Effects of Re–B modification on the strength and toughness of 30CrMn2Si cast steel

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The effects of multi-modification on the strength and toughness of 30CrMn2Si cast steel were investigated. The mechanical properties tested include tensile strength; Charpy impact toughness from room temperature to $-60\,^{\circ}C$; hardness and fracture toughness. Micro-analyses were carried out by optical microscopy, transmission electron microscopy, scanning electron microscopy, and X-ray diffraction, and included the microstructure and submicrostructure of martensites, residual austenites, the size and distribution of non-metallic inclusions, and the original austenite grain size. It was concluded that, with the hardness unchanged, the fracture toughness of the modified steel was raised to 95 $MPa\,m^{1/2}$, 34% more than that of the un-modified steel, and the impact toughnesses at normal and low temperatures raised to 62 and 61.2 $J\,cm^{-2}$, respectively, 67 and 75% more than those of the un-modified steel. Furthermore, the fracture strength and yield strength of the steel were increased by over 200 MPa.

1. Introduction
Hadfield steel has been used as an abrasive resistant material for more than a century in mining, the cement and metallurgy industries, thermopower plants and agricultural machinery. The super-abrasive resistance of the steel originates from its high impact toughness and strain-hardenability. Under severe impact, Hadfield steel is strain-hardened in the contact surface layer. If the impact force is large enough, the severe strain-hardened austenite microstructure can be transformed into martensite of higher hardness, thus obtaining a layer of good wear resistance. However, for many components under non-severe impacts, Hadfield steel is not strain-hardened efficiently, and thus applications are not satisfactory. For many years, there has been an urgent need to develop new materials with good resistance against non-severe impact abrasive wear.

30CrMn2Si martensite cast steel, a newly developed anti-abrasive material, has far higher hardness than Hadfield steel, good wear resistance and low manufacturing costs. It can best substitute for Hadfield steel in many fields where the impact energy is low. Unfortunately, the strength and toughness of 30CrMn2Si steel are not high enough for the steel to be used in severe impact conditions. Therefore it is necessary to increase the strength and toughness, while maintaining the hardness.

In this paper, a rare-earth and boron agent was used to raise the strength and toughness of 30CrMn2Si martensite cast steel. The strengthening mechanism was investigated with scanning electron microscopy (SEM), transmission electron microscopy (TEM) and X-ray diffraction (XRD).

2. Experimental procedure
2.1. Specimens
The alloy was melted in a 150-kg induction furnace. The composition of the steel was C 0.30–0.35%, Si 0.60–1.00%, Mn 1.30–1.63%, Cr 0.60–1.00%, S < 0.03%, P < 0.03%. Before the melt was tapped at 1620–1640 °C, the Re–B modifier was added to the bottom of the ladle. At a temperature of 1540–1560 °C, the alloy melts, modified and un-modified, were poured into sand moulds to be solidified as keel blocks. All the specimens were cut from the keel blocks. The heat treatments applied included high-temperature austenitizing, oil quenching and low-temperature tempering. Fig. 1 shows the specimens for the impact, tensile and fracture toughness tests.

2.2. Mechanical test
The tensile properties of the steel were determined on a WE–30 tensile tester. The impact tests were carried out on a JB–30A tester. For low temperature impact testing, the specimens were cooled to a temperature range from 0 to $-60\,^{\circ}C$, and tested according to GB4159-84 (Chinese national standard 4159-84). The hardnesses of the specimens were determined on a HR–150D tester. Finally, according to GB4161-84 (Chinese national standard 4161-84), the fracture toughnesses of the steel were tested on a WE-30 tensile tester, and calculated to conform to the following:

$$P_{max}/P_a < 1.1. \quad (1)$$

$$a, B, (W-a) \geqslant 2.5\left(\frac{K_q}{\sigma_s}\right)^2 \quad (2)$$

2.3. Microstructure analysis
The microstructures of the modified and non-modified steels were analysed with H-800 TEM, AJS-35C SEM and Ricon-2 X-ray diffractors.

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3. Results

3.1. Strength and impact toughness at room temperature

In Table I, the tensile properties and room-temperature impact toughnesses of both modified and non-modified steels are shown. With little change in hardness, the impact toughness had been raised from 37.0 J cm^{-2} of non-modified steel to 62.0 J cm^{-2}, tensile strength from 1539.0 to 1772.0 MPa, yielding strength from 1184.7 to 1398.0 MPa, and elongation from 1.7 to 2.8%. The rare-earth and boron agent is effective in increasing the room-temperature properties of the steel.

