Review Article

A review on relationship between morphology of boride of Fe-B alloys and the wear/corrosion resistant properties and mechanisms

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\textbf{A B S T R A C T}

Fe-B alloys have attracted much attention as a new kind of wear-resistant and corrosion-resistant materials. It is interesting that the boride morphology of Fe-B alloys determines their superior wear resistant or corrosion resistant property. The review of Fe-B alloys' research and development status claims more attention to controlling boride morphology that is net-like, broken and oriented to design wear resistant or corrosion resistant alloy. Besides, this review focuses on the relationship between boride morphology and wear/corrosion resistant properties and mechanisms.

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1. Introduction

Wear and corrosion lead to a considerable amount of economic loss. It is of great importance to materials to develop high wear resistant and corrosion resistant alloys in order to cut down loss and meet harsh environmental requirements. In recent years, the innovation of Fe-B alloys is considered a breakthrough due to their excellent wear resistance and good corrosion resistance with moderate impact toughness, higher chemical and mechanical stability compared to Cr cast irons or stainless steels [1–8]. Besides, literature reported that Fe-B alloys have large hard neutron capture cross section [9] and good oxidation resistance [10, 11]. Furthermore, the introduction of the B element in stainless steel [12–14] or high-speed steel [15–17] can improve their wear resistance. To date, Fe-B alloys have been applied to wear resistant or corrosion resistant parts, for instance, glass moulds [18, 19], ball mill liners [20], guide rolls [21], hammer head [22], grinding ball [23], high-boron high-speed steel roll [24, 25] and hot-dip galvanizing, etc.

In past years, boron had been used as a micro-alloying element to enhance the mechanical properties of carbon steel [26, 27]. However, in recent years, boron has been used to fabricate Fe-B alloys by adding more boron (>0.05 wt.%) in Fe alloy, which would form FeB, because boron has a very low solubility in iron (<0.02 wt.% in α-iron and 0.0081 wt.% in γ-iron), as shown in Fig.1 [28, 29]. Borides have very high hardness (FeB:1800–2000 HV; Fe₂B:1400–1600 HV) [30], which are widely used to increase the wear resistance of the surface layer, such as in boriding treatment [31, 32]. Lakeland [1] first fabricated this kind of alloy and carried out the idea by taking M₃B as a wear resistant skeleton, which exhibited excellent wear resistance. Besides, the hardness and toughness of the alloys could be adjusted (hardness 22–62 HRC and toughness 8–15 J/cm²) [1]. This kind of alloy has a significant advantage that the matrix and wear resistant phase could be controlled by adjusting carbon and boron concentration, respectively, which makes it possible to design the microstructure in order to achieve different properties.

In addition, Fe-B alloys have great corrosion resistance to liquid zinc because of the dense continuous boride network in Fe-B alloys which hampers the Fe/liquid Zn interface reaction [33–35]. By comparison with 1Cr18Ni9Ti stainless steel, the corrosion resistance of Fe-B alloys with different boron concentration (3.5 wt.% and 6.0 wt.%) is improved by about 56 times, therefore, Fe-B alloys exhibit excellent corrosion resistance in hot-dip galvanization baths [36]. In comparison with inorganic non-metal molten zinc corrosion resistant materials such as Si₃N₄, Al₂O₃ and ZrO, Fe-B alloys have a better toughness. This kind of alloy has a potential to become a superior corrosion resistant material in molten zinc. Fe-B alloys own good wear resistance and corrosion resistance because the Fe₂B intermetallic with body-centred tetragonal structure has high hardness and non-wetting in molten zinc [37, 38].

It is interesting that, by controlling the boride morphology, Fe-B alloy becomes a new kind of wear resistant material or corrosion resistant material. Fe-B alloys, which are used as wear resistant materials, are expected that boride network will be broken up to achieve high toughness. However, Fe-B alloys, which are used as corrosion resistant materials, are expected that boride network will be continuous in order to resist the corrosive attack from liquid zinc. Recently, a new research has discovered that the Fe-B alloys with oriented boride that are perpendicular to the corrosion interface, which can originate the corrosion interface pinning effect, shows a higher corrosion resistance than that with net-like boride in molten zinc [39]. It is important to clarify the relationship between wear resistance and corrosion resistance of Fe-B alloys and boride morphology. Therefore, this paper reviews research progress of Fe-B alloys by controlling the boride morphology to design wear resistant or corrosion resistant alloy. Furthermore, pure Fe₂B intermetallic has also been reviewed.

