Interface characterization and erosion–corrosion behavior of directional Fe-3.5 wt.% B steel in flowing **liquid zinc at various temperatures**

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Abstract

The interface characterization and erosion–corrosion behavior of directional Fe-3.5 wt.% B steel in the flowing zinc at 460°C to 550°C were investigated. The result indicated that directional Fe-3.5 wt.% B steel possesses better erosion–corrosion resistance to liquid zinc with the [002] orientation of Fe₂B boride perpendicular to the erosion–corrosion interface. Liquid zinc temperature, Fe₂B orientation in steel, and micromechanical scour have a significant effect on erosion–corrosion interface structure, which in turn governs the corrosion behavior of the matrix by influencing the dissolution and diffusion process, erosion-enhanced corrosion, the Fe₂B boride failure mode, and further erosion–corrosion resistance.

Key words: A. Steel; A. Zinc; B. Erosion; B. SEM; C. Interfaces;

1. Introduction

It is acknowledged that molten zinc is one of the most aggressive melts **because of** its high affinity for oxygen and its ability to dissolve a **wide variety** of materials[1-4]. In the continuous hot dip galvanizing process, it is the principal problem in the erosion–corrosion of immersed equipment parts (e.g., sink, stabilizer rolls, and supporting bearings etc.)[5-7]. Generally, coatings obtained **by** high-temperature hot dip galvanizing possess beneficial surface characteristics, such as improved corrosion, wear and abrasion resistance compared with **those** obtained at 460°C, the conventional galvanizing temperature [8, 9]. However, the immersed bath equipment is subjected to more severe erosion–corrosion damage at high liquid zinc temperatures. **Compared with static corrosion, flowing liquid zinc erosion-corrosion, in which the mechanical process of material removal through erosion and the chemical process of corrosion are coupled, results in accelerated destruction of these parts [6, 10]. The elevated liquid zinc temperature facilitates the erosion–corrosion process because it increases the activation of liquid zinc and decreases liquid zinc viscosity [7, 11]. Moreover, the accelerated deterioration results in significant economic losses from maintenance and replacement of eroded parts.**

Recently, much attention has **been** paid to cast Fe-3.5 wt.% B steel **because of** its unique structure (two-phase microstructures with **a** Fe₂B erosion-resistant phase and **an** α -Fe matrix), which exhibits **good** properties, such as high hardness, good process performance, and good corrosion resistance to molten zinc[12-16]. The Fe-B steel containing 3.5 wt.% B therefore has great potential **for** manufacturing the **various** parts of galvanizing equipment.

Previous **studies have** indicated that material properties, such as plastic deformation and strength of metal, direction of intergranular crack propagation, oxidation dissolution, and corrosion behavior,

are strongly dependent on crystal orientation [17-22]. The reason for this is that the close-packed crystal planes have higher atomic coordination and binding energy, giving the materials superior properties. Ligenza reported that oxidation of silicon exhibits a strong orientation dependency in high-pressure steam. The silicon grains are denoted in ascending order of oxidation resistance as [110], [311], and [111] orientation [23]. Based on these research, it can be inferred that the orientation of Fe₂B boride in Fe-3.5 wt.% B steel may impact its erosion–corrosion resistance in flowing liquid zinc at 460°C to 550°C.

However, the effects of liquid zinc temperature on the erosion–corrosion behavior of directional Fe-3.5 wt.% B steel, which contains orientated erosion-resistant phase Fe₂B, are not clearly understood. For this reason, this study focuses on the effect of liquid zinc temperature on the damage behavior of the directional Fe-3.5 wt.% B steel in flowing liquid zinc. In addition, the effects of Fe₂B orientation on the erosion–corrosion behavior of Fe-3.5 wt.% B steel at 460°C to 550°C are discussed.

2. Materials and methods

2.1 Materials

The directional Fe-3.5 wt.% B steel under investigation was melted in a 10-kg capacity medium-frequency induction furnace. Fig. 1 shows a schematic representation of the equipment used to perform directional solidification of Fe-3.5 wt.% B steel. In the early stage, clean pure iron, Fe-19.80 wt.% B ferro-steel and steel scrap were added to the furnace, following which a little Al was added to slag-free molten steel to minimize oxidation loss and slag formation. The directional Fe-3.5 wt.% B steel was melted at 1550°C–1600 °C and then poured into sand molds at 1420°C–1450°C to solidify the desired microstructures.