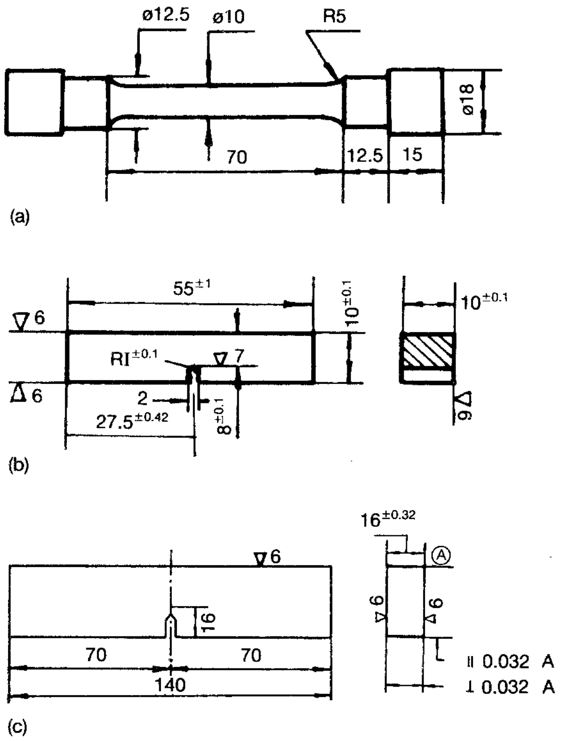

Figure 1 Specimens of (a) tensile, (b) Charpy, (c) fracture toughness tests.

3.2. Impact toughness at lower temperatures

The impact toughnesses of the tested steels at several temperatures from room temperature to − 60 °C are given in Table II. At each of the testing temperatures, the toughness of modified steel is far higher than that of the unmodified steel. In addition, there is little drop of the toughness data, from 62.0 J cm^{-2} to 61.2 J cm^{-2}. The impact values are sufficient for the tested steel to be safely used in winter with the temperature above − 60 °C.

3.3. Fracture toughness

The fracture toughness indicates the resistance of the material to crack propagation. In Table III, there is a comparison between the fracture toughnesses of both modified and unmodified steel. From 70.89 to 94.94 MPa $m^{1/2}$, the fracture toughness has been raised by 34% after Re–B modification.

With the hardness maintained, the strength and toughness of 30CrMn2Si martensite cast steel have been increased effectively by Re–B multi-modification.

4. Discussion

4.1. Microstructural refinement

In Fig. 2, the austenite grains of the steel have been refined by modification. As boundary concentrating atoms, most boron and rare-earths exist in the boundaries of austenite grains to limit their growth at high temperatures, for which rare-earth is more effective than boron [1]. This is because rare-earths reduce the

TABLE I Mechanical properties of the tested steels

Specimen	Modification	Hardness (RC)	Impact toughness (J cm^{-2})	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
A	Unmodified	51.0	37.0	1184.7	1539.0	1.7
B	Re–B-modified	50.5	62.0	1398.0	1772.0	2.8

TABLE II Charpy toughnesses of the tested steel

Specimen	Modification	Impact toughness (J cm^{-2}) at temperatures				
		25 °C	0 °C	− 20 °C	− 40 °C	− 60 °C
A	Unmodified	37.0	36.3	36.2	36.0	35.0
B	Re–B-modified	62.0	61.5	62.5	61.8	61.2

TABLE III Fracture toughness of the tested steels

Specimen	Modification	Fracture toughness K_q (MPa $m^{1/2}$)			K_{Ic} (MPa $m^{1/2}$)
A	Unmodified	67.42	76.90	68.30	70.89
B	Re–B-modified	81.37	94.45	108.98	94.94