2. Fe-B alloys used as wear resistant alloys

2.1. Composition, microstructure and mechanical properties

At present, Fe-B alloys are mainly classified into two types: Fe-Cr-B alloys and Fe-C-B alloys. These alloys are commonly prepared by sand casting. Besides, some studies on the alloy elements on microstructure and mechanical properties of Fe-B alloys have been carried out. Table 1 summarizes the composition and mechanical properties of Fe-B alloys, in which the basic elements of Fe-B alloys are C, B, Cr, Mn, Si. Among these alloy elements, C, B and Cr elements are found to be effective for further enhancement of Fe-B alloys. It can also be found from Table 1, that the Cr concentration of Fe-Cr-B alloys exceeds 8 wt.% and Fe-C-B alloys also has Cr content at about 2 wt.%. Why does Fe-C-B alloys need certain amounts of Cr content? Huang et al. [40] studied the fracture toughness of Fe₂B with different Cr content (0 wt.%, 0.49 wt.%, 1.02 wt.%, 2.1 wt.%, 3.2 wt.%) and discovered that the fracture toughness of Fe₂B was increased first and then decreased. Moreover, 2.1 wt.% Cr addition could achieve maximum fracture toughness. Jia et al. [41, 42] further researched the influence of Cr content on the two-body and three-body abrasive wear behavior of Fe-B alloys and discovered that 2 wt.% Cr addition could achieve maximum wear resistance, which indicated the toughness of Fe₂B was of great benefit to wear resistance of Fe-B alloys. In addition, it also can be found from Table 1, the mechanical properties of this kind of alloy are similar with that of cast iron, therefore, this kind of alloy is also named high boron cast iron in some literature.

The solidification microstructure of Fe-Cr-B alloys is composed of a dendritic matrix and inter-dendritic M₂B borides, which constitute a three-dimensional network surrounding the dendritic matrix [50]. The typical solidification microstructure of the Fe-Cr-B alloys is shown in Fig.2(a) and (b) [44]. Fu et al. [4] designed the Fe-C-B alloys by reducing Cr content and removing Ni, Mo, V, Nb, etc, precious elements in Fe-Cr-B alloys. The alloy composition is 0.080±0.20 C, 2.24±0.8 B, 0.5±1.0 Si, 0.51±0.0 Mn, and 0.52±0.0 Cr. The solidification microstructure result shows that Fe-C-B alloys consist of Fe₂B, ferrite and pearlite, and Fe₂B is net-like distribution along grain bound-
aries. The typical as-cast microstructure of the Fe-C-B alloys is shown in Fig. 2(c) and (d) [51].

The effect of heat treatment on Fe-B alloys has been investigated. The matrix of Fe-C-B alloy transforms to martensite, and the net-like boride is almost unchanged and only the corner of boride is round after 1050° quenching, as shown in Fig. 3(a) [51]. Precipitation is not found in the alloy. The matrix of Fe-Cr-B alloy converts to martensite, and the net-like boride is almost unchanged after 1020° quenching and 200° tempering, as shown in Fig. 3(b) and (c) [44]. However, some precipitates are observed in the matrix grains, which are the mixture of different kinds of boro-carbides [44,52-55]. The precipitates are regarded as M23(B,C)6 (M equals Fe, Cr, or Mn). Why do M23(B,C)6 precipitates appear in Fe-Cr-B alloy during tempering? Guo et al. [53] have demonstrated that the Cr element would enlarge the crystal lattice parameter by means of replacing Fe by Cr atom when it is dissolved in Fe, because the diameter of the Cr atom is larger than that of Fe atom. Therefore, with more Cr addition, more B would dissolve in the matrix of Fe-Cr-B alloy, which leads to boro-carbides precipitation.

Many investigations have shown that boride morphology was not changed by high temperature heat treatment [51,56,57]. It is difficult to break the boride network by using this method because B has a very low solubility in Fe (0.02 wt. % at 1149° C).