The long axis of columnar Fe₂B boride in directional Fe-3.5 wt.% B steel eroded in flowing liquid zinc was either perpendicular to the erosion–corrosion interface (vertical sample) or parallel to the erosion–corrosion interface (parallel sample). In other words, two erosion–corrosion behaviors can occur between Fe₂B orientation and the erosion–corrosion interface of flowing liquid zinc, as shown in Figs. 2a and 2b. Fig. 2c shows how the vertical and parallel samples were cut from the directional ingot. The directional Y-type ingot was then cut into the desired erosion–corrosion specimens (vertical and parallel samples) with dimensions of 120 mm×15 mm×5mm by a wire electric discharge machine based on the modes shown in Fig.2c. The 316L stainless steel was selected as a standard sample. The chemical composition of Fe-3.5 wt.% B steel, as analyzed by a spark emission spectrometer, and of 316L stainless steel is given in Table I.

2.2 Erosion–corrosion test

Prior to the flowing liquid zinc erosion–corrosion test, the specimens were ground by 2000 mesh carborundum paper and washed with alcohol and acetone. The initial thickness between two sides face of the tested specimens was obtained from average value measured twelve times at multiple locations using a micrometer. A schematic of the erosion–corrosion tester is shown in Fig.3. To ensure that the iron in the liquid zinc was unsaturated, 30 kg pure zinc (99.99 wt. %) was melted (i.e., the volume of liquid zinc is about $4.6 \times 10^{-3} \text{ m}^3$) in the alumina crucible for each erosion–corrosion test, and a K-type thermocouple was immersed into the liquid zinc to monitor the temperature. The erosion–corrosion tests of vertical, parallel and standard samples were then carried out in flowing liquid zinc. A rotating disk speed of 60 rpm (i.e. $0.314 \text{ m} \cdot \text{s}^{-1}$) was used, based on the relative velocity of immersed parts surface and molten zinc in a continuous hot-dipping line[24]. The liquid zinc temperature varied from 460 to 550 °C in 30 °C interval. Then, the eroded specimens were removed

from liquid zinc and implanted in the resin. The thickness measurement of each erosion–corrosion specimen was measured microscopically at 1-mm-intervals across the cross-section according to Ref. [7, 25]. The following equation was used to estimate the erosion–corrosion rate of the tested steel.

$$R = \frac{a-b}{2t} \quad (1)$$

where R , a , b , t are the erosion–corrosion rate ($\mu\text{m}\cdot\text{h}^{-1}$), original thickness (μm), final thickness (μm), and the test time (h), respectively. The factor of 1/2 in Eq. (1) shows the average change in specimen thickness caused by erosion–corrosion of both faces of the specimen.

2.3 Characterization

The microstructures of the specimens were analyzed via using a scanning electron microscopy (SEM) (Tescan VEGA II XMU, Brno, Czech Republic), a secondary electron (SE), and a back-scattered electron image (BSE). The Energy Dispersive Spectrometer (EDS) was used to analyse compositions of erosion–corrosion layer. Phase analysis of the as-cast sample was undertaken by XRD in a MXP21VAHF diffractometer using copper $K\alpha$ radiation coupling continuous scanning in a 2θ ranging from 20° to 100° with current flow of 200 mA and electric voltage of 40 kV and scanning speed of $2^\circ/\text{min}$ and step space of 0.02° .

3. Results and discussion

3.1 As-cast microstructure

Fig.4 shows the SE morphologies of the directional Fe-3.5 wt.% B steel. From Fig.4a, it is **apparent** that the longitudinal section (i.e., parallel to the heat-squeeze direction) consists of α -Fe and columnar Fe_2B boride with **its** growth direction opposite to **the** heat-squeeze direction (as shown in Fig. 1). The columnar Fe_2B borides are directionally arranged, and the average distance **between**