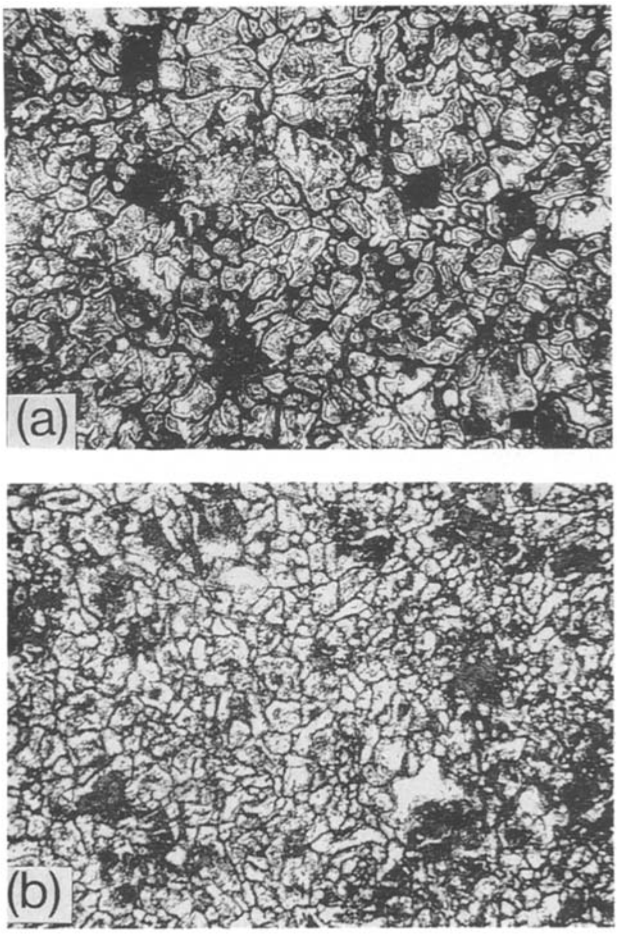

Figure 2 Austenite grain sizes of the tested steels. (a) Unmodified, (b) modified. Magnification × 100.

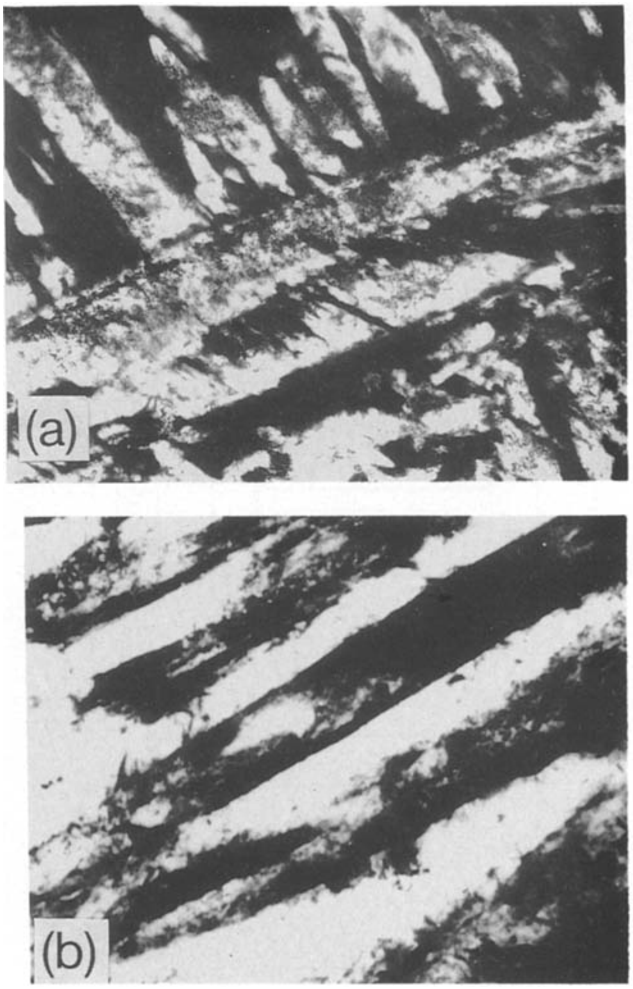

Figure 3 TEM micrographs of martensites. (a) Unmodified, × 15 000; (b) modified, × 30 000.

boundary energy when they are concentrated at the austenite boundaries, and the oxides of rare-earths are also obstacles to the movement of austenite boundaries [2].

Fine austenite grains correspond to fine quenched martensite grains, and have high values for mechanical properties. According to the Hall–Petch formula [3], the yielding strength of steel is inversely proportional to the square root of the grain size, and the toughness and elongation also increase as the grains of steel are refined.

4.2. Transformation of martensite submicrostructure

The submicrostructure of 30CrMn2Si martensites includes dislocated and twinned martensites. Re–B modification decreases the proportion of twinned martensite and increases that of dislocated martensite, and also makes the martensite laths narrower. The martensite structures for the tested steel are given in Fig. 3.

