Control of solidification structure of wear-resistant austenite–bainite polyphase steel with nodular eutectic

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A new austenite–bainite polyphase steel with nodular carbides can be obtained by controlling the solidification structure of the steel melt, which only contains manganese and silicon, with modification of Si–Ca–B compound and air-hardening. The result indicates that the nodular carbide is in the eutectic form of austenite and (Fe, Mn)$_3$C, which is formed between the austenitic dendrites during solidification due to element segregation. The modifying elements (calcium, silicon, etc.) have the following functions: (1) their chemical compounds (CaS, SiO$_2$) are formed preferentially during solidification to act as heterogeneous nuclei for nodular eutectic crystallization, (2) the eutectic can be turned into the nodular shape after modification because of the decrease in the amount of the adsorbed impurity elements (oxygen and sulphur) and silicon enriched on the eutectic growth interface. The quantity of nodular eutectic makes up 10%–20%, with a size of 15–25 μm. The hardness and the toughness of this steel are 40–50 HRC and 20–40 J, respectively, and hence its wear-resistance can be more greatly increased than that of the austenite–manganese steel and the austenite–bainite steel.

1. Introduction
Austenite–bainite steel as a wear-resistant material has been used widely because it has excellent properties [1, 2]. But it is obtained by austempering and using a large amount of elements such as molybdenum and nickel. At the same time, its wear resistance is poor because there are no carbides in the matrix. Therefore, the application of this steel is strictly limited. Under these conditions for ensuring sufficient strength–toughness, the most ideal structure is austenite–bainite with nodular carbides, which has strong resistance to abrasive wear, such as white cast iron. The difficulty is that the formation of carbide requires a high carbon content, which is not beneficial to the formation of austenite–bainite. In this research, the solidification structure of the steel melt, which only contains manganese and silicon, was controlled by modification of Si–Ca–B. Numerous nodular carbides dispersed in the matrix were obtained in the as-cast state. An austenite–bainite matrix is obtained by air-hardening. This new steel shows good strength–toughness and wear resistance.

2. Experimental procedure
The chemical compositions of the steel are (wt %) 1.0–2.0 C, 3.0–5.0 Mn, 1.0–3.0 Si. The steel was prepared by a non-oxidation process in a 5 kg induction furnace. After deoxidizing with aluminium, the steel was poured at 1600 °C and modified by Si–Ca–B compound (the quantity added was 0.5–1.5 wt %). The specimens were cast into sand moulds of dimensions 12 mm × 12 mm × 60 mm. The specimens were austenitized at 860 °C for 40 min and hardened in air, and then ground into 10 mm × 10 mm × 55 mm size (without notch) for impact tests, hardness test, wear test and the observation of metallographic structure. The TEM (H-800) and SEM (JXA-840) were used in the observations.

3. Results and discussion
3.1. Microstructure of austenite–bainite steel with nodular eutectic
After modification by Si–Ca–B compound, carbide in the form of a network at the grain boundary was transformed into numerous nodular eutectics dispersed between dendrites when the steel is in the as-cast state, as shown in Fig. 1a–c.

Fig. 1d shows the bainite structure of this steel. It is different from typical bainite. The residual austenite is distributed between ferrite plates, and there is no carbide [3].

As shown in Fig. 1e, the nodular eutectic essentially is a eutectic of austenite and (Fe, Mn)$_3$C by analysis of the diffraction pattern. The manganese content of eutectic is up to 13.30 wt % (shown in

