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Effect of chromium content on the erosion-corrosion behavior of Fe-Cr alloy produced by ball milling liner in weakly alkaline slurry

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Abstract

Fe-Cr alloys with different chromium contents have been designed in the current study for the ball mill liner working in weakly alkaline slurry. The structure, mechanical properties, corrosion behavior and erosion-corrosion behavior of the alloys were investigated. The result shows that with the increasing Cr content, the hardness and corrosion resistance of the alloy are improved. However, the impact toughness of the alloy shows a decreasing trend with the increase of Cr content. The alloy with the Cr content of 6.978 wt% exhibits the best erosion-corrosion resistance among all alloys in the weakly alkaline slurry. Further analysis shows that the erosion-corrosion mass loss of these alloys in weakly alkaline slurry mainly results from pure mechanical erosion and the interaction between corrosion and erosion. The damage process has also been discussed by interaction models of corrosion and erosion. The result is beneficial to provide reference for selection and development of erosion-corrosion resistant material for ball mill liner working in weakly alkaline medium.

1. Introduction

Mill liner used in mineral industry suffers heavy damage, especially under wet grinding condition. The damage is ascribed to the impact erosion from grinding balls and mineral stones, as well as the continuous corrosion from the corrosive slurry\[1–4]. It is reported that the service life of mill liner is usually less than a year\[5, 6\]. Researches show that the combined action of corrosion and impact erosion contributes to a mutual interaction beyond the individual contributions of the two processes. As a result, the mass loss rate for the same material working in certain corrosive media may be quite more than that in dry condition\[7–10\]. How to effectively alleviate the damage from the interaction between corrosion and erosion in wet grinding condition has become an urgent problem to be solved.

Alloying is an effective way to improve the erosion-corrosion resistance of ball mill liner used steel. Traditional method focused mainly on the adjustment of mechanical properties such as hardness, strength and toughness of materials\[11–16\]. However, researches show that attentions should be paid more to the improvement of corrosion resistance of materials especially under corrosive condition. It is commonly believed that the formation of passive film or high-quality corrosion scale on the surface effectively increases the corrosion resistance of materials. Wang\textsuperscript{et al.}\[17\] pointed out that the oxides in the passive film such as Cr$_2$O$_3$ maintained a more stable condition with the increase of Cr content in Fe-Cr alloy steel and the corrosion resistance of Fe-Cr alloy was further improved. Xu\textsuperscript{et al.}\[18\] studied the corrosion behavior of alloy steel under the circumstances of CO$_2$. The result showed that alloys with low Cr content were of spontaneous passivation and the passive film with Cr(OH)$_3$ could decrease the corrosion rate only when the Cr content was more than or equal to 3\% (mass fraction). It is generally accepted that passive film is considered to be the first defense of material to corrosion and erosion-corrosion\[19–22\]. Sasaki and Burstein\[23\] have observed the threshold
impact energy which was described to be the minimum kinetic energy required for the particles in slurry to rupture the passive oxide film on alloy surface. Therefore, it is possible to improve the erosion-corrosion resistance of material by forming a dense passive film \[24, 25\].

Although the increase of Cr content may contribute to the better corrosion resistance of alloys, the performance of alloys in wet milling condition is still ambiguous. The change of mechanical properties due to the increase of Cr content affects the impact erosion resistance of alloys to some extent. Therefore, it is really interesting to study the effect of Cr content on the erosion-corrosion behavior of alloys in corrosive slurry.

In this work, several Fe-Cr alloys have been designed for the ball mill liner working in weakly alkaline slurry with Ti-magnetite. To work under wet grinding condition, the alloys used for ball mill liners were considered to be phase structures with high hardness, toughness and corrosion resistance \[11, 26, 27\]. Efremenko et al \[28\] studied the effect of microstructure and chemical components on the impact erosion behavior of Fe-based alloy, and pointed out that the martensite microstructure showed the best anti-corrosion and erosion resistance. Therefore, the alloys in the current work were adjusted to martensite. The erosion-corrosion behavior of alloys under simulated condition has been investigated by a modified dynamic-load erosion tester. Electrochemical method has been used to analyze the corrosion behavior of alloys under impact erosion. Furthermore, the interaction between corrosion and erosion of all alloys has also been discussed. The work is beneficial to clarify the erosion-corrosion mechanism of steel in the wet milling condition, as well as to provide reference for selection and development of new erosion-corrosion resistant material for ball milling liner used in weakly alkaline medium.