As is well known, the toughness of martensite steel depends mainly on both the substructure and grain size of martensites. In other words, fine dislocated martensite is superior to coarse and twinned martensite. For the coarse, twinned martensite with large tetragonality, cracks are easy to initiate under normal stress. The initiated cracks can propagate through and cross the twinned martensites. A fractograph of unmodified steel is shown in Fig. 4a. By modification, fine dislocated martensite grains are obtained. In the martensite phase, Re can reduce the solute concentration around the dislocations; then the obstruction of solute atoms to the dislocations becomes smaller and the dislocations are easy to move when stresses are applied. As a result, more energy is necessary for the cracks in dislocated martensite steel to initiate under stress. Also, the sliding movement of dislocations at the top area of the crack, which induce plastic deformation in the crack area, causes the stress concentration to decrease, and the propagation of the initiated crack is delayed as it requires higher stress values. Fig. 4b is a fractograph of dislocated martensite steel, where more fine ductile parts are presented.

4.3. Residual austenite in the structure of tested steel

Residual austenite may yield as a ductile phase in martensite steel, and thus reduce the stress concentration in the crack areas. The deformation of residual austenite in the crack propagation area means that more energy is required for propagation [5], and thus the toughness is increased.

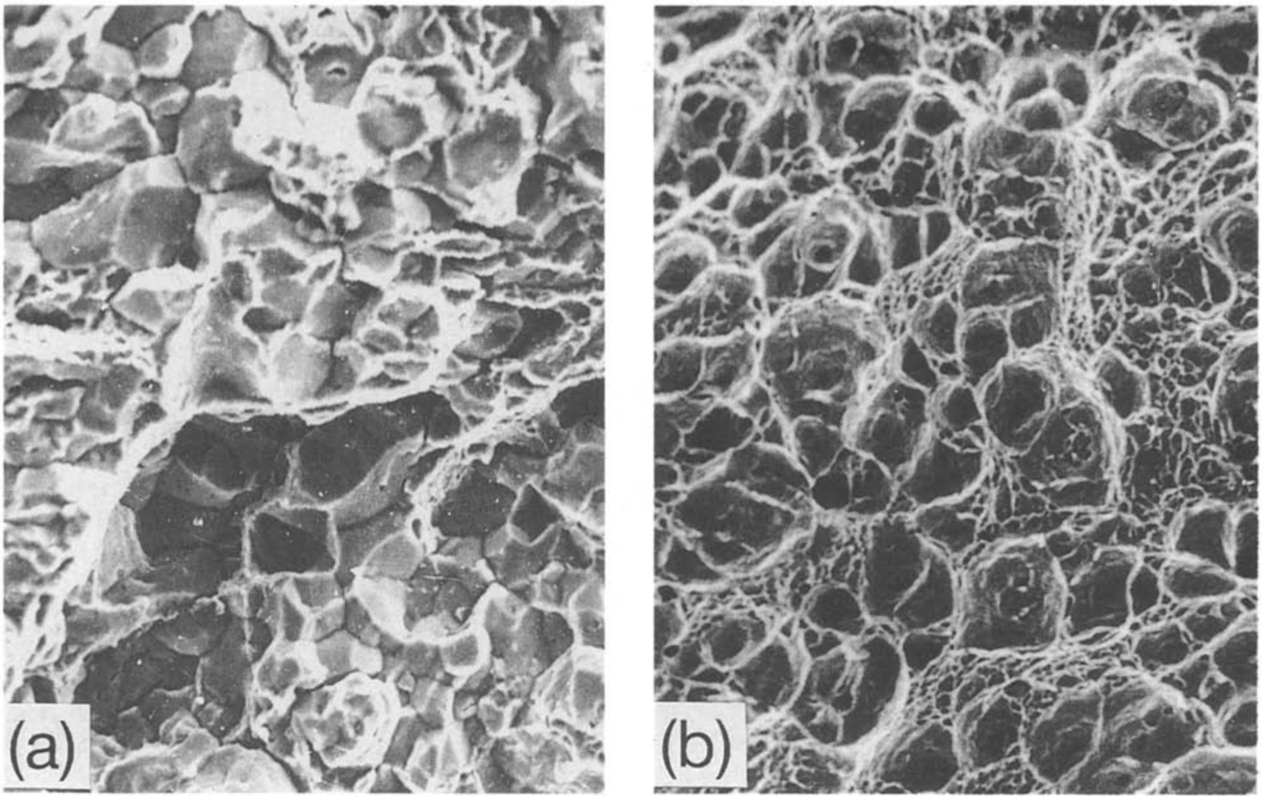

Figure 4 SEM fractrographs of tested steels. (a) Unmodified, × 1000; (b) modified, × 3000.