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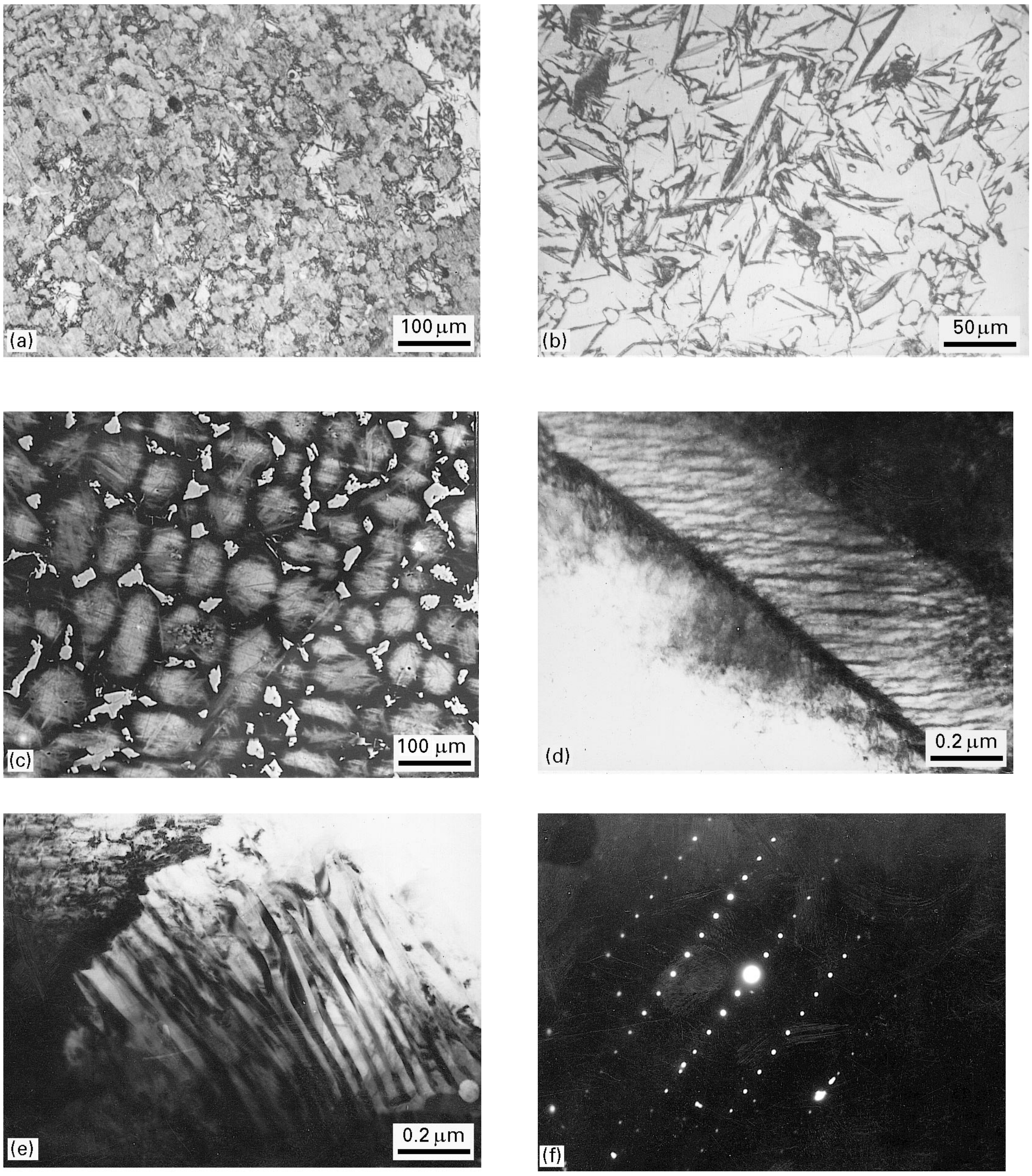

Figure 1 Microstructures of unmodified and modified steel. (a) Optical micrograph (unmodified 1); (b) optical micrograph (modified 2); (c) dispersion of eutectic (SEM); (d) bainite morphology (TEM); (e) nodular eutectic (TEM); (f) diffraction pattern of nodular eutectic. $B_{Fe_3C} = [1\,0\,0]$ (SAD).

