Postprint: Abrasive Wear Behavior of Lower Bainite Ductile Iron in Corrosive Media

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Abstract

The corrosion-abrasion wear behavior of lower bainitic ductile iron materials was investigated through corrosion-abrasion wear tests, and the main factors influencing the corrosion-abrasion weight loss rate were analyzed. SEM and TEM were employed to analyze the characteristics of the worn surfaces; the strain hardening effect of the material surface layer during the corrosion-abrasion process was investigated based on the microhardness of the longitudinal section of the worn surface layer; the influence of load on corrosion resistance was studied in conjunction with the electrochemical behavior of lower bainitic ductile iron. The results indicate that the corrosion-abrasion mechanism of lower bainitic ductile iron involves chemical corrosion weight loss and plowing abrasive wear. Increasing the load exerts a significant influence on surface roughness, the friction force between the material surface and abrasive particles, and the depth of abrasive particle penetration into the material surface, thereby causing a significant increase in the abrasive wear weight loss rate; moreover, under higher loads, lamellar structures and banded graphite appear on the material surface, forming local micro-galvanic cells that accelerate the corrosion rate, while fatigue fracture of the lamellar structures also contributes to further increases in the weight loss rate; however, the increase in load leads to the formation of numerous dislocation tangles within the retained austenite in the matrix, promoting surface hardening of the material and thereby enhancing its wear resistance to a certain extent. When the load increased from 10 N to 200 N, the corrosion-abrasion weight loss rate increased from 0.16 $\mathrm{g/(cm^2 \cdot h)}$ to 0.42 $\mathrm{g/(cm^2 \cdot h)}$; when the surface roughness Ra value increased from 0.12 μm to 5.2 μm, the corrosion current rose from 0.56 mA to 5.62 mA. Additionally, the corrosion-abrasion weight loss curve of lower bainitic ductile iron can be divided into three stages: the point-contact accelerated wear stage in the initial wear period, the surface-contact steady wear stage in the middle wear period, and the fatigue wear instability stage in the final wear period.

Full Text

Abrasive Wear Behavior of Lower Bainite Ductile Iron in Corrosive Media

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Abstract

The corrosion-abrasive wear behavior of lower bainite ductile iron was investigated through corrosion-abrasive wear experiments, analyzing the main factors influencing the mass loss rate. SEM and TEM were employed to characterize worn surface features. The strain-hardening effects in the subsurface layer during corrosion-abrasive wear were examined via microhardness profiles of the worn surface cross-section. The influence of load on corrosion resistance was studied in conjunction with the electrochemical behavior of lower bainite ductile iron. Results demonstrate that the primary corrosion-wear mechanism involves both chemical corrosion mass loss and furrow-type abrasive wear. Increasing load significantly affects surface roughness, friction between the material surface and abrasive particles, and the depth of abrasive particle penetration, leading to a sharp rise in abrasive wear mass loss rate. Under higher loads, delamination structures and ribbon-like graphite appear on the material surface, forming localized micro-galvanic cells that accelerate corrosion rates. Simultaneously, fatigue fracture of delamination structures further increases mass loss. However, increased load also generates extensive dislocation tangles within retained austenite in the matrix, promoting surface hardening and thereby improving wear resistance to some extent. As load increases from 10 N to 200 N, the corrosion-abrasive mass loss rate rises from 0.16 g/(cm^2 · h) to 0.42 g/(cm^2 · h). When surface roughness Ra increases from 0.12 m to 5.20 m, corrosion current increases from 0.56 mA/cm^2 to 5.62 mA/cm^2. The mass loss curve for lower bainite ductile iron can be divided into three stages: an initial point-contact accelerated wear stage, an intermediate surface-contact excessive wear stage, and a final fatigue wear stage.