adjacent columnar crystals of Fe_2B boride is $3.67\text{ }\mu\text{m}$ as measured by the method from Ref. [26, 27]. On the other hand, the transverse section (i.e., perpendicular to the heat-squeeze direction) displays rectangle-shaped Fe_2B boride and $\alpha\text{-Fe}$, and the grain size of Fe_2B boride is somewhat heterogeneous (as shown in Fig. 4b). Fig. 4c shows the X-ray diffraction patterns of the directional Fe-3.5 wt.% B steel. The cast microstructure of Fe-3.5 wt.% B steel is made up of $\alpha\text{-Fe}$ and eutectic Fe_2B boride, which are accurately indexed by JCPDS 65-4899 and 65-2693 respectively. A remarkably strong peak representing the (002) plane can be detected from the Fe_2B crystals in transverse section (JCPDS 36-1332). However, the (002) peak in the longitudinal section has evidently disappeared (Fig. 4c). This indicates that the Fe_2B boride in directional Fe-3.5 wt.% B steel displays an obviously textured structure and that its preferred growth direction is the [002] orientation, which is consistent with previous investigation results[28-30].

3.2 Erosion–corrosion properties of flowing liquid zinc

Fig.5 shows the erosion–corrosion rate as a function of liquid zinc temperature. The 316L stainless exhibits a higher erosion–corrosion rate than the directional Fe-3.5 wt.% B steel at the same temperature. This means that the directional Fe-3.5 wt.% B steel has better erosion–corrosion resistance to flowing liquid zinc. Moreover, the erosion–corrosion rates increase sharply with an increase in liquid zinc temperature, as shown in Fig.5. Obviously, the orientation of columnar Fe_2B boride in steel has a significant effect on the erosion–corrosion rate. The vertical sample shows a lower erosion–corrosion rate than the parallel sample under the same erosion–corrosion conditions, indicating that the directional Fe-3.5 wt.% B steel has better erosion–corrosion resistance to liquid zinc when the Fe_2B boride [002] orientation is perpendicular rather than parallel to the interface. This phenomenon arises from the different erosion–corrosion interfaces, which depend on the Fe_2B

orientation and liquid zinc temperature.

3.3 Erosion–corrosion interfaces of the directional Fe-3.5 wt.% B steel

The erosion–corrosion interface morphologies of directional Fe-3.5 wt.% B steel in flowing liquid zinc are shown in Fig.6 and 7. The columnar Fe₂B boride orientation and the liquid zinc temperature have a significant effect on the erosion–corrosion interface, thereby leading to the erosion–corrosion resistance discrepancy between the vertical and parallel samples at various temperatures.

Fig.6 shows the interface morphologies of the vertical sample in flowing liquid zinc at 460°C to 550°C. The liquid zinc temperature has a significantly influence on erosion–corrosion interface morphology (i.e., the morphology and distribution of corrosion products and the length of residual Fe₂B boride). Approximately 20-μm-thick columnar Fe₂B boride protrudes from the substrate at 460 °C, as shown in Fig.6a. The spaces between the residual Fe₂B boride are filled with corrosion products with a particular orientation. Moreover, the residual Fe₂B boride fragments gradually, as shown in the embedded image in Fig.6a, due to the significant stresses stemming from the formation of corrosion products[31, 32]. A strong pinning effect between the corrosion products and columnar Fe₂B boride occurs in the erosion–corrosion interface at 460 °C (Fig. 6a) and acts as a barrier to obstruct the diffusion of reactants (i.e., the iron and zinc atoms) and to suppress the corrosion reaction and buffer the micromechanical scour of the flowing liquid zinc[33]. The vertical sample has therefore a minute material loss at 460°C. With an increase in liquid zinc temperature, the length of the residual Fe₂B increases significantly, as shown in Figs. 6b, 6c, and 6d. The corrosion products between the columnar Fe₂B boride, however, decrease significantly under higher-temperature erosion–corrosion conditions. The increase in liquid zinc temperature aggravates the interface

corrosion reaction between the α -Fe matrix and the liquid zinc, resulting in more corrosion products. Previous studies reported that freshly generated corrosion products can quickly dissolve in the flowing liquid zinc bath at high liquid zinc temperature [34]. In addition, the micromechanical scour produced by the flowing zinc facilitates the removal of corrosion products. Therefore, the decreased corrosion products and the increased residual Fe₂B boride zone form an erosion–corrosion interface at high liquid zinc temperature, as shown in Figs. 6b, 6c and 6d. An increase in material loss from the vertical sample therefore occurs with increasing liquid zinc temperature.

