Modeling of spatial distribution of the eutectic M_2B borides in Fe-Cr-B cast irons

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Fe-Cr-B cast irons are a family of ferrous alloys containing high chromium (about 12 wt%) and boron (1.35 wt%). Like conventional high chromium white cast irons, the microstructures of the Fe-Cr-B alloys consist of a dendritic matrix and inter-dendritic M_2B borides, which constitute a three-dimensional networks surrounding the dendritic matrix [1]. As the spatial distribution of the eutectic M_2B borides in Fe-Cr-B cast irons has a vital influence on the mechanical properties, it is necessary to carry out relevant research on this topic.

Normally, the determination of spatial distribution of eutectics is conducted by metallography. In addition to for the traditional methods, the current authors have adopted strain models to predict the spatial distribution of the eutectic M_2B borides in Fe-Cr-B cast irons. The results show that the models are successful in the prediction of the spatial distribution of the eutectic M_2B borides. Thus, the models are helpful for prediction of mechanical properties, as well as interpretation of mechanical property difference of Fe-Cr-B cast irons.

The compositions of experimental Fe-Cr-B cast irons are listed in Table I. The alloys were melted in an electric induction furnace using a magnesite lining and cast in "Y" sample molds following ASTM A 781/A 781M-95. The test blocks 32 mm × 55 mm × 235 mm were cut from the lower part of the "Y" blocks and the surface ground to remove 3 mm from the surface and thus eliminate any oxidized layer. The test specimens 10 mm × 10 mm × 20 mm were cut from these blocks and tempered at 750 °C for alloy 1 and 720 °C for alloy 2 for 0.25, 0.5, 1.5, 2.5, 3.5 and 4.5 h. The macro-hardness and micro-hardness measurement on various constituents of the microstructures were then conducted on these specimens.

TABLE I The composition of experimental alloys (wt%)

No	C	B	Si	Mn	Cr	Mo	V	Ni	Cu
1	0.164	1.4	1.16	0.24	11.3	0.88	0.66	1.1	0.55
2	0.188	1.59	0.535	0.287	13.47	0.523	0.061	1.03	–

The spatial distribution of the eutectic M_2B borides of Fe-Cr-B alloys was revealed by SEM using deep-etched specimens. The etchant used was 10 vol%HNO_3 + 3 vol%HCL + 10 vol%saturated $FeCl_3$ + 77 vol%ethanol. The specimens were immersed in the etchant for about 20 h to deeply remove the matrix from specimen surface. After etching, the specimens were repeatedly rinsed in clean water and ethanol and finally, dried by fan.

The large hard phases in Fe-Cr-B cast irons can be considered to be distributed in the matrix grains somewhere between the two extreme cases, shown schematically in Fig 1a and b. In case (a), the large hard phases are continuous to the extent that individual particles are in contact with each other and form a network capable of supporting load, even in the absence of a matrix. Since each individual phase in a multi-phase system can support part of the load, the load taken by each phase (Li) depends on the hardness of the phase (Hi) and the effective cross-sectional area of that phase (Ai).

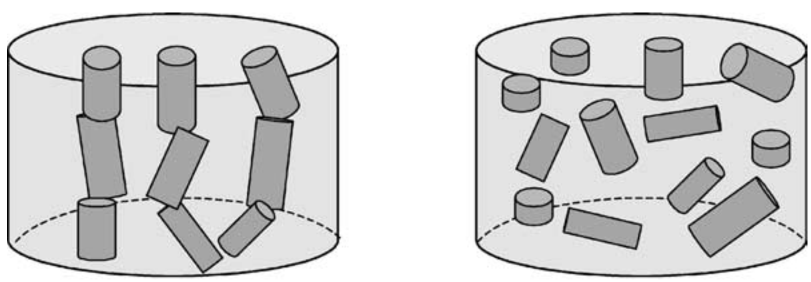

Figure 1 Two possible distributions of the large hard phases in Fe-Cr-B cast irons.