KEY WORDS lower bainite ductile iron; corrosion-abrasive wear; electrochemical behavior; galvanic corrosion; mass loss rate

Introduction

Ductile iron, developed in the 1950s, is a high-strength cast iron material that has found widespread applications in automotive manufacturing, agricultural machinery, railways, construction, and military equipment, particularly for components requiring high wear resistance such as gears and shafts. The emergence of bainitic ductile iron has further enhanced the comprehensive mechanical properties of ductile iron, providing higher ductility, fracture toughness, and fatigue strength. To date, researchers worldwide have conducted extensive studies on bainite, classifying it into upper bainite and lower bainite based on different transformation temperature ranges. Studies have shown that upper bainite transformation is based on the migration of low-coherency ferrite/austenite grain boundaries, whereas lower bainite transformation occurs through near-diffusionless processes while maintaining original coherency at grain boundaries.

With the application of ductile iron in wear-resistant fields, its wear behavior has been thoroughly investigated. Abedi et al. found that austempered ductile iron exhibits three wear mechanisms during abrasive wear: oxidative wear, adhesive wear, and delamination fracture. Slatter et al. studied the impact wear behavior of low-carbon steel and lamellar graphite cast iron, confirming that surface deformation has a positive effect on wear resistance, with lamellar graphite cast iron showing more significant improvement than low-carbon steel. Zhou et al. investigated the corrosion-wear mechanisms of martensitic ductile iron with different alloy compositions in corrosive environments of varying pH, concluding that corrosion-wear resistance improves with increasing pH of the slurry medium and additions of Cu, Ni, and Cr. Efremenko et al. examined the effects of microstructure and chemical composition on impact-abrasive-corrosion wear performance of iron-based alloys, noting that corrosion-wear resistance is influenced by both corrosion resistance and deformation resistance, with martensite-austenite microstructures exhibiting the best performance for corrosive-wear applications. Lü Zhenlin studied the corrosion-wear characteristics of martensitic ductile iron, finding it superior to low-chromium white cast iron under both static three-body abrasive wear and static three-body corrosive wear conditions, with appropriate Si content enhancement improving corrosion-wear resistance, particularly in acidic slurries.

Although numerous studies have been conducted on ductile iron with various microstructures, comprehensive and in-depth investigations of the corrosion-abrasive wear mechanisms in lower bainite ductile iron remain limited. This work examines the corrosion-wear behavior of lower bainite ductile iron, focusing on the main factors affecting corrosion-wear mass loss rate. SEM and XRD were used to analyze worn surface characteristics. The strain-hardening effects in the surface layer during corrosion-wear were studied through microhardness measurements of worn surface cross-sections. The influence of corrosion-wear load on material corrosion-wear resistance was investigated in conjunction with the electrochemical behavior of lower bainite ductile iron, aiming to provide a thorough understanding of its corrosion-wear behavior and explore its potential applications.

Experimental Procedures

The experimental material was bainitic ductile iron with the following chemical composition (mass fraction, %): C 3.3–3.7, Si 4.5–5.6, Mn 3.0–3.5, $P < 0.1$, $S < 0.04$, Mg 0.04–0.055, RE 0.02–0.045, Mo 0.015, and Fe balance. The molten iron was heated to 1500 °C using a ZG-0.01 vacuum medium-frequency induction furnace. A ladle injection method was employed to add 2.2% (mass fraction) of rare earth silicon-magnesium nodularizer (QRMg8RE3) and 1.6% ferrosilicon inoculant (FeSi72). Secondary inoculation with 0.4% addition was performed during pouring to increase graphite nucleation sites, improve nodularity, and refine graphite nodules. To refine the cast structure, metal molds were coated with a mixture of NaOH and KOH, which accelerated cooling and optimized the hereditary microstructure of the grinding balls. The castings were then heated to 860 °C, held for 2 h, continuously cooled to room temperature using a saturated solution of sodium nitrate and sodium nitrite, and finally tempered at 250 °C for 2 h before air cooling. The resulting microstructure consisted of spheroidal graphite, lower bainite, and retained austenite, as shown in [Figure 1: see original paper].