Compared with the vertical sample, the parallel sample shows entirely different erosion–corrosion interface morphologies, as shown in Fig. 7. Significant amounts of tetragonally shaped corrosion products occupy the erosion–corrosion interface. With increasing in liquid zinc temperature, the amount of corrosion products increases sharply, but their size decreases significantly (Fig. 7). This phenomenon can be attributed to the synergy of micromechanical scour, an aggravated chemical corrosion reaction, and dissolution of corrosion products at high liquid zinc temperature. Moreover, unlike the vertical sample, severe spalling of columnar Fe₂B boride occurs in front of the erosion–corrosion interface in the parallel sample. From Figs. 7c and 7d, it is apparent that spalling of columnar Fe₂B boride is more significant at higher liquid zinc temperature due to the synergy of severe corrosion of the α -Fe matrix and micromechanical scour. In this case, the erosion–corrosion interface consists of three zones (inner corrosion products, middle exfoliated Fe₂B boride, and outer zinc zones), as shown in Figs. 7c and 7d. Based on Fig. 7, it can be inferred that the erosion–corrosion process for the parallel sample proceeds layer by layer (i.e., corrosion of the α -Fe matrix followed by spalling of columnar Fe₂B boride). The increase in liquid zinc temperature significantly facilitates the erosion–corrosion process (i.e., corrosion of the matrix and spalling of

columnar Fe₂B borides), thereby leading to the poor erosion–corrosion resistance of the parallel sample compared with the vertical sample.

According to Fig. 6, for the vertical sample eroded in flowing liquid zinc, the strong pinning effect between the oriented columnar Fe₂B borides and the corrosion products takes place at 460°C. This special interfacial structure impedes zinc atom diffusion and also mitigates micromechanical scour. With increasing liquid zinc temperature, the corrosion products dissolve quickly in the flowing liquid zinc bath. This pinning effect therefore disappears due to dissolution and removal of corrosion product at high liquid zinc temperatures, as shown in Figs. 6b, 6c and 6d. In addition, because the corrosion part of the erosion–corrosion process is thermally activated, corrosion of directional Fe-3.5 wt.% B in flowing zinc can be described, in general, by the Boltzmann equation; i.e.,

$$C = C_0 \exp\left(\frac{-Q}{kT}\right) \quad (3)$$

where C is the controlling factor of the process, such as diffusion coefficient and reaction rate, C_0 , Q , k , T are a constant, the activation energy, the Boltzmann constant, and temperature respectively. Examining Eq. 3 reveals that high liquid zinc temperature can accelerate this thermally activated process. In other words, the corrosion reactions between the α -Fe matrix and liquid zinc become worse at high liquid zinc temperatures compared to those at 460 °C and yield a much greater quantity of corrosion products. Micromechanical scour subsequently facilitates removal of these corrosion products, generating corrosion-enhanced erosion. In this case, the zinc atom diffusion into the α -Fe matrix becomes faster because the absence of corrosion products in the erosion-corrosion interface and the erosion caused by flowing liquid zinc. The corrosion reaction can be further facilitated by the micromechanical scour, i.e., the erosion-enhanced corrosion. As a result of fast chemical corrosion of the α -Fe matrix and the removal of corrosion products, few corrosion products and amounts of

columnar Fe_2B borides with a certain length exist in the erosion-corrosion interface, as shown in Figs .6b, 6c and 6d. Accordingly, the increase in liquid zinc temperature, the removal of corrosion products, and the accelerated zinc atom diffusion stemming from micromechanical scour significantly aggravate the corrosion reaction. In turn, the severe corrosion reaction yields many more corrosion products and facilitates erosion. Eventually, severe erosion-corrosion causes severe damage to the vertical sample at high liquid zinc temperature.

Similar to erosion of the vertical sample in flowing liquid zinc, for the parallel sample, micromechanical scour accelerates removal of corrosion products and the spalling of columnar Fe_2B boride. However, unlike the vertical sample, the columnar Fe_2B in the parallel sample spalls severely because it loses support from the α -Fe matrix due to corrosion by liquid zinc and micromechanical scour. To some extent, the residual Fe_2B borides located in the erosion-corrosion interface of the vertical sample still impede zinc atom diffusion. However, the barrier effect of the columnar Fe_2B borides in the parallel sample is extremely weak. This means that erosion-enhanced corrosion is more significant during the erosion-corrosion process in the parallel sample. As a result, the corrosion reaction becomes much more severe than in the vertical sample due to the synergy of erosion-enhanced corrosion and increased liquid zinc temperature. This yields many more corrosion products, removes the support of the α -Fe from the columnar Fe_2B , and results in a stronger erosion-corrosion process. In addition, the high liquid zinc temperature accelerates dissolution of corrosion products, thus leading to a decrease in corrosion product size with increasing liquid zinc temperature, as shown in Fig.7.