### 2.2. Controlling morphology of boride in Fe-B alloys

The morphology of boride plays a key role in Fe-B alloys. However, the net-like eutectic boride is continuous in Fe-B alloys after solidification, as shown in Fig. 4 [51,58], which damages the continuity of the matrix and leads to the brittleness of the alloy.

As wear resistance, Fe-B alloys are expected to own high hardness and good toughness. So, to break the network of eutectic boride, researchers tried the rare earth (RE) modification [50,59-67]. Table 2 lists the modified Fe-B alloys with various RE additions, such as RE and titanium [50], V, Ti and RE-Mg [59], RE, titanium and nitrogen [60], RE-Mg [61,62], Ti, Mg and RE [63], RE-N [64], RE (Ce) [65,66], RE and Al [67]. As shown in Table 2, the hardness of modified Fe-B alloys is closed to unmodified Fe-B alloys, and the impact toughness of modified Fe-B alloys are greater than that of the unmodified Fe-B alloys. That is because the boride in the modified Fe-B alloys display visible necking and cracking occurrences.

However, it is not satisfactory controlling the morphology of boride by RE modification. Because the change of boride network is not obvious. Therefore, improvement in toughness is marginal since RE modification cannot completely eliminate the boride network. Some researchers tried other methods to change the morphology of boride. Yi et al. [68] prepared the Fe-B alloys by a semi-solid method and found that the boride

<table>
<thead>
<tr>
<th>System</th>
<th>Compositions (wt.%)</th>
<th>Mechanical properties</th>
<th>References</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
<td>B</td>
<td>Cr</td>
</tr>
<tr>
<td>Fe-Cr-B</td>
<td>0.28</td>
<td>1.44</td>
<td>9.25</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>1.62</td>
<td>10.85</td>
</tr>
<tr>
<td></td>
<td>0.31</td>
<td>1.88</td>
<td>8.05</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>1.44</td>
<td>9.25</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>3.25</td>
<td>0.5-2.0</td>
</tr>
<tr>
<td>Fe-C-B</td>
<td>0.12</td>
<td>3.25</td>
<td>0.5-2.0</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>1.44</td>
<td>9.25</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>3.25</td>
<td>0.5-2.0</td>
</tr>
<tr>
<td></td>
<td>0.4-0.7</td>
<td>1.5-2.0</td>
<td>0.8-1.5</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>1.44</td>
<td>9.25</td>
</tr>
<tr>
<td></td>
<td>0.1-0.25</td>
<td>1.5-2.5</td>
<td>1.0-1.5</td>
</tr>
</tbody>
</table>
was greatly refined, but there had been no obvious change in the network of boride. In previous research, we have found that hot deformation is the most effective method used in the breakup of boride network in Fe-C-B alloys [69–71]. After hot deformation, the impact toughness of Fe-C-B (0.350–0.40 wt.% C, 0.380–0.42 wt.% B) alloys could be improved by about 20 times because the matrix of the alloys became continuous [69]. Feng and Zhenhua [72] also adopt the method of hot deformation to improve the morphology of boride to enhance mechanical properties of Fe-C-B (0.36 wt.% C, 1.48 wt.% B) alloys. Their experiment results showed that hot deformation could break the continuous boride network. In another study, hot-rolling technology was applied to Fe-C-B alloy to improve the microstructure and mechanical properties, which disrupted the continuous grain-boundary FeB network [73]. It is known that white cast iron cannot be processed by plastic working. Why does Fe-C-B alloy withstand hot deformation? Our previous study [69] has discovered that the dislocation slipping and pile-up in boride after hot deformation lead to the deformation of boride.