Corrosion-abrasive wear tests were conducted using a custom-designed abrasive wear tester, schematically illustrated in [Figure 2: see original paper]. The abrasive medium consisted of Al O with Mohs hardness 9H. The corrosive solution was a Cl environment at pH 4 (HCl concentration 1×10 mol/L, NaCl concentration 0.1 mol/L). To ensure a stable corrosive environment, drain and inlet valves were used to replace the corrosive solution every 5 min without stopping the test (manual online operation). Specimens measured 60 mm in diameter and 20 mm in length, fixed with a clamp and rotated by an AC motor at 300 r/min. Load was applied via dead weights, with data measured by a pressure sensor and transmitted to a display. Test loads of 10, 50, 100, 150, and 200 N were selected, with a test duration of 1 h. Specimens were removed every 10 min to measure mass loss using an SE602F electronic balance with 0.01 g precision.

To further investigate the effect of surface roughness on corrosion behavior, electrochemical tests were performed on lower bainite ductile iron specimens with different surface finishes. Polarization curves were measured using a VMP3 multi-channel electrochemical workstation. Specimen surfaces measured 10 mm × 10 mm and were ground with SiC abrasive papers of 60, 200, 800, and 2000 grit, yielding measured surface roughness Ra values of 5.20, 1.60, 0.28, and 0.12 m, respectively. All specimens were connected as working electrodes in a three-electrode system, with Pt foil as the counter electrode and a saturated calomel electrode as the reference electrode. The specimen exposure area was 1 cm^2. The corrosive medium contained HCl at 1×10 mol/L and NaCl at 0.1 mol/L. Tests were conducted at 25 °C with electrode potential scanned from -1000 mV to -100 mV. Electrochemical corrosion behavior was evaluated through anodic potentiodynamic polarization curves to determine corrosion potential and corrosion current.

Worn surface microstructures were analyzed using a Leica DMR optical microscope (OM), an EVO18 scanning electron microscope (SEM), and a JEOL-2010 transmission electron microscope (TEM). Microhardness of the worn surface layer was measured using an HVS-1000 microhardness tester.

Results

2.1 Surface Morphology of Corrosion-Wear Layer

Corrosion-wear experiments effectively simulate material wear behavior in actual corrosive environments and reveal microstructural evolution in the surface layer during corrosion-wear processes. [Figure 3: see original paper] shows the corroded surface morphologies of lower bainite ductile iron under various loads. Due to point contact between specimens and abrasive particles, worn surfaces exhibit numerous parallel furrows. As load increases, furrow depth gradually increases and surface roughness rises sharply. Notably, at 10 N, the worn surface shows only minor furrows without apparent corrosion features [Figure 3a: see original paper]. At 50 N, small pits appear from graphite nodule detachment [Figure 3b: see original paper]. With further load increase, pit density increases and fine needle-like lower bainite matrix features become visible, indicating accelerated chemical corrosion at loads above 100 N [FIGURE:3c and d]. At 200 N, graphite nodules are nearly completely removed, revealing a clearer needle-like lower bainite matrix morphology [Figure 3e: see original paper]. These observations suggest that at lower loads, furrow-type abrasive wear dominates over corrosion, causing corrosion features to be removed by cutting action before they can be retained. At higher loads, corrosion rate increases significantly, and extensive graphite nodule detachment further contributes to material loss.

[Figure 4: see original paper] presents cross-sectional morphologies under different loads, with arrows indicating friction direction (FD). The worn surface layer undergoes plastic deformation due to metal flow under frictional stress, with deformation magnitude increasing with load. Graphite nodules also deform with the matrix [FIGURE:4a and b]. At loads exceeding 100 N, originally spherical graphite becomes severely deformed, distributing as ribbons along the metal flow direction [FIGURE:4c–e]. When ribbon graphite extends to the worn surface, delamination occurs in the surface layer.