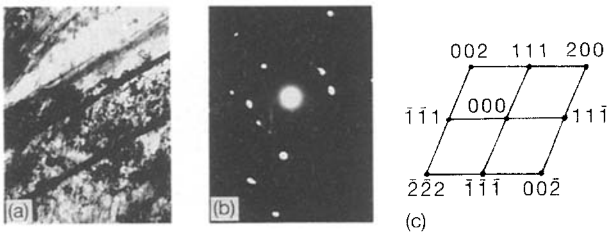

Figure 5 Austenite in the modified steel. (a) Austenite, (b) electron diffraction pattern, (c) determination of the pattern. Magnification × 50 000.

Residual austenite is increased effectively by Re–B modification. There is almost no austenite trace for unmodified steel under TEM observation. For the modified steel, as in Fig. 5a, a small proportion of residual austenite is found as narrow films at the boundaries of lath martensites. The electron diffraction pattern of austenite and the determination of the pattern are given in Fig. 5. Table IV gives the austenite volume fraction of the tested steels, which were quenched at 1050 °C and then tempered at 175 °C, determined by XRD. The residual austenite has been increased by modification.

The austenite films between the martensite grains made it difficult for the cracks to propagate, so the toughness is raised by modification.

4.4. Carbide participation in martensite grains

The strength and toughness of martensite cast steel are determined to some degree by the size and contribution of dispersed carbides. The TEM patterns of tempered carbides are presented in Fig. 6. In the tempered

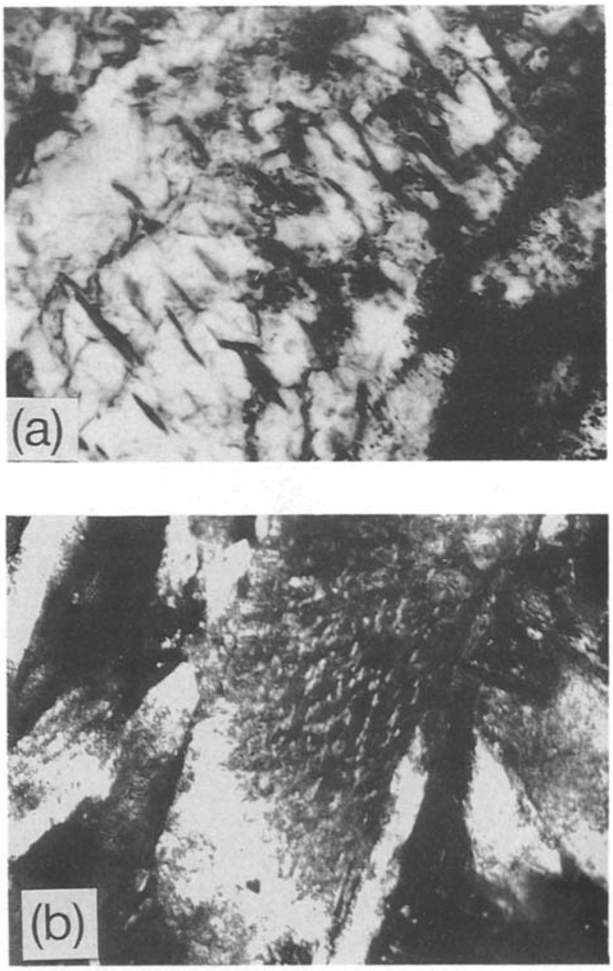

Figure 6 Tempered carbides in the tested steels. (a) Unmodified, (b) Re-B modified. Magnification × 60 000.