In summary, the increase in liquid zinc temperature and the Fe_2B orientation control the erosion-corrosion interface. In turn, this erosion-corrosion interface governs the further reactant

diffusion, the corrosion reaction between the α -Fe matrix and liquid zinc, the Fe_2B failure mode and further erosion-corrosion process.

3.4 EDS analysis of the erosion–corrosion interface

The phase compositions as measured by energy dispersive spectroscopy and illustrated in Fig. 6 and 7 are given in Table II. Compared with previous research results[31, 35], it was found that the main phases in the erosion–corrosion layer are Zn, FeZn_{10} , and FeZn_{13} . This indicates that the orientation of Fe_2B boride in directional Fe-3.5 wt.% B steel does not change the types of corrosion products. However, it is noteworthy that the main corrosion product with an increase in temperature is FeZn_{10} in the erosion–corrosion interface of the vertical sample, but FeZn_{13} in the parallel sample. In fact, the type of corrosion products in the corrosion interface depends on the concentration of iron and zinc atoms, which is determined by the erosion-corrosion interface structure [36, 37].

Fig 8 shows an EDS line analysis of the erosion–corrosion layer at 550°C. From Figs. 8a and 8b, it can be seen that the zinc content exhibits a significant and gradual concentration gradient (the Fe-Zn phase transformation zone) from the outer residual Fe_2B zone to the inner matrix zone. The zinc content in the erosion–corrosion layer of the parallel sample, however, shows a sudden decrease from the outer corrosion product zone to the inner matrix zone, as shown in Figs. 8c and 8d. The residual Fe_2B in the erosion–corrosion layer effectively impedes the zinc atom diffusion, leading to low zinc content adjacent to the substrate. This results that the corrosion product located in the erosion-corrosion interface of the vertical sample is mainly FeZn_{10} . The columnar Fe_2B boride in the parallel sample, however, spalls severely because the support of α -Fe the matrix has been lost due to corrosion by liquid zinc and micromechanical scour, as shown in Fig. 7. Zinc atoms diffuse quickly into the substrate, leading to high zinc content adjacent to substrate. Therefore, the corrosion product

in the erosion-corrosion layer of the parallel sample is mainly FeZn_{13} . Based on these analyses, the liquid zinc temperature, presence of oriented Fe_2B borides, and the micromechanical scour all control the erosion–corrosion interface, which in return impacts the zinc diffusion, determining the zinc content adjacent to the substrate and ultimately the types of corrosion products in the erosion-corrosion interface.

Fig. 9 shows the length variation of the residual Fe_2B and the erosion thickness loss of the vertical sample. The length of the residual Fe_2B boride increases significantly with increasing temperature. Specifically, the length of these Fe_2B boride can be as great as $522\text{ }\mu\text{m}$ at $550\text{ }^\circ\text{C}$, which is very close to the erosion thickness of the vertical sample. This indicates that the columnar Fe_2B borides spall only slightly. Moreover, the difference between erosion thickness and the length of residual Fe_2B borides decreases obviously with increasing temperature. As reported earlier, micromechanical scour of fluid is a function of fluid viscosity, and higher liquid zinc temperature results in a decline in liquid zinc viscosity [4, 11, 38]. This means that during the liquid zinc erosion–corrosion process, the increase in temperature weakens micromechanical scour, leading to slight spalling of residual columnar Fe_2B borides and significant amounts of the residual Fe_2B borides located in front of the erosion–corrosion interface. Because of the non-wetting characteristics between Fe_2B borides and liquid zinc, these residual protruding Fe_2B borides located in the erosion–corrosion layer obstruct zinc atom diffusion significantly and also buffer micromechanical scour. In this case, both erosion-enhanced corrosion and corrosion-enhanced erosion can be well mitigated. This is consistent with the minute material loss in the vertical sample compared with the parallel sample. The parallel sample, however, exhibits completely different erosion–corrosion behavior in flowing zinc. According to Fig. 7, the parallel sample shows a layer-by-layer failure