2. Materials and methods

2.1. Materials, structure and mechanical properties tests

Materials used in the experiment were the medium-carbon Fe-Cr alloys. The detailed chemical composition was determined by optical spark emission spectrometry over three times and is given in table 1. The key element Cr has also been determined by a more accurate method, inductively coupled plasma-optical emission spectroscopy (ICP-OES). The alloys are marked as ‘S1’, ‘S2’, ‘S3’ and ‘S4’ depending on the chromium content, respectively. All alloys were cast from an intermediate frequency furnace and followed by annealing at 1100 °C, oil quenching and tempering at 250 °C.

Metallographic specimens were polished by abrasive papers. After polishing down to a diamond finish of 1.5 μm, all specimens were etched using a mixed solution with 1 wt% picric acid (C₆H₃N₃O₇), 5 wt% hydrochloric acid (HCl) and alcohol (CH₃CH₂OH). Microstructure of the specimens was detected by Leica DMI 3000 M optical metallographic microscope.

The impact test was conducted at room temperature using a JBN500 impact tester. Hardness of specimen was carried out on a HR-150A Rockwell hardness tester. The final result was an average value from five tests. Other tests were repeated at least three times to ensure the reproducibility.

2.2. Electrochemical measurements

To simulate the real working condition of mill liner, the corrosive medium was composed of Ti-Magnetite and deionized water. The main compositions of the Ti-Magnetite are (weight percentage): TiFe-35.1%, Al₂O₃-7.86%, TiO₂-7.74%, CaO-14.71%, MgO-13.68%, SiO₂-17.45% and small amount of Mn/S. The weight percent of solid reached 65%, and the pH value of the mixed solution measured by PH500 Meter is ranged from 8.6 to 8.8.

Electrochemical measurements were conducted using a multichannel electrochemical workstation CS354. Before the tests, samples were ground with 240, 400, 600 and 1000 grid abrasive papers in sequence, degreased in alcohol, washed in distilled water and dried in air. The traditional three-electrode system comprising a standard saturated calomel reference electrode (SCE), a platinum counter electrode and the working electrode was applied. Standard saturated calomel electrode was connected to the cell via a Luggin probe. The open circuit potential test which lasted up to 160 h was carried out to evaluate the corrosion behavior of the alloys in the

| Table 1. Chemical composition of the Fe-Cr alloys (weight percentage/%). |
|-----------------|-----|-----|-----|-----|-----|-----|
| Alloys          | C   | Si  | Mn  | Cr  | P, S| Fe  |
| S1              | 0.263 ± 0.018 | 0.673 ± 0.021 | 0.565 ± 0.034 | 2.168 ± 0.142 | <0.04 | Bal. |
| S2              | 0.261 ± 0.013 | 0.676 ± 0.014 | 0.581 ± 0.015 | 4.645 ± 0.237 | <0.04 | Bal. |
| S3              | 0.266 ± 0.022 | 0.668 ± 0.006 | 0.574 ± 0.026 | 6.978 ± 0.132 | <0.04 | Bal. |
| S4              | 0.263 ± 0.011 | 0.655 ± 0.035 | 0.557 ± 0.023 | 10.161 ± 0.276 | <0.04 | Bal. |
simulated corrosive medium. Potentiodynamic polarization was swept from $-1.2$ to $1.4$ V\textsubscript{SCE} (relative to SCE) with the scanning rate of $0.5$ mV s\textsuperscript{-1}. At least two replicate tests were carried out to determine the experimental errors.

### 2.3. Erosion-corrosion tests

A modified MLD-10 dynamic-load erosion tester was used to investigate the erosion-corrosion behavior of the designed Fe-Cr alloys in weakly alkaline Ti-magnetite slurry. In order to point out the effect of impact and erosion on the corrosion behavior of alloys, electrochemical measurement under impact erosion has been realized on this tester. Figure 1 shows the schematic diagram of the tester. The upper specimen made of high Cr cast iron with the compositions of (weight percentage): C–3.5%, Cr–18%, Mn–1.0%, Si–1.0%, P, S < 0.05% and Fe bal., works as the grinding balls in ball mill. The lower specimen made of the Fe-Cr alloy which acts as the working electrode rotates along with the spindle. The structure diagrams of upper sample and lower sample are shown in figure 2. A hole is machined on the lower sample to connect with a copper wire for electrochemical test. Electrical signals produced by corrosion are sent to copper rings through the wire in the keyway of the principal axis and then received by the electrochemical workstation CS354 through carbon brush.