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TABLE II The volume fraction and the measured microhardness of each phase and the measured macrohardness and the value of macrohardness predicated by each model

Alloy	Matrix Vol	Matrix VHN	Boride Vol	Boride VHN	Matrix-based particles Vol	Matrix-based particles VHN	Mo-rich boride Vol	Mo-rich boride VHN	HVN Law of mixtures prediction	HVN Sum of strains prediction	HVN Experimental
Alloy1-as-cast	84.16	520	14.5	2028	0.3	659.5	1.05	407.7	737.95	581.31	588
Alloy1-750 °C-0.25 h	82.1	351	15.75	1402	0.3	659.5	1.375	407.7	508.63	399.59	492
Alloy1-750 °C-0.5 h	82.9	322	15.3	988.8	0.32	659.5	1.475	407.7	426.38	360.69	385
Alloy1-750 °C-1.5 h	81.52	297	15.78	824	0.95	659.5	1.925	407.7	385	333.94	368
Alloy1-750 °C-2.5 h	79.59	274	17.25	841.8	1.12	659.5	2.035	407.7	379	314.8	336
Alloy1-750 °C-3.5 h	79.59	254	17.25	920	1.12	659.5	2.035	407.7	376.57	376.57	330
Alloy1-750 °C-4.5 h	79.59	243	17.25	946	1.12	659.5	2.035	407.7	372.3	372.3	320
Alloy2-as-cast	79.25	508	20.75	2028	0.4	659.5	0	407.7	826	599.37	626
Alloy2-700 °C-0.25 h	78.5	420	21.15	1533	0.5	659.5	0.1	407.7	650.48	510.19	510
Alloy2-700 °C-0.5 h	78.65	376	21.35	849	0.55	659.5	0.15	407.7	481.2	424.58	408
Alloy2-700 °C-1.5 h	77.25	325	22.75	1015.3	0.58	659.5	0.2	407.7	486.72	382.44	383
Alloy2-700 °C-2.5 h	77.25	295	22.95	1034.7	0.58	659.5	0.22	407.7	470.11	350.3	394
Alloy2-700 °C-3.5 h	77.25	274	22.95	1097	0.58	659.5	0.22	407.7	468.16	328.64	383
Alloy2-700 °C-4.5 h	77.25	259	22.95	1168	0.58	659.5	0.22	407.7	472.89	313.15	374

If the strain in each phase is the same, the load taken by phase i can be expressed as,

$$Li = Hi \times Ai$$
$$L = \sum Li$$
$$\therefore \quad H = L/A = \sum Hi \times Ai/A$$

But $Ai/A = Vi$, where Vi stands for the volume fraction of phase i, so that:

$$H = \sum Hi \times Vi \qquad (1)$$

Equation 1 represents the "law of mixtures" model.

In case (b), the large hard phases are not continuous and so are not capable of supporting load in the absence of the matrix. The overall hardness depends on the strain in each of the individual phases (Si). Supposing that load on each phase depends only on Vi and is transmitted from one phase to another phase, the load taken by phase i can be expressed as,

$$Li = k_1 \times Hi \times Si$$

But $Li = L \times Vi$

$$\therefore \quad Si = k_2 \times L \times Vi/Hi$$
$$S = k_2 \times L/H = k_2 \times L \times \sum(Vi/Hi)$$
$$\therefore \quad 1/H = \sum(Vi/Hi) \quad \text{or}$$
$$\therefore \quad H = 1/\sum(Hi/Vi) \qquad (2)$$

where, k_1 and $k_2$are constants. Equation 2 represents the "sum of strains" model.

Table IIpresents the volume fraction and the microhardness of each phase in microstructures, and measured and the predicted macrohardness in alloy 1 and alloy 2 alloys using the "law of mixture" and "sum of strains" models. Fig. 2a and b respectively show the predicted hardness vs. the measured hardness in these alloys. According to Fig. 2b, for alloy 2 the "sum of strains" model gives a better fit with experiment than the "law of mixtures" model. This implies that the hard phases in alloy 2 alloys are not well connected. By comparison, for alloy 1 alloys, the results fall between the two models, suggesting a degree of interconnection between the hard phases.

Microstructural investigation revealed the eutectic M_2B borides being irregular plates and these plates are in contact each other in the inter-dendritic spaces,