### Table 2 – Modified Fe-B alloys with various additions.

<table>
<thead>
<tr>
<th>Compositions</th>
<th>Mechanical properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quenching Hardness/HRC</td>
<td>Quenching Toughness/(\text{J/cm}^2)</td>
</tr>
<tr>
<td>Fe-C-B/Fe-C-B+(RE+Ti)</td>
<td>55.3/55.7</td>
<td>12.3/22.3</td>
</tr>
<tr>
<td>Fe-C-B/Fe-C-B+(V+Ti+RE-Mg)</td>
<td>56.1/56.9</td>
<td>11.4/15.6</td>
</tr>
<tr>
<td>Fe-C-B/Fe-C-B+(RE+Ti+N)</td>
<td>(60-62)/(60-62)</td>
<td>(12-15)/(28-32)</td>
</tr>
<tr>
<td>Fe-C-B/Fe-C-B+RE-Mg</td>
<td>56/56</td>
<td>13/17.5</td>
</tr>
<tr>
<td>Fe-Cr-B/Fe-Cr-B+(Ti+Mg+RE)</td>
<td>60.5/62.3</td>
<td>9/12.5</td>
</tr>
</tbody>
</table>

2.3. **The relation between boride morphology and wear resistance of Fe-B alloys**

Fe-B alloy using M_2B (or Fe_2B) as wear phase is different from the high Cr cast iron using M_7C_3 as wear resistant phase.
Fig. 3 – The typical microstructures of the Fe-B alloys after heat treatment: (a) Fe-C-B alloy [51]; (b) Fe-Cr-B alloy held at 1293K for 2 h, quenched in air, tempered at 473K for 1 h low magnification and (c) high magnification [44].

Fig. 4 – The typical morphology of boride in Fe-B alloys after deep etching: (a) Fe-Cr-B alloy [58]; (b) Fe-C-B alloy [51].

Fig. 5 – Schematic illustration of (a) the pin-on-disc two-body abrasion test [70] and (b) the three-body abrasion test [71].
Therefore, the research on the wear resistance during different conditions and on the relation between wear resistance and boride morphology is meaningful. Two-body abrasion and three-body abrasion test are typical methods to test the wear properties of Fe-B alloys. The two-body abrasion test machine uses a pin on the abrasive disc to conduct the experiment, shown in Fig. 5(a) [70]. The principle of this method is that the wear of the material proceeds chiefly by the micro-cutting mechanism. Whereas, the three-body abrasion test is conducted by sliding a specimen against a circular track of soft steel immersed in loose abrasives according to the work of Boyes [74], shown in Fig. 5(b) [71].

Several works reported that Fe-B alloys with net-like boride showed excellent abrasion resistance in two-body abrasion property [4,75,76]. The two-body abrasion property of Fe-C-B (0.080.2 wt.% C, 2.24.0 wt.% B) alloys was higher than that of Ni-hard white cast iron, Cr15 and Cr12MoV, and was close to that of high Cr white cast iron [4]. Fu et al. [75] tested the wear property of Fe-C-B (0.10.25 wt.% C, 0.81.2 wt.% B) alloys during the two-body abrasion, which was superior to that of the martensitic cast steel and was close to the high Cr white cast iron. Song [77] has systematically studied the wear resistance of Fe-C-B alloys with varying carbon concentration and boron concentration. These alloys have been designed with low carbon-low boron alloys (0.20.4% C, 1.0% B), medium carbon-alterable boron alloys (0.30.45% C, 0.53.0% B) and high carbon-high boron alloys (0.51.0% C, 2.0% B). Under two-body abrasion, the wear resistance of Fe-C-B alloy with low carbon-low boron content was lower than that of high Cr cast iron regardless of load or high load. When the boron content of medium carbon-alterable boron alloys was less than 1.5%, the wear resistance of Fe-C-B alloys was equal to that of high Cr cast iron. When boron content of alloys was more than 1.5%, wear resistance of the alloys was significantly higher than that of high Cr cast iron. The higher the B content, the higher the wear resistance of Fe-C-B alloys. The wear resistance of Fe-C-B alloys with high carbon-high boron content is higher than that of high Cr cast iron.