Before the test, all samples were ground to 1000 grid abrasive papers, cleaned in alcohol by ultrasonic vibration for 5 min and dried in air before weighted using an analytical balance with an accuracy of $0.1$ mg. During the erosion-corrosion tests, the impact frequency of the upper sample was set at 100 times min$^{-1}$ and the rotate speed of the lower sample was $200$ r min$^{-1}$. After tests for 30 min, the samples were cleaned, dried and weighted. The average of five mass losses of a sample was used to calculate the mass loss rate. Scanning electron microscope (SEM) JXA-8100 was used to observe the morphology features of the samples after erosion-corrosion.
3. Results

3.1. Microstructure and mechanical properties

The microstructure of Fe-Cr alloys is shown in figure 3. Combined with the results from other researches, it is known that during the heat treatment at 1100 °C, the phase in all alloys is mainly austenite [29–31]. After quenching, it is reasonable to detect that the main structures of all the alloys are lath martensite and retained austenite. The sizes of martensite in the samples S2 and S3 are relatively finer. It is also obvious that carbides formed in the alloys, especially when the Cr content reaches 10.161% (S4). It is well known that during the tempering of steels alloyed with carbide-forming elements (e.g. Cr and Mn et al), cementite can form with partitioning of these alloying elements and the interlath film like retained austenite decomposes into cementite (θ-Fe₃C) [32, 33].

Figure 4 shows the curves of Rockwell hardness and impact toughness of Fe-Cr alloys. The hardness of the alloy shows an increasing trend with the increase of Cr content and reaches the maximum 50.5 HRC when the Cr content of material is 10.2%. There are two possible reasons for the increasing hardness. The first reason is that element chromium is a medium-strong carbide forming element. Carbides with high hardness were easily formed in high chromium alloy as seen in figure 3(d). The other possible reason is that element chromium delays
the transformation of supercooled austenite to martensite and improves the hardenability. In the process of quenching, the critical cooling speed of martensite decreased and the harden-ability of material was improved. As a result, the amount of residual austenite decreased and more martensites formed. Therefore, the hardness of the alloy increases with the increasing Cr content.

Different from the increasing hardness, the impact toughness of the alloy shows a decreasing trend with the increase of Cr content. The maximum value of the impact toughness is 85.5 J·cm$^{-2}$ when the Cr content is 2.2% (S1). However, the impact toughness decreases to only 31 J·cm$^{-2}$ when the Cr content increases to 10.161% (S4). The decreasing impact toughness is mainly related to the following reasons. First, more carbide precipitated with the increase of Cr content. The increasing amount of phase boundaries between carbides and martensite might be the propagation path of cracks during the transformation of alloys. Second, as stated above, the amount of residual austenite decreased and more martensites formed with more Cr content. It is known that austenite contributes much to the toughening of steel compared with martensite. Therefore, the impact toughness decreased with the increasing Cr content. The result shows that, although excessive addition of Cr element can increase the hardness of the alloy effectively, the impact toughness is getting worse. Both the hardness and impact toughness need to be taken into account when the alloy services under the condition of impact-erosion in corrosive medium.

### 3.2. Open circuit potential

Figure 5 shows the open circuit potential curves of alloys in the simulated corrosive slurry during 160 h of immersion. It is seen that the changes of the open circuit potentials for the four materials are similar. Three stages can be distinguished in the long-term immersion. In the first stage, the potential shows a rapid decline. This is usually due to the dissolution of the oxide film formed on alloys in the air. After immersion for about 10 h, corrosion scale or passive film starts to form on the alloy, resulting in the increase of open circuit potential. As time goes on, the potential tends to be stable. In this stage, the formation and the dissolution of surface film reaches a state of dynamic balance. When the immersion time reaches 160 h, the open circuit potentials of alloys S1, S2, S3, and S4 are $-545$ mV, $-514$ mV, $-334$ mV, and $-281$ mV, respectively. In general, the potential is the result of a conjugation reaction occurs on the surface of metal and reflects the stability of thermodynamics. Generally speaking, for an ideal system, the higher potential suggests that the thermodynamics is more stable. For the material covered with passive film or corrosion scale, higher potential also means a better corrosion resistance. Therefore, the increase of Cr content is conducive to improving the thermodynamics stability of the alloy in the current corrosive slurry.