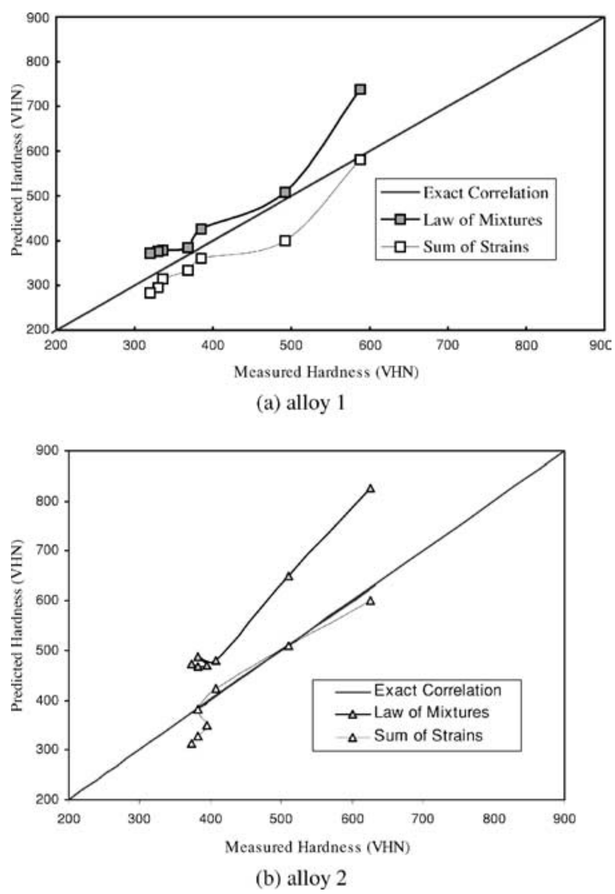

Figure 2 Comparison of measured macro-hardness with macro-hardness predictions using the strain models.

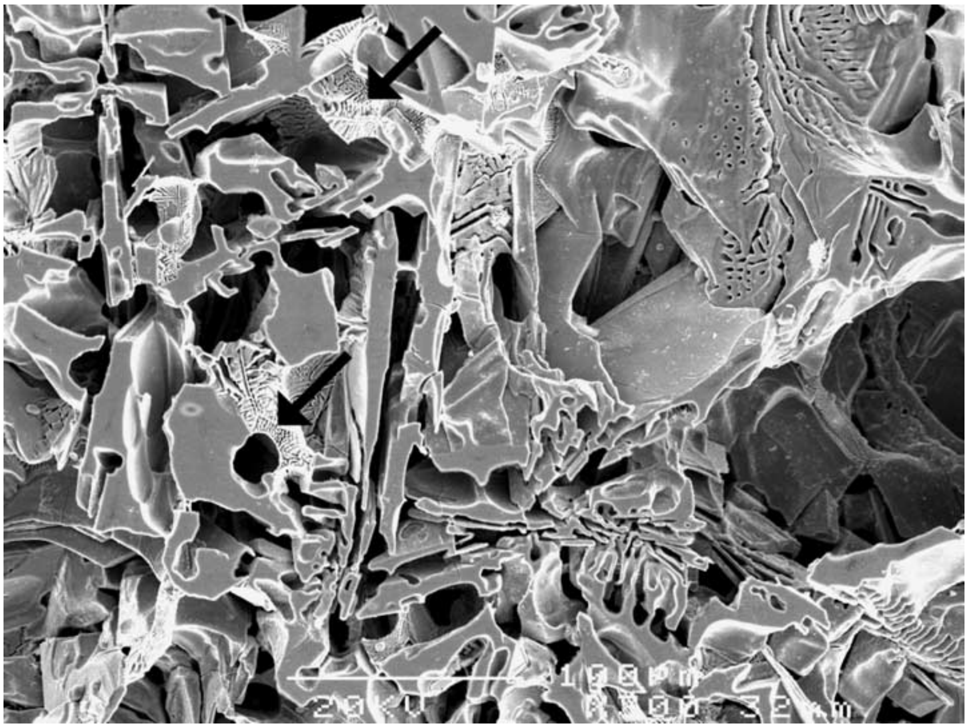

Figure 3 Morphology and distribution of the borides in the alloy 1.

forming a continuous three-dimensional network. With heat treatment, the thickness of the eutectic plates was increased and the connections between the plates were more prominent, particularly in alloy 1. This is because, except for the growth of the eutectic M_2B borides with heat treatment, small amounts of the Mo-rich borides also precipitated in the inter-dendritic spaces in the alloy 1—see marked arrows in Fig. 3. Therefore, the predicted distributions of the large hard phases in Fe-Cr-B cast irons are basically consistent with the SEM microstructural investigations.

It should be noted that the calculation of hardness via the two models used the mean microhardness value of the matrix-based boro-carbides and the matrix-based borides in RNB1 alloys that have similar compositions and microstructures to alloy 1 for microhardness of the matrix-based particles, and the mean microhardness value of the Mo-rich boride agglomerate[2]. This is because the dimensions of these hard phases in the RNB1 alloys are larger than in other Fe-Cr-B alloys and thus, can more accurately represent true value. Since the volume fractions of these hard phases are quite small ($<5\%$), compared with the higher volume fraction of the matrix grains and the eutectic M_2B borides, this approximation should have a negligible effect on the predicted hardness.

In summary, we have show, that the spatial distribution of the eutectic M_2B borides in Fe-Cr-B cast irons can be modeled using strain models. The predicted distribution is basically consistent with the real microstructural investigation.

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