When the boride in Fe-B alloys is broken, the impact toughness of the alloys can be improved. How superior are the two-body abrasion property of the alloys? In our previous work, boride morphology was found to affect the wear properties of Fe-B alloys [70]. In the two-body abrasion test, the wear resistance of Fe-B alloys with broken boride was lower than that of Fe-B alloys with net-like boride. It has been demonstrated that the load is transferred to the underlying matrix of Fe-B alloys with net-like boride [70]. The schematic diagram was shown in Fig. 6 [70]. We compared the wear resistance of Fe-B alloys with net-like boride and broken boride. The results showed that the wear resistance of Fe-B alloys with broken boride was higher than that of Fe-B alloys with net-like boride using three different kinds of abrasives. In the three-body abrasion test, we have compared the wear resistant property of Fe-B alloys with net-like boride and broken boride. The wear resistant property of Fe-B alloys with broken boride was higher than that of Fe-B alloys with net-like boride [71]. Yi et al. [68] compared the three-body abrasive wear property of semi-solid Fe-B alloys to that of ordinary Fe-B alloys. The results showed that the wear resistant property of semi-solid Fe-B alloys with broken boride was higher than that of ordinary Fe-B alloys with net-like boride.

Therefore, the investigations mentioned above indicate that the wear resistance of Fe-B alloys is highly related to boride morphology. In the two-body abrasion test, the wear resistance of Fe-B alloys with broken boride is lower than that of Fe-B alloys with net-like boride. However, in the three-body abrasion test, the wear resistance of Fe-B alloys with broken boride is higher than that of Fe-B alloys with net-like boride.

### 3. Fe-B alloys used as corrosion resistant alloys

#### 3.1. Composition and corrosion resistance

The composition of Fe-B alloys used as corrosion resistant alloys is similar with that of Fe-B alloys used for wear resistant alloys and the major difference is the boron content. Many researches proved that Fe-B alloys with boron concentration near eutectic component exhibited excellent corrosion resistance [36,78,79]. Ma et al. [36] studied the effects of boron content on the corrosion resistance of Fe-B alloys (1.5 wt.%, 3.5 wt.% and 6.0 wt.% B) in liquid zinc. Compared with 1Cr18Ni9Ti stainless steel, the corrosion resistance of Fe-B alloy with 3.5 wt.% boron addition improved by about 5 times, showing excellent corrosion resistance, shown in Fig. 7(a) [36]. The corrosion resistance of the Fe-B alloys...
increased significantly with increasing the boron content from 1.5 wt.% to 3.5 wt.%. However, the corrosion resistance improved marginally with increasing the boron content from 3.5 wt.% to 6.0 wt.%, shown in Fig. 7(a) [36]. A further study by these authors considered the effect of RE on the corrosion resistance of Fe-B alloys in liquid zinc. It is discovered that there was not a significant increase compared to Fe-B alloys without RE addition, shown in Fig. 7(a) [36].

Fe-B alloys used as corrosion resistant materials are mainly from the Fe-C-B alloy system. On the contrary, the Fe-Cr-B alloy system is rarely used. Ma et al. [80] investigated effects of Cr addition (0, 2, 5, 8, 12, 18 wt.%) on corrosion resistance of Fe-3.5B alloy in molten zinc. The corrosion resistance of Fe-3.5B alloys could be significantly improved with 2 and 5 wt.% Cr addition. However, the corrosion resistance decreased marginally with the 8, 12 and 18 wt.% Cr addition, shown in Fig. 7(b) [80]. That was because that boride network of Fe-3.5B alloy with 2 and 5 wt.% Cr addition still maintained the net-like structure. However, more Cr addition (8, 12 and 18 wt.%) would lead to breaking the net-like boride. Many researches confirmed that Cr would destroy the continuity of boride in Fe-B alloys [46,52,55]. Hence, Fe-Cr-B alloy system used as corrosion resistant alloys in liquid zinc is inappropriate.

The solidification microstructure of Fe-B alloys used as corrosion resistant materials is similar to that of the alloys used as wear resistant materials.

3.2. Controlling morphology of boride

In general, Fe-B alloys used as corrosion resistant materials have high concentration continuous boride network, which can hamper the Fe/liquid Zn interface reaction. However, a new research has discovered that the Fe-B alloys with oriented boride showed higher corrosion resistance than that with net-like boride in molten zinc [39]. They studied the orientation of Fe2B by directional solidification on corrosion interface of Fe-B alloys in molten zinc, shown in Fig. 8 [39]. It was discovered that the best corrosion resistance was obtained when the Fe2B was perpendicular to the corrosion interface. That is because the oriented Fe2B induces the formation of an interface-pinning multilayer. This discovery is considered a breakthrough, which has drawn interests of many researchers.