In order to study the effect of erosion on the corrosion behavior of the alloys, the open circuit potential was also detected when the alloys were subjected to the dynamic erosion condition in the simulated slurry. Due to the strong mechanical effect, electrochemical behavior of the surface is complicated. The open circuit potential curves show apparent dynamic property under this condition as shown in figure 6. Overall, the open circuit potentials are more negative compared to the potentials under static condition. The average potentials of the alloys S1, S2, S3 and S4 under erosion are $-620$, $-590$, $-417$ and $-391$ mV, respectively. Among the four alloys, the dynamic open circuit potential of alloy S4 drops the most dramatically by about 110 mV, compared with the static open circuit potential. There are several possible reasons for the negative shift of open circuit potential.
under impact erosion. First, the corrosion scale or passive film which can protect the alloy from serious corrosion is destroyed by the impact erosion of the corrosive slurry. The strong fluctuation of open circuit potential under dynamic impact condition reflects the processes of formation and destruction of surface film [34]. Second, the surface of the alloy is rougher and more complicated after mechanical damage, increasing the corrosion tendency of materials. Besides, the movement of corrosive ions toward the alloy is accelerated by the stir of slurry, promoting the corrosion behavior.

3.3. Potentiodynamic polarization
Figure 7 is the potentiodynamic polarization curves of all alloys in the static simulated slurry. It is clear that the cathodic processes of the four alloys are relatively similar to one another, while the anodic processes are quite different. For the alloy S1 with the Cr content of only 2.168%, active dissolution occurs on the surface. When the content of Cr reaches 4.645%, a small passive region is detected in the polarization curve of alloy S2. With the increase of Cr content in the alloy, the passive region is expanded and the passive current density decreases. Pitting potential also increases much in the alloy with high Cr content. In conclusion, the corrosion resistance of alloy is obviously improved by the increase of Cr content. Furthermore, the alloy S4 shows a spontaneous passive behavior in the simulated slurry when the Cr content reaches 10.161%. The corrosion potential ($E_{corr}$) and corrosion current density ($i_{corr}$) were further calculated from the potentiodynamic polarization curves by the software C-View to compare the corrosion resistance of all alloys and the result is showed in table 2. It is quite clear that the corrosion current density decreases with the increasing Cr content and the alloy S4 exhibits the best corrosion resistance among the alloys. Moreover, the passive film on the surface of S4 is of high quality. The pitting corrosion resistance is also excellent for its high pitting potential. It is concluded that the increase of Cr content promote the forming of a stable passive film and increase the corrosion resistance of this kind of alloy much.

3.4. Erosion-corrosion behavior of the alloys in weakly alkaline slurry
Erosion-corrosion behavior can be affected by many factors such as mechanics, electrochemistry and environmental parameters. The mass loss of materials resulted from erosion-corrosion cannot be simply viewed as the linear superposition of mass losses caused by pure erosion and pure corrosion. The mutual promotion of
erosion and corrosion obviously accelerates the mass loss of the metal \[35\]. It is generally considered that the total mass loss rate of the material \(W_t\) is the sum of pure erosion component \(W_w\), pure corrosion component \(W_c\) and the interaction between the two components \(\Delta W\) as the following formula \[36, 37\]:

\[
W_t = W_w + W_c + \Delta W
\]  

(1)

In the current work, the mass loss of the alloy before and after the erosion-corrosion test in the simulated slurry was measured. The mass loss rate was further calculated and regarded as the total mass loss rate of the material \(W_t\). As described above, corrosion current densities of all alloys in the static slurry were measured from potentiodynamic tests. The mass loss rate due to pure corrosion \(W_c\) can be calculated according to Faraday’s law as follows (2):

\[
W_c = \frac{M}{nF}i_{corr}
\]  

(2)

Where \(F\) is the Faraday constant \(96500 \text{ C mol}^{-1}\), \(M\) is the atomic weight of Fe, and \(n\) is the valency.