2.2 Surface Layer Hardness

To systematically characterize the corrosion-wear surface layer, microhardness measurements were conducted, with results shown in [Figure 5: see original paper]. The as-heat-treated lower bainite ductile iron exhibits a microhardness of 645 HV. After corrosion-wear testing, a low-hardness surface region forms due to corrosive medium attack. However, microhardness gradually increases with distance from the worn surface, eventually exceeding the original 645 HV. The low-hardness zone shrinks while the hardened zone expands with increasing load. Under 10 N, the low-hardness thickness is 140 m with minimal hardened zone depth. Under 200 N, the low-hardness zone reduces to 15 m while the hardened zone depth reaches 1585 m [Figure 5a: see original paper]. Maximum microhardness values increase with load, reaching 716 HV at 200 N [Figure 5b: see original paper].

2.3 Corrosion-Wear Mass Loss Rate

[Figure 6a: see original paper] shows cumulative mass loss curves for lower bainite ductile iron under various loads. During initial wear, mass loss rates are high, exceeding 0.50 g/(cm^2 · h) for all specimens, with 0.92 g/(cm^2 · h) at 200 N. After the initial period, mass loss rates decrease and enter a transitional stage. With continued loading, mass loss rates increase significantly above the second stage before stabilizing, marking the onset of steady-state wear. [Figure 6b: see original paper] illustrates the three stages of mass loss rate evolution under 200 N. As shown in [Figure 6a: see original paper], steady-state mass loss rates increase from 0.19 g/(cm^2 · h) at 10 N to 0.41 g/(cm^2 · h) at 200 N.

2.4 Polarization Curves

Corrosion current is a critical parameter characterizing corrosion resistance in corrosive media and estimating corrosion mass loss rates. Higher corrosion currents correspond to greater corrosion mass loss and mass loss rates. Polarization curves were measured for lower bainite ductile iron specimens with different surface roughness values in a corrosive medium containing HCl at 1×10 mol/L and NaCl at 0.1 mol/L, as shown in [Figure 7: see original paper]. Corrosion potential (Ecorr) and corrosion current (Icorr) were determined using Tafel extrapolation [18], with results summarized in . While corrosion potentials remain essentially constant across different roughness values, corrosion current increases dramatically with surface roughness, reaching 5.62 mA/cm^2 at Ra = 5.20 m. As shown in [Figure 8: see original paper], corrosion current Icorr is proportional to surface roughness Ra, with linear fitting yielding the relationship:

$$\mathrm{Icorr} = 0.471 + 0.977\mathrm{Ra}$$

Discussion

3.1 Effect of Load on Abrasive Wear Mass Loss Rate

Load significantly influences the abrasive wear of lower bainite ductile iron. Increased load substantially raises friction between material and abrasive particles and deepens abrasive penetration, causing extensive graphite detachment from the matrix and increasing abrasive wear mass loss rate. Additionally, delamination structure formation in the surface layer markedly affects mass loss rate. Research indicates that under surface tensile stress, microcracks first initiate at graphite-matrix interfaces and propagate along them. Most matrix cracks extend along bainitic ferrite-austenite interfaces, with differently oriented matrix structures causing crack deflection or branching, while main cracks continuously encounter graphite-matrix interface cracking ahead of their tips [19,20]. Furthermore, delamination structures on worn surfaces undergo fatigue after repeated deformation [21,22]. Consequently, internal microcracks initiate and propagate to the surface, causing entire delamination layers to spall off and significantly increasing mass loss rate.

However, increased microhardness in the subsurface layer somewhat improves wear resistance. Lower bainite ductile iron matrix contains small amounts of retained austenite. During plastic deformation, increasing external stress induces dislocation multiplication and tangles or martensitic transformation within retained austenite [23]. Retained austenite near bainite can continuously absorb dislocations from surrounding bainite, reducing average dislocation density in bainite while increasing it in austenite. [Figure 9: see original paper] shows high-dislocation-density austenite adjacent to low-dislocation-density lower bainite after corrosion-wear testing. Consequently, bainite does not undergo work hardening, enabling high plastic deformation compatibility between bainite and retained austenite [24]. Additionally, studies [8] have shown that when steel contains appropriate amounts of austenite with coherent or semi-coherent interfaces between austenite and bainite or martensite, retained austenite can enhance the toughness of bainite-martensite steels.