Wang et al. [81–83], Liu et al. [84], and Ma et al. [85] obtained the orientation of Fe2B by the directional solidification and discovered the existence of corrosion interface pinning effect in flowing liquid zinc.

Ma et al. [39] demonstrated the interface pinning effect. The oriented Fe2B and the intermetallic compound ζ-FeZn13, which were induced by epitaxial growth, could form a corrosion reaction film, shown in Fig. 9(a) [39]. According to analysis of the orientation relationship between Fe2B and ζ-FeZn13, which revealed (001)Fe2B/(-402)ζ, FeZn13 and (002)Fe2B/(110)ζ-FeZn13 orientations, shown in Fig. 9(b) [39], could effectively hinder the diffusion and infiltration of molten zinc, thus preventing further attacks. Ma et al. [39] further discovered that the strong pinning effect of the interface of directional solidification Fe-B alloys depends on the geometric constraints, volume expansion, and size effect, which was schematically represented in Fig. 10 [39]. The results of this research may provide a method to obtain a pinned interface by controlling boride.

3.3. The relation between boride morphology and corrosion resistant mechanism of Fe-B alloys in liquid zinc

The non-oriented and oriented boride morphology results in distinct corrosion morphology in liquid zinc. They are compared in Fig. 11 [86,39]. The corrosion interface of non-oriented Fe-3.5B alloy was formed by Fe-Zn compound and bulgy Fe2B. Some cracks were discovered in the corrosion layer, and they proliferated in the corrosion products close to the matrix, thus resulting in fractures of the Fe2B, shown in Fig. 11(a) [86]. The corrosion interface of vertical-oriented Fe-3.5B alloy was columnar corrosion products, which protruded a corrosion resistant Fe2B skeleton at the interface in which a pinning layer was formed, thus only minimal flaking occurred as Fe2B peeled off into the corrosion layer, shown in Fig. 11(b) [39]. However, many small granular corrosion products were found at the corrosion interface of the parallel-oriented Fe-3.5B alloy in which no Fe2B skeleton zone was discovered, shown in Fig. 11(c) [39]. The columnar Fe2B may spill off from the matrix layer by the layer upon corrosion of the iron matrix, which may lead to the premature failure and inadequate corrosion resistance of the Fe2B in molten zinc. Furthermore, more flakes
Fig. 8 – The set-up of directional solidification (DS) equipment of Fe-B alloy and corrosion manners of DS Fe-B alloy in liquid zinc [39]: (a) Device of DS; (b) Vertical sample with Fe$_2$B [002] orientation perpendicular to corrosion interface; (c) Parallel sample with Fe$_2$B [002] orientation parallel to corrosion interface.

Fig. 9 – (a) Interface morphologies of pinning zone for the vertical sample in liquid zinc [39]; (b) TEM micrograph of parallel dislocation in $\zeta$ and the SADP for $\zeta$/Fe$_2$B interface [39].

Fig. 10 – Schematic representation for verticality of [002] orientation to interface and lamellar spacing of Fe$_2$B as a function of the interface-pinning zone [39].

of Fe$_2$B became wrapped in the corrosion layer, as shown in Fig. 11(c) [39]. The corrosion mechanism of liquid zinc on non-oriented Fe-B alloy has been proposed by Ma et al. [86]. The corrosion process is governed by the diffusion of zinc atoms and the dissolution mechanism, which is the preferential dissolution of $\alpha$-Fe, the formation of intermetallic compounds, and the spalling of Fe$_2$B. Subsequently, the continuous net-like Fe$_2$B,
which acts as a barrier from the further reaction of Fe/liquid Zn, hampers the diffusion of zinc atoms between the substrate and molten zinc effectively [86]. The corrosion resistant mechanism of oriented Fe-B alloy is different from that of non-oriented Fe-B alloy. Ma et al. [39] studied the interfacial orientation-pinning effect existing in DS Fe-B alloy and corrosion resistant mechanism in liquid zinc. They discovered that the corrosion damage of the vertical-oriented Fe$_2$B in molten zinc was controlled by the competitive mechanisms of Fe$_2$B/FeB transformation and microcrack-spallation resistance, which was proposed as the result of a multiphase synergistic effect in the micro-structures [39].