In order to remove the effect of corrosion on the mass loss, cathodic protection has been applied to measure the pure erosion mass loss rate of all alloys. The cathodic protection potential was calculated by formula (3) with self-corrosion potential \(E_{corr}\) and anode Tafel slope \(B_a\), which were acquired from the potentiodynamic test. Figure 8 shows the surface morphology of the alloy after erosion-corrosion under the condition of cathodic protection. It is clear that the cutting furrow topography on the surface is mainly caused by stress and it is hard to observe any damages due to corrosion. Therefore, the potential for cathodic protection in this work is accepted.

\[
E_{pi} \cong E_{corr} - 4.605B_a
\]  

(3)

Figure 9 shows the mass loss rates of the alloys in the simulated corrosive slurry due to the effects of pure corrosion, pure erosion and erosion-corrosion, respectively. It is obvious that the mass loss rate due to the effect of corrosion is really insignificant compared with the total mass loss rate. The alloy with the most Cr content shows the least mass loss rate due to the effect of corrosion. It is unexpected to find that the alloy S4 which is the hardest does not show the least mass loss rate due to the effect of pure erosion, indicating that hardness is not the only index for the design of alloys used in the impact erosion condition. The total mass loss rate of the alloy decreases with the Cr content first and increases after the Cr content is beyond 6.978%, similar with the mass loss rate due to pure erosion.

In order to further analyse the interaction between corrosion and erosion, the mass loss rate due to the interaction \(\Delta W\) was calculated from formula (1). Table 3 presents the mass loss percentage of each effect for

![Figure 7. Potentiodynamic polarization curves of alloys with different Cr contents in the static simulated slurry.](image-url)

**Table 2.** Corrosion potential and corrosion current density for alloys with different Cr contents in simulated slurry.

| Condition | S1  | S2  | S3  | S4  |
|-----------|-----|-----|-----|-----|
| \(E_{corr}\) (mV) | -545 | -514 | -334 | -281 |
| \(i_{corr}\) (A cm\(^{-2}\)) | \(1.07 \times 10^{-3}\) | \(0.91 \times 10^{-5}\) | \(0.73 \times 10^{-5}\) | \(0.28 \times 10^{-5}\) |
the four alloys in the simulated slurry. Generally speaking, pure erosion occupies the largest proportion for the total damage which indicates that mechanical effect of simulated slurry is the main factor for the erosion-corrosion behavior. It is also noticed that the interaction between corrosion and erosion contributes much to the damage of alloy under this kind of condition. Although the damage from corrosion seems insignificant, the improvement of corrosion resistance by adding more Cr elements can decrease the effect of interaction to some extent, and the erosion resistance of alloy is supposed to be more important for the high corrosion resistant alloy. In the current condition, erosion resistance of the alloy should be considered first.
3.5. Erosion-corrosion morphology observation

Figure 10 shows the morphologies of the four alloys after erosion-corrosion. It is seen that the damages on the S1 and S2 are quite different from that on the S3 and S4. Corrosion pits and layered delamination are the typical damage morphologies on the S1 and S2. The corrosion surface of S2 is observed to be tougher with few cutting furrows and peeling pits. Clear layered delamination can also be detected, together with many tiny corrosion pits at the bottom with the feature of corrosion peeling. However, no big corrosion pits have been discovered on the surfaces of S3 and S4, which indicates that the corrosion resistance has been improved by the addition of Cr. Besides, layered delamination is also hardly found on the damaged surface of high Cr alloys. The alloy S3 keeps a comparatively complete surface with little transformation and less wide cutting furrows. Corrosion is mainly centered in plastic deformation area. Obviously, cracks are observed on the surface of alloy S4, which is related to the high hardness and low impact toughness of the material. Corrosion medium seeps into the crack and accelerates the corrosion along the direction of crack expansion. When the mechanical property of the material has been weakened, partial corrosion peeling occurs with the synergistic action of corrosion and erosion. This is the key reason for the unexpected low erosion-corrosion resistance for S4.

4. Discussion

Erosion-corrosion is affected by many factors especially the mechanical properties, chemistry and electrochemistry of material. Two possible erosion-corrosion models of the current Fe-Cr alloy are inferred as described in figure 11.