TABLE I Microdistribution of alloying elements (wt %)

Microarea	Composition					Remarks
	Si	S	Ca	Mn	Fe	
Matrix	0.68	0.01	0.00	3.76	95.55	Unmodified
	1.24	0.00	0.00	2.95	95.84	Modified
Grain	0.98	1.06	0.00	4.02	93.94	Unmodified
boundary	1.42	0.21	0.09	3.98	94.30	Modified
Eutectic	1.89	0.00	0.00	13.30	84.81	
Centre of eutectic (A)	17.59	0.32	1.62	5.72	74.75	Spot A in Fig. 2c
Boundary of eutectic in matrix	2.72	0.00	0.05	5.73	91.50	Spot B in Fig. 2c
Interface of eutectic after eutectic removed	12.30	0.00	0.03	4.56	83.11	Frame C in Fig. 2d

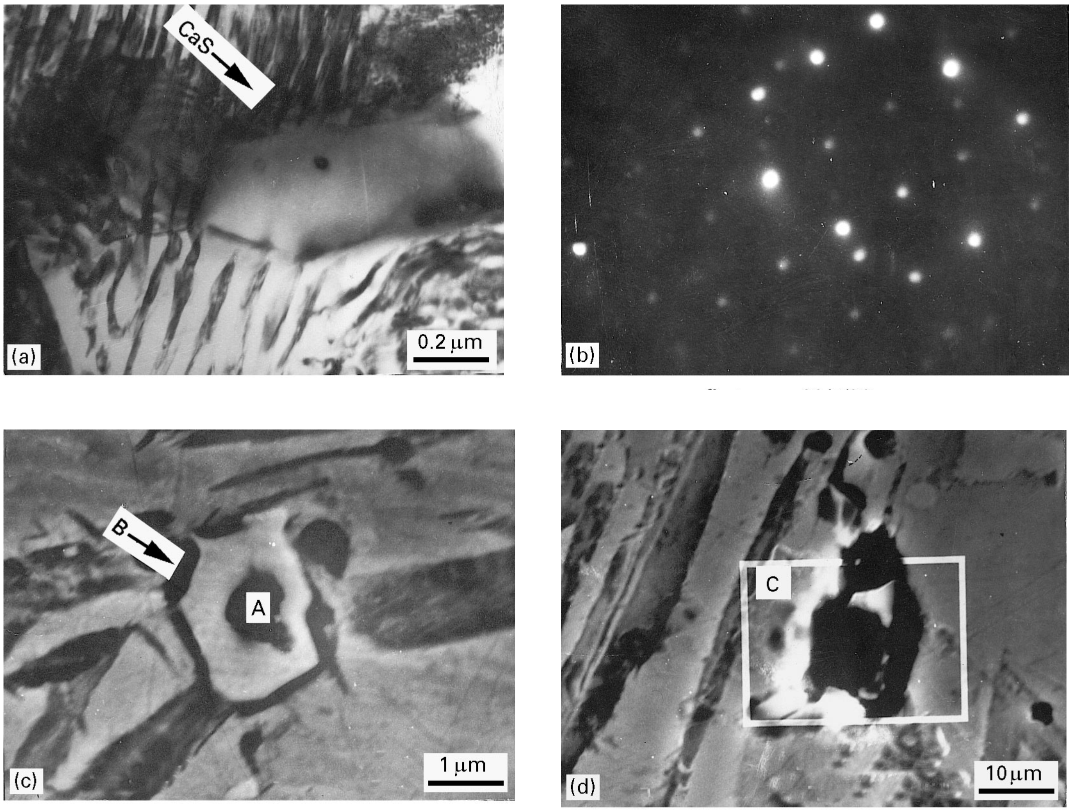

Figure 2 (a) Growth of eutectic on CaS (TEM): (b) $B_{CaS} = [1\,1\,0]$ $B_{Fe_3C} = [2\,1\,5]$ (SAD); (c) nodular eutectic (SEM); (d) microstructure after the eutectic failed.

Table I) and its microhardness is HV 800–1200. Its size is 15–25 μm and its quantity is 10%–20%.

