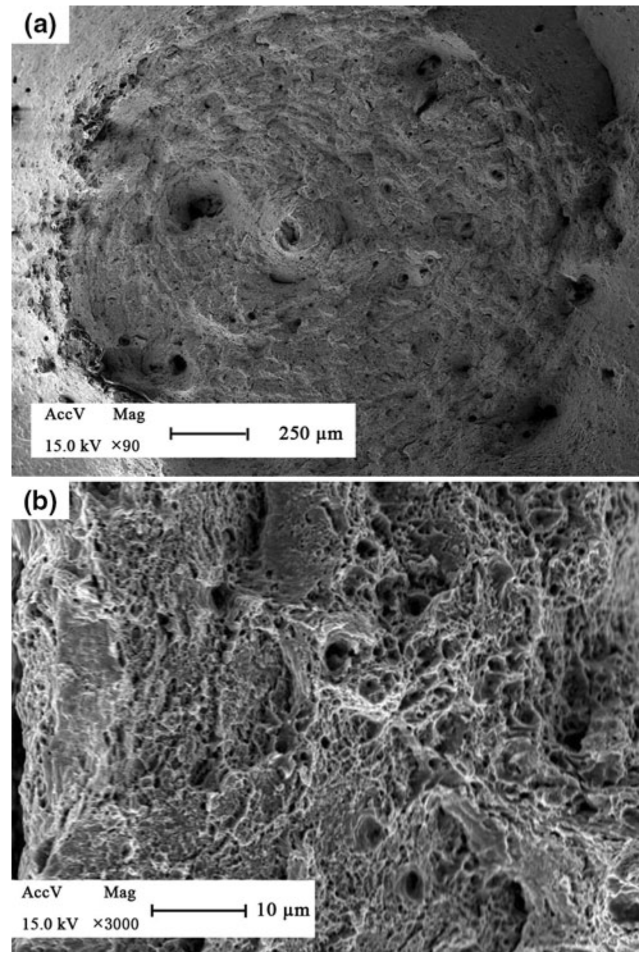

Fig. 8 SEM micrographs of fracture surface at ambient temperature under uniaxial tension, water-quenched and 450 °C tempered: (a) overall morphology and (b) voids and dimples

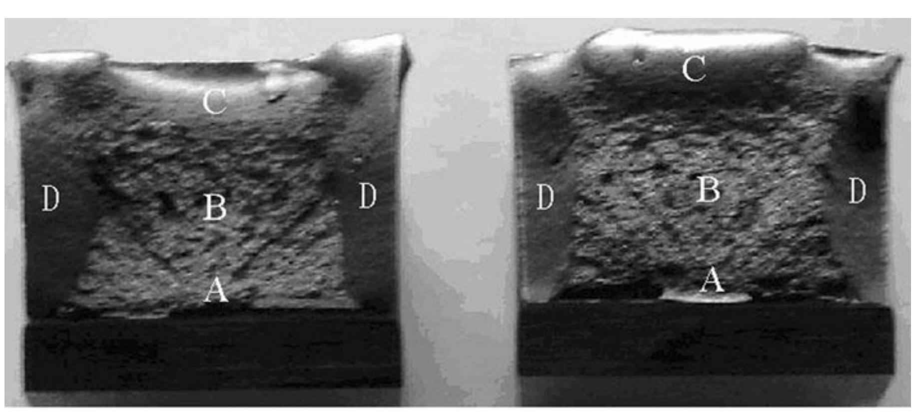

Fig. 9 The overall morphology of macro-fractographic appearance, water-quenched and 450 °C tempered, broken at −40 °C

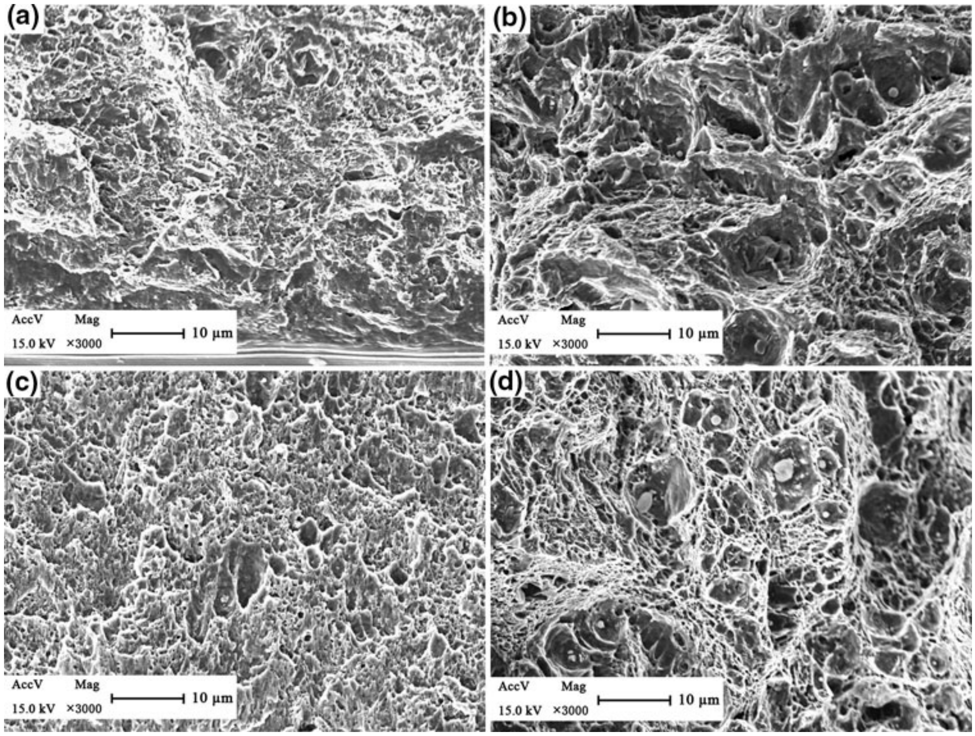

Fig. 10 SEM micrographs of fracture surface of a Charpy V-notch impact test specimen, water-quenched and 450 °C tempered, broken at −40 °C: (a) position A in Fig. 9, (b) position B in Fig. 9, (c) position C in Fig. 9, and (d) position D in Fig. 9

- The MnB cast steel can obtain better combination of strength and low-temperature impact toughness at low cost due to the simple alloying scheme and heat treatment. The impact energy at −40 °C reached 70-88 J, while the yield strength was also high, more than 880 MPa.

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