3.2 Effect of Load on Corrosion Mass Loss Rate

Load affects corrosion rate through three mechanisms. First, increasing load generates numerous furrows and delamination structures that enlarge the contact area between material and corrosive medium, thereby increasing corrosion mass loss rate. Second, in corrosive media, delamination structures and ribbon graphite form corrosion micro-cells. When spherical graphite deforms into ribbons parallel to delamination structures, the electrode potential difference between graphite (higher potential) and Fe matrix (approximately -0.44 V) drives galvanic corrosion [25]. In H -containing corrosive media, ribbon graphite acts as the cathode where reduction reactions occur, while delamination structures serve as the anode undergoing oxidation [Figure 10: see original paper], intensifying localized galvanic corrosion and increasing corrosion rate. Third, increasing load raises surface roughness [Figure 11: see original paper], which significantly increases corrosion current. At Ra = 5.20 m, corrosion current reaches 5.62 mA/cm^2, demonstrating that load markedly affects corrosion resistance during abrasive wear testing. Higher loads increase worn surface roughness and corrosion current, leading to increased corrosion mass loss rate.

3.3 Analysis of Corrosion-Wear Mass Loss Rate

The corrosion-wear mass loss curve reveals three distinct stages. During initial wear, high mass loss rates occur because polished specimen surfaces primarily experience point contact with abrasive particles. With material hardness to abrasive hardness ratio $Hm/Ha < 1$, abrasive edges rapidly penetrate the surface and generate numerous furrows through rapid relative motion [26]. After this initial period, mass loss rates stabilize as specimen surfaces establish stable contact with abrasive particles, entering a periodic wear cycle where chemical and electrochemical reactions generate surface products that are subsequently removed by abrasion, exposing fresh surfaces for continued corrosion and wear. This transitional stage shows lower mass loss rates than the initial stage.

In the third stage, mass loss rates increase significantly above the second stage due to accumulated plastic deformation during prolonged wear. Surface layer metal flows along the friction direction, forming delamination structures and ribbon graphite. Spalling of entire delamination layers constitutes a major factor for increased mass loss rate. Additionally, delamination structures and surface-reaching ribbon graphite create numerous localized micro-galvanic cells in the corrosive medium, further accelerating corrosion rates. Therefore, significantly increased galvanic corrosion rates also contribute to higher mass loss rates in this stage. Furthermore, [Figure 6a: see original paper] shows that mass loss rates increase noticeably with load due to enhanced friction and deeper abrasive penetration. Higher loads also shorten the transitional wear stage and accelerate the onset of steady-state wear by increasing subsurface plastic deformation and surface fatigue effects.

Conclusions

1. Surface roughness significantly affects electrochemical behavior. In corrosive media containing HCl at 1×10   mol/L and NaCl at 0.1 mol/L, corrosion current is proportional to surface roughness, reaching 5.62 mA/cm² at Ra = 5.20 m.

2. The corrosion-wear mechanism of lower bainite ductile iron involves both corrosion-induced mass loss (chemical and galvanic corrosion) and abrasive wear dominated by parallel furrows.

3. The corrosion-wear mass loss curve exhibits three stages: initial point-contact wear, intermediate surface-contact excessive wear, and final fatigue wear.

4. Increased load significantly raises friction and abrasive penetration depth while causing fatigue spalling of delamination structures, leading to substantially higher abrasive wear mass loss rates. However, load-induced dislocation tangles in retained austenite increase surface hardness, providing some improvement in wear resistance.

5. Higher loads increase surface roughness and corrosion current, degrading corrosion resistance. The formation of delamination structures and ribbon graphite creates localized micro-galvanic cells that accelerate corrosion rates.

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