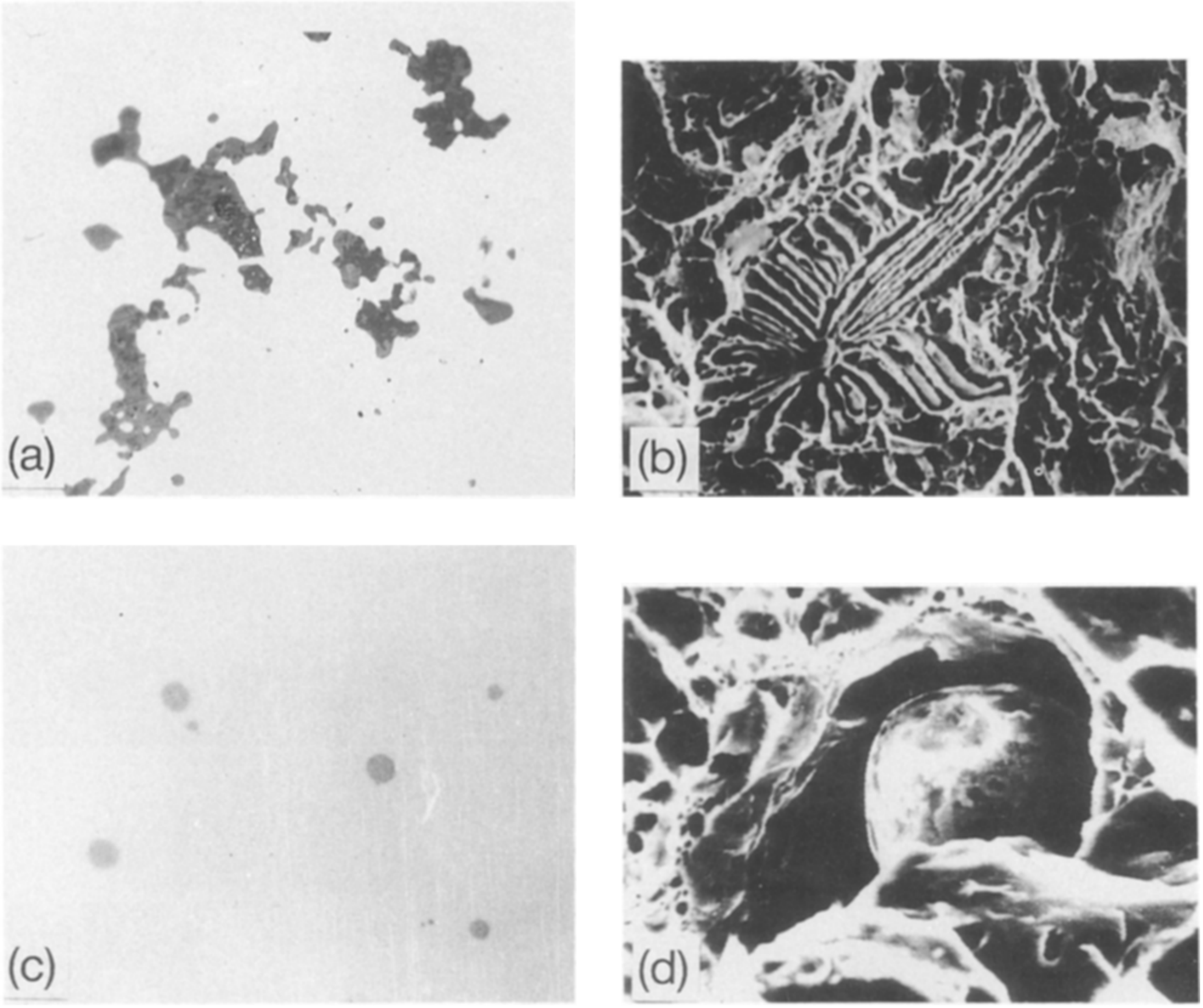

Figure 7 Distributions and micrographs of inclusions in the tested steels. (a) Unmodified, OM, × 100; (b) unmodified, SEM, × 1000; (c) Re–B modified, OM, × 100; (d) Re–B modified, SEM, × 3000.

TABLE IV Austenite volume fraction of the tested steels

Specimen	Modification	Fraction of austenite (%)
A	Unmodified	0.6
B	Re–B-modified	1.22

microstructure of unmodified steel, needle carbides precipitate along the twinned-crystal boundaries. As a result, the boundaries become brittle faces for the cracks to propagate along. Compared with this, in the modified steel the tempered carbides are dispersed over lath martensites in fine granules. The lath martensites are then dispersion-strengthened with little loss of toughness.

4.5. Non-metallic inclusions in the tested steels

Non-metallic inclusions are a destructive factor for the strength and toughness of steel. Fig. 7 shows the inclusion pattern of the steels. By modification, the inclusions have been transformed from a multi-angular to a nodular shape, which limits the destructive effect.

5. Conclusions

1. With the hardness maintained, the 30CrMn2Si martensite steel was modified by Re–B multi-agent to obtain higher strength and toughness.
2. The Charpy impact toughness of the tested steel at $-60\,^{\circ}C$ was raised to more than $60\ J\,cm^{-2}$, 75% more than that of unmodified steel.
3. The fracture toughness, from 70.89 to $94.94\ MPa\,m^{1/2}$, was also increased.

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