For the alloy with low Cr content, no passive film forms on the surface. When the alloy is impacted and cut by the slurry, the surface is susceptible to plastic deformation as shown in figure 11(a). Moreover, the abrasive particle with proper shape and direction impacts the surface of the alloy and is further embedded into the alloy. Furrow occurs and the excess material is extruded. As a result, the plastic bulge area is formed on the material surface [38]. Due to different electrochemical features between the un-deformation area and the plastic deformation area on the material surface, ‘strain differences corrode cells’ is formed [39, 40]. Because of a high physical and chemical activity, flanks of the furrow lose electron easily and become anode. Corrosion reaction occurs preferentially on the furrow. In this process, erosion plays an accelerating effect on corrosion. Meanwhile, the enhanced corrosion weakens the mechanical properties of the plastic deformation area, which will be removed easily in the later action of erosion-corrosion. Thus, the interaction between erosion and corrosion is built and the alloy is damaged.

The element Cr is one of the unstable elements in thermodynamics. A dense passive film can easily form on the alloy with sufficient Cr. The passive film formed on the alloys in this weak alkaline solution detected by x-ray
photoelectronic spectroscopy (XPS) in our former research mainly contains chromic oxide and chromic hydroxide [41]. In the current work, for the alloy with high Cr, passivation is considered in the process of erosion-corrosion as shown in figure 11(b). Under the impact erosion, passive film is removed by the slurry and the active surface is exposed freshly to the impact and cutting from abrasive. However, the exposed fresh surface is quickly passivated in the corrosive medium, and remains good resistance to corrosion. The addition of high Cr element brings two other important changes to the alloy. One is the formation of carbides in the alloy as shown in figure 4(d), the other is the decrease of impact toughness. The formation of the carbides with high hardness plays a key role in the improvement of erosion resistance at the beginning of erosion-corrosion [42]. As the passive film has been removed mechanically, the exposed activated surface generates a larger potential difference with the cathodic phase carbides owing to its less Cr content, and then the interphase electrochemical reaction occurs [43]. The interphase corrosion weakens the interface between alloy and carbide. As a result, the carbides are easily peeled off under the further impact erosion, reducing the erosion resistance of alloy. Besides, the decreasing impact toughness increases the fracture possibility of alloy under impact erosion as shown in figure 10(d). The crack propagation will further accelerate the corrosion and erosion damage both. This explains why the alloy with the highest Cr content does not show the best erosion-corrosion resistance.

5. Conclusions

(1) The main structures of the Fe-Cr alloy are lath martensite and retained austenite after heat treatment. The hardness of the alloy shows an increasing trend with the increase of Cr content and reaches the maximum 50.5 HRC when the Cr content of material is 10.161%. While the impact toughness of the alloy shows a decreasing trend with the increase of Cr content.

(2) Corrosion behavior of the alloy changes from active dissolution to spontaneous passivation in the simulated corrosive slurry when the Cr content varies from 2.168% to 10.161%. The corrosion resistance of the alloy is improved obviously by adding more Cr.

(3) The mass loss rate of alloys with different Cr contents under the erosion-corrosion from the simulated slurry decreases first and then increases with the increasing Cr content. The alloy with the Cr content of 6.978% exhibits the best erosion-corrosion resistance in the current condition. The alloy with excessive chromium is prone to cracking under impact erosion, which accelerates the expansion of the crack under the action of corrosion and the peeling of the alloy, resulting in the high mass loss rate.

(4) The main damages of the four alloys under erosion-corrosion of the simulated slurry are caused by the effect of pure erosion and the interaction of corrosion and erosion. Two different erosion-corrosion mechanisms have been discovered for the alloys with different Cr contents.
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References