3.2. Existential form and distribution of modifying elements

The microsegregation and distribution of alloying elements in the matrix, grain boundary and the eutectic, or on the interface of the eutectic, were analysed using an electron probe. The results are given in Table I.

From Table I and Fig. 2 it can be seen that the silicon, calcium and sulphur contents of the centre of the nodular eutectic are very high. On the basis of thermodynamic stability, SiO_2 and CaS can be formed in the liquid of the steel. SiO_2 can be formed preferentially during solidification to act as the heterogeneous nuclei for the nodular eutectic [4, 5].

According to the mathematical model of two-dimensional lattice disregistry [6] the lattice disregistry between the (0 0 1) of CaS and the (1 0 0) of Fe_3C is 10.56% and is less than 12%. Therefore, CaS can act as the heterogeneous nucleation for nodular eutectic crystallization. As shown in Fig. 2a, the eutectic depends on the growth of CaS.

Table I and Fig. 2a show that silicon and calcium segregate mainly on the grain boundaries and the interface of the nodular eutectic.

3.3. Mechanism of nodulizing of the eutectic

During the solidification process, as the temperature decreases continuously in the small melt pools located in the interstices between austenitic dendrite arms and austenitic grains, f_L (the volume fraction of the remaining liquid) becomes gradually smaller and the contents of calcium, silicon and carbon increase continuously because their segregation coefficient values are less than 0.001, 0.83, 0.02 and 0.03, respectively. Eventually, the thermodynamic and kinetic conditions for the formation of SiO_2 and CaS are satisfied and SiO_2 and CaS (whose melting points are 1713 and 2525 °C, respectively) form preferentially in the small pools.

As the solidification process continues further, the liquid in small melting pools reaches the eutectic composition because of the segregation (the distribution coefficients of carbon and manganese are about 0.28 and 0.75, respectively). At the same time, the increase in silicon content helps the carbon activity to increase. If the thermodynamic and kinetic conditions are satisfied, the eutectic reaction will occur. In this case, the SiO_2 and CaS formed previously can act as heterogeneous nuclei for the eutectic phase, as shown in Fig. 2a.

3.4. Mechanical properties and wear-resistance of austenite–bainite polyphase steel with nodular eutectic

The hardness and the toughness of the steel are increased by 114% and 152%, respectively, after modification, as shown in Table II.

The wear tests were performed on an ML-10 abrasive wear testing machine. The results are given in Table III, which shows that this steel has good wear resistance because austenite–bainite structure has

TABLE II Compositions and mechanical properties of the steel

Specimen	Chemical composition (wt %)					Modif. agent	Mech. properties	
	C	Si	Mn	P	S		Toughness (J)	Hardness (HRC)
1	1.17	0.85	4.32	0.031	0.025	No	14.5	21.0
2	1.21	1.80	4.28	0.028	0.012	Added[a]	36.5	45.0

[a] The added amount of Si–Ca–B compound was 0.80 wt %.

TABLE III Wear test results

Specimen	Weight loss (mg)	Relative wear resistance (ε)
Mn13	0.1041	1
High C medium Mn steel [8]	0.0709	1.47
Austenite–bainite steel [1]	0.0589	1.77
Austenite–bainite steel with nodular eutectic	0.0502	2.07

high yield strength, toughness and strain-hardening ability, which can bear more plastic deformation [9]. In addition, the nodular eutectic can help resist impact and indentation of an abrasive.

4. Conclusions

1. The nodular eutectic in the austenite–bainite matrix obtained by modification of Si–Ca–B compound is essentially a eutectic of austenite and $(Fe, Mn)_3C$.

2. SiO_2 and CaS formed preferentially during solidification can act as the heterogeneous nuclei for nodular eutectic crystallization.

3. The eutectic can be turned into nodular shape after modification because of the decrease in the amount of adsorbed elemental oxygen and sulphur and silicon enriched on the eutectic growth interface.

4. Austenite–bainite polyphase steel with a nodular eutectic has good strength–toughness and wear-resistance.

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