Furthermore, the Fe-B alloys with interfacial orientation-pinning effect has been applied in flowing molten zinc [81–85]. The erosion-corrosion interfacial morphologies of non-oriented Fe$_2$B in Fe-B alloy was compared with that of oriented Fe$_2$B boride in flowing molten zinc [81]. It has been discovered that the network of Fe$_2$B in the non-oriented Fe-B alloy was broken down by the accelerated spallation and flaking due to the eroding by flowing molten zinc. However, the oriented Fe$_2$B in parallel and vertical samples failed via layer-by-layer spalling and corrosion with slight spallation, respectively. When Fe$_2$B was perpendicular to the erosion-corrosion interface, the strong pinning effect of the corrosion occurred, which strongly hampered the diffusion of molten zinc and hindered the spalling of Fe$_2$B. The erosion-corrosion mechanism scheme of Fe-B alloy with non-oriented and oriented Fe$_2$B boride in flowing molten zinc was illustrated in Fig. 12 [81].

4. Pure Fe$_2$B Intermetallic

In this study, Fe$_2$B phase plays an important role in Fe-B alloys, and thus enabling Fe-B alloys to have superior wear resistant or corrosion resistant property. It is essential to investigate pure bulk Fe$_2$B phase. Some methods were adopted to prepare the pure bulk Fe$_2$B [38,87,88]. Ma et al. [38] fabricated pure bulk Fe$_2$B with pure iron and Fe-19.55 wt.% B ferro-alloy by using vacuum medium frequency induction melting furnace. Huang et al. [87] fabricated pure bulk Fe$_2$B crystals with mixed Fe and B powders by using the method of mechanical ball milling and plasma activated sintering. The results showed that the fracture toughness of pure Fe$_2$B intermetallic was low (between 3.01 and 3.96 MPa m$^{1/2}$). Cr [89] or Mo [90] was added to improve the toughness of pure Fe$_2$B. Li et al. [88] studied the wear behavior of pure bulk Fe$_2$B/silicon nitride ceramic pair under dry sliding condition and discovered that the lubricating film, which consists of Fe$_2$O$_3$, B$_2$O$_3$, SiO$_2$, and H$_2$BO$_3$, reduced the friction coefficient. Li et al. [91] investigated tribological properties of bulk Fe$_2$B under dry friction and water lubrication. It was discovered that the friction coefficient under water lubrication was lower than that under dry friction. Ma et al. [38,92] studied the interface characteristics, corrosion behavior and crystal orientation on microstructure, properties and corrosion behavior of bulk Fe$_2$B intermetallic. It was discovered that unidirectional Fe$_2$B intermetallic with long axis perpendicular to the direction of liquid zinc corrosion displayed the best corrosion resistance to liquid zinc owing to its beneficial barrier effect. Moreover, Fe$_2$B/FeB phase transi-
tion occurred due to the gradient of chemical potential in the solid Fe$_2$B-liquid zinc system.

5. Summary and conclusions

Fe-B alloys, as a new kind of wear/corrosion resistant materials, can be controlled by the boride morphology, which is net-like, broken and oriented. Therefore, this paper reviews the research progress of Fe-B alloys by controlling the boride morphology in order to design wear resistant or corrosion resistant alloy. The conclusions have been drawn as follows:

(1) It is not satisfactory controlling the morphology of boride by heat treatment, rare earth modification and alloying, because these methods cannot completely eliminate the boride network along the grain boundaries. However, hot deformation is the most effective method used to break up boride network in Fe-B alloys.

(2) In two-body abrasion test, the wear resistance of Fe-B alloys with broken boride is lower than that of Fe-B alloys with net-like boride. However, in three-body abrasion test, the wear resistance of Fe-B alloys with broken boride is higher than that of Fe-B alloys with net-like boride.

(3) Fe-B alloys with vertical-oriented boride, which can originate the corrosion interface pinning effect, show a higher corrosion resistance than that with net-like boride in molten zinc.

(4) The corrosion resistant mechanism of the directional solidification Fe-B alloys with interfacial orientation-pinning effect is dominated by competitive mechanisms of Fe$_2$B/FeB transformation and microcrack-spallation resistance in molten zinc.

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