[1] Ige O O, Aribio S, Obadale B A, Langa T and Olubambi P A 2017 Tribol. Int. 109 441–6
[2] Gawlik J, Schmid J, Nowak T, Wójcicki Z and Zagórski A 2017 Arch. Civ. Mech. Eng. 17 926–34
[3] Holmberg K, Kiviirtyo-Reponen P, Härkisaari P, Valtonen K and Erdemir A 2017 Tribol. Int. 115 116
[4] Xiao X, Ye S, Yin W and Xue Q 2012 J. Iron. Steel. Res. Int. 19 13–9
[5] Natarajan K A 1996 Int. J. Miner. Process 66 285–13
[6] Peng Y, Ni X, Zhu Z, Yu Z, Yin Z, Li T, Liu S, Zhao L and Xu J 2017 Tribol. Int. 115 506–17
[7] Qiao Y, Tian Z, Cai X, Chen J, Wang Y, Song Q and Li H 2019 Tribol. Lett. 67 1
[8] Stack M M 1999 Wear 233 484–96
[9] Wood R K J 2017 Wear 376–377 893–910
[10] Deuis R L, Subramanian C and Yellup J M 1998 Wear 214 112–30
[11] Chenje T W, Simbi D J and Navara E 2004 Mater. Des. 25 11–8
[12] Shi Z, Wang Z, Wang J, Qiao Y, Chen H, Xiong T and Zheng Y 2019 Acta Metall. Sin. (Engl. Lett.) 33 415–424
[13] Gates J D, Dargusch M S, Walsh J J, Field S L, Hermand M J P, Delaup B G and Saad J R 2008 Wear 265 865–70
[14] Shaeri M H, Saghaefian H and Sabestari S G 2010 J. Iron. Steel. Res. Int. 17 53–8
[15] Rendón J and Olsson M 2009 Wear 267 2055–61
[16] Chenje T W, Simbi D J and Navara E 2003 Miner. Eng. 16 1387–90
[17] Wang Y, Li C and Lin Y 2017 Acta Metall. Sin. 53 622–30
[18] Xu L, Wang B, Zhu J, Li W and Zheng Z 2016 Appl. Surf. Sci. 379 39–46
[19] Qiao Y X, Cai X, Chen Y P, Cui J, Tang Y B, Li H B and Jiang Z H 2017 Mater. Technol. 51 933–8
[20] Hu X and Neville A 2005 Wear 258 641–8
[21] Lu B T, Luo J L, Guo H X and Mao L 2011 Corros. Sci. 53 432–40
[22] Dalbert V, Mary N, Normand B, Verdu C, Douillard T and Saedlou S 2018 Wear 420–421 245–56
[23] Sasaki K and Burstein G T 2000 Phil. Mag. Lett. 80 489–93
[24] Zheng Z B and Zheng Y G 2016 Corros. Sci. 112 657–68
[25] Huttenen-Saarivirta E, Kilpi L, Hakala T J, Carpen L and Ronkainen H 2016 Tribol. Int. 95 358–71
[26] Du X, Ding H, Wu K and Wang K 2007 J. Mater. Eng. Perform 16 746–51
[27] Iwasaki I, Pozzo R, Natarajan K, Adam K and Orlich J 1988 Int. J. Miner. Process 22 345–60
[28] Efremenko V G, Shimizu K, Noguchi T, Efremenko A V and Chabak Y G 2013 Wear 305 135–65
[29] Benz R, Elliott J F and Chipman J 1974 Metall. Trans. 5 2235–40
[30] Khvan A V, Hallstedt B and Broeckmann C 2014 Calphad 46 24–33
[31] Anderson J O 1988 Metall. Trans. A 19 627–36
[32] Wu Y X, Sun W W and Styles M J 2018 Acta Metall. 159 209–24
[33] Malheiro L R C, Rodriguez E A P and Arlazarov A 2017 Mat. Sci. Eng. A 706 38–47
[34] Zheng Z B and Zheng Y G 2016 Corros. Sci. 102 239–68
[35] Mischler S 2008 Tribol. Int. 41 573–83
[36] Watson S W, Friedersdorf F J, Madsen B W and Cramer S D 1995 Wear 181 476–84
[37] Zhang T C, Jiang X, Li S Z and Lu X C 1994 Corros. Sci. 36 1953–62
[38] Du X, Wang J, Sun G and Man D 2008 Mat. Sci. Eng. A-Struct. 477 277–81
[39] Iwasaki I, Riemer S C, Orlich J N and Natarajan K A 1985 Wear 103 253–67
[40] Gangopadhyay A K and Moore J J 1985 Wear 104 49–64
[41] Chen S Q, Wang H Y, Song D F and Zheng K H 2017 Materials Protection 50 73–6
[42] Wang H W and Stack M M 2000 J. Mater. Sci. 35 5263–73
[43] Zhang A F, Xing J D, Fang L and Su Y J 2004 Wear 257 198–204