mechanism. The corrosion reaction between the α -Fe matrix and liquid zinc takes place first and results in the loss of the matrix supporting the columnar Fe_2B boride in front of erosion–corrosion interface. Some cracks may also be generated in the columnar Fe_2B borides. Micromechanical scour strongly facilitates crack growth and propagation. These phenomena accelerate spalling of the columnar Fe_2B borides, which have lost the support of the α -Fe matrix. Furthermore, increasing temperature promotes the corrosion reaction and crack propagation, which facilitates the layer-by-layer removal process (severe corrosion reaction and columnar Fe_2B borides spallation), as shown in Figs. 7c and 7d. As a result, stronger erosion-corrosion takes places in response to significant material loss from the parallel sample at higher bath temperature compared with the vertical sample.

3.5 Erosion–corrosion mechanism in directional Fe-3.5 wt.% B steel

Considering previous investigations of Fe-B steel and its boronizing layer (Fe_2B or $\text{Fe}_2\text{B}/\text{FeB}$ layers) corroded in static liquid zinc, corrosion processes are governed by multiple corrosion dissolution mechanisms, formation of Fe-Zn compounds, and spalling of borides[39-41]. Nevertheless, the interfacial characteristics and erosion–corrosion behavior of directional Fe-3.5 wt.% B steel eroded in flowing liquid zinc vary greatly with temperatures, which can be attributed to the synergistic effect of liquid zinc flowing velocity, liquid zinc temperature and Fe_2B boride orientation.

The schematic in Fig. 10 illustrates the erosion–corrosion mechanism of directional Fe-3.5 wt.% B steel in flowing liquid zinc at 460°C and 550 °C. It reveals that the orientation of columnar Fe_2B borides in this steel, micromechanical scour produced by flowing liquid zinc and an increase in liquid zinc temperature have a significant effect on the erosion-corrosion interface, which determines the erosion-corrosion behavior of this steel. Fig. 10a shows the erosion–corrosion mechanism of the

vertical sample in flowing liquid zinc. At 460°C, the strong pinning effect between the corrosion product and the columnar Fe₂B boride due to the expansion of the former and the extrusion effect of the latter significantly impedes the diffusion of zinc atoms into the matrix, suppresses the corrosion reaction, reduces spalling of the columnar Fe₂B boride, and resists micromechanical scour. The result is that the columnar Fe₂B borides in the vertical sample fail primarily through corrosion, with only slight spalling at 460°C. An increase in liquid zinc temperature together with micromechanical scour aggravates the corrosion reaction, yielding more corrosion products and accelerating corrosion product dissolution. Again, micromechanical scour facilitates removal of these corrosion products without complete dissolution. This removal modifies the erosion–corrosion interface (the pinning effect disappears, and few corrosion products and mass of residual Fe₂B borides are found in the interface). The residual Fe₂B borides located in the erosion–corrosion interface buffer micromechanical scour and retards zinc atom diffusion, thus affecting the corrosion reaction. In this case, matrix corrosion is the main factor causing material degradation of the vertical sample at higher liquid zinc temperature. The parallel sample, however, shows a completely different erosion–corrosion mechanism, as shown in Fig. 10b. The α-Fe matrix and Fe₂B boride are arranged in alternating layers, resulting in layer-by-layer spalling of the columnar Fe₂B boride. Furthermore, the corrosion reaction in the matrix between the columnar Fe₂B borides worsens due to increasing liquid zinc temperature and micromechanical scour. In this case, many of the columnar Fe₂B borides spall severely as shown in Fig.10b (T=550°C). Significant erosion–corrosion takes place (i.e., erosion significantly facilitates corrosion, and corrosion promotes the erosion) and corresponds to a large material loss from the parallel sample. Accordingly, the micromechanical scour, the liquid zinc temperature, and the Fe₂B boride orientation determine the erosion–corrosion interface structure,

which in turn governs the interfacial corrosion reaction, the fracture and spalling mode of the Fe_2B , and further erosion-corrosion.

4. Conclusion

This study has been carried out to investigate the interface characterization and erosion–corrosion behavior of directional Fe-3.5 wt.% B steel in flowing zinc at 460 °C to 550 °C. The present work supports the following conclusions:

- (1) Fe_2B boride orientation, liquid zinc temperature and micromechanical scour have a significant effect on the erosion–corrosion interface, which in turn governs the diffusion, the interfacial corrosion reaction, the fracture-spalling mode of the Fe_2B , and the erosion–corrosion resistance of the directional Fe-3.5 wt.% B steel.
- (2) An increase of liquid zinc temperature accelerates the corrosion products dissolution, and micromechanical scour facilitates corrosion product removal, leading to the loss of the “pinning effect” of corrosion products and of oriented Fe_2B boride and significant amounts of residual Fe_2B boride located in the erosion–corrosion interface of vertical sample.
- (3) Failure of oriented Fe_2B boride in the parallel sample takes place layer by layer. Increase both in liquid zinc temperature and in micromechanical scour significantly facilitate failure by worsening the corrosion reaction between the iron matrix and the liquid zinc.

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List of Table Captions

Table I Chemical composition of the investigated Fe-B steel and 316L stainless / wt. %

Table II The composition results of the phases measured by EDS analysis in Fig.6 and 7.

List of Figure Captions

Figure 1 Schematic device of directional solidified Fe-3.5 wt.% B steel (Solidification rate of about 17 °C measured by a thermocouple)

Figure 2 (a)-(b) The erosion–corrosion manners of directional Fe-3.5 wt.% B steel: (a) Parallel sample (i.e. preferred growth direction of Fe₂B parallel to erosion–corrosion interface); (b) Vertical sample (i.e. preferred growth direction of Fe₂B perpendicular to erosion–corrosion interface). (c) The cutting manners of the vertical and parallel samples from the directional ingot.

Figure 3 Schematic map of the erosion–corrosion testing device: 1-Rotation shaft; 2-Disk for controlling erosion angle; 3-Furnace; 4-Sample holder; 5-Crucible; 6-Test sample; 7-Liquid zinc.

Figure 4 (a)-(b) SE morphologies of the directional Fe-3.5 wt.% B steel: (a) longitudinal section of directional Fe-3.5 wt.% B steel (i.e. parallel to the heat-squeeze direction); (b) transverse section of directional Fe-3.5 wt.% B steel (i.e. perpendicular to the heat-squeeze direction). (c) X-ray diffraction patterns of the directional Fe-3.5 wt.% B steel.

Figure 5 Erosion–corrosion rates as a function of liquid zinc temperature.

Figure 6 Interfacial morphologies of the vertical sample in flowing liquid zinc at various bath temperatures: (a) 460 °C; (b) 490 °C; (c) 520 °C; (d) 550 °C.

Figure 7 Interfacial morphologies of the parallel sample in flowing liquid zinc at various bath temperatures: (a) 460 °C; (b) 490 °C; (c) 520 °C; (d) 550 °C.

Figure 8 EDS line analysis of erosion–corrosion layer at 550 °C: (a) BEI of the vertical sample; (b) Compositional profile measured by EDS along line segment AB in Fig. 8a; (c) BEI of the Parallel sample; (d) Compositional profile along line segment CD in Fig. 8c.

Figure 9 The variation of extruding Fe_2B and the erosion thickness loss of vertical sample vs liquid zinc temperature

Figure 10 The erosion–corrosion mechanism of directional Fe-3.5 wt.% B steel in flowing liquid zinc at 460°C and 550 °C: (a) vertical sample; (b) parallel sample.

Table I Chemical composition of the investigated Fe-B alloy and 316L stainless / wt.%

Elements	B	C	Mn	P	Si	Cr	Ni	Fe
Fe-B	3.49	0.19	-	-	0.60	0.82	-	Bal.
316L	-	0.024	1.191	0.0371	0.59	17.09	10.41	Bal.

Table II The composition results of the phases measured by EDS analysis in Fig.6 and 7

Number	Fe		Zn		Phase
	wt. %	at. %	wt. %	at. %	
1	6.02	6.98	93.98	93.02	δ -FeZn ₁₃
2	1.91	2.23	98.09	97.77	η -Zn
3	8.68	10.01	91.32	89.99	δ -FeZn ₁₀
4	9.86	11.35	90.14	88.65	ϵ -FeZn ₁₀
5	5.46	6.33	94.54	93.67	δ -FeZn ₁₃
6	5.86	6.79	94.14	93.21	δ -FeZn ₁₃
7	6.60	7.64	93.40	92.36	δ -FeZn ₁₃

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

a .

b.

c.

d.

Figure 7

a.

b.

c.

d.

Figure 8

a.

b.

c.

d.

Figure 9

Figure 10