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Microstructure and mechanical properties of Hadfield steel matrix composite reinforced with oriented high-chromium cast iron bars

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Abstract To obtain a compatible material of high hardness and high toughness, Hadfield steel matrix was reinforced by oriented high-chromium cast iron bars. The mechanical behaviors of the as-cast and water-quenched composites were comparatively studied with a Hadfield steel substrate. The experimental results showed that the alloy powders inside the flux-cored welding wires could be melted by the heat capacity of Hadfield steel melt and became high-chromium cast iron bars. The impact toughness of the water-quenched composite was higher than that of the as-cast composite and lower than that of the Hadfield steel. The wear rate of the water-quenched composite was 1.23 mg/h m^2 at 0.3 kg and 2.93 mg/h m^2 at 1.2 kg, which was lower compared with those of the as-cast composite and Hadfield steel. The impact toughness and wear resistance of the water-quenched composite were related not only to the combining actions of the Hadfield steel matrix and high-chromium cast iron bars but also to the effect of heat treatment. The wear behavior of the water-quenched composite was industrially tested as pulverizer plate.

Introduction

Traditionally, Hadfield steel is a well-known wear-resistant alloy containing austenite phase in its structure. Due to the combination of high strain hardening, excellent toughness, and high-stress abrasive wear resistance, it has been widely applied in various fields, including in excavators, mineral crushing and milling equipments, and railroad rail [1]. Also, martensitic wear-resistant cast steel with a high carbon content is intensively being used because of its high hardness and wear resistance compared to the Hadfield austenitic steel [2]. However, most of martensitic wear-resistant cast steels are not cost-effective even though they exhibit better properties. Nevertheless, the shortcomings of the Hadfield austenitic steel have been a main focus of several research works in the recent past [3–6], but the most promising results have not been fully achieved so far, particularly in terms of wear resistance.

Cast iron is a low-cost engineering material that has a wide range of industrial applications, including pipes, machine, and automotive industry parts owing to its castability, excellent machinability, and abrasive and erosive resistance [7]. These properties are usually resulted from its unique microstructure consisting of an austenitic dendrite/martensitic matrix and a high volume fraction of hard carbides. The use of conventional techniques for this iron alloy leads to impact strength, ductility, and fatigue resistance. One of the strategies employed to improve the mechanical properties of this alloy is microstructural control of eutectic carbides. However, studies of the morphological modification and carbide distribution based on conventional foundry techniques could not solve this limitation completely [8]. The production of compatible austenitic steel with high hardness and high toughness simultaneously is a challenging topic. Therefore, the purpose of the present work is to manufacture the Hadfield steel matrix composite having high hardness and high toughness by reinforcement with oriented high-chromium cast iron bars. The microstructure and mechanical properties of the as-cast and water-quenched Hadfield steel matrix composites were comparatively investigated with Hadfield steel as reference.

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Experimental

Preparation

As starting materials, high-chromium alloy powder (mean particle size was 150–200 μm), steel bands ($h = 0.25$ mm and $l = 15$ mm), and Hadfield steel were selected. Their chemical compositions (in wt%) are listed in Table 1. The Hadfield steel matrix composites were prepared according to the following procedure: first, the flux-cored welding wires with a diameter of 3.2 mm were produced using high-chromium alloy powder and steel bands, as shown in Fig. 1a. The flux-cored welding wires were then processed into a preform with a specified shape (Fig. 1b), which was inserted into the meshes of a net providing uniform distribution of reinforcement during processing. A series of the flux-cored welding wires were arranged in parallel, and the obtained precursor (Fig. 1c) was then dried at 150 °C for 2 h. The sand mould was prepared using quartz sand with a sodium silicate binder, and its size was slightly larger than that of the precursor. The sand mould was also dried at 400 °C for 2 h. After deoxidation and removal of slag, the Hadfield steel melt was poured into the sand mould at 1500 ± 10 °C, and then the flux-cored welding wires-based precursor was immediately inserted into the melt using a steel plate beneath a load. After 24 h, the as-cast samples were taken out of the sand mould. Some of the as-cast samples were subjected to heat treatment at 1050 °C for 2 h, and finally specimens were water quenched. Further comparative investigation was carried out using the three specimens: as-cast, water-quenched, and Hadfield steel.

Characterization

A high stress three-body abrasive wear test was carried out on a self-made tester. All the samples were machined to the shape with an inversion trapezoidal cross-section (Fig. 2a) and horizontally rotated with a speed of 60 rpm against counter-face under different applied loads for 30 min. The counter-face was made of M2 tool steel (HV = 820) and covered with quartz sand (mean particle size was 40 μm) with the thickness of 0.1–0.2 mm as an abrasive layer (Fig. 2b). The wear test was repeated at least three times for each sample, and wear rates were calculated by dividing the weight loss by the period and the wear area. The weight losses of the test samples were measured on an electronic balance with an accuracy of 0.001 g.

The hardness and impact toughness tests were performed on a Tukon 2100B Vickers/Knoop Hardness Tester (Wilson Instrument, Norwood, MA) and a JB-30A impact toughness tester, respectively. The sizes of V-shaped samples were 10 × 10 × 55 mm. The metallographic specimens were first ground using a 80-1200 grit SiC paper and polished using a 1 and 6 μm diamond paste. Afterwards, the polished specimens were etched with a 2% Nital solution. The microstructures of the samples were examined using a Vega II LMU scanning electron microscope (Tescan, Brno, Czech Republic) equipped with an energy dispersive X-ray spectrometry (EDS). X-ray diffraction (XRD) data were recorded on a PW 1730 X-ray diffractometer (Philips, The Netherlands) with monochromated CuKα radiation at 40 kV and 40 mA.

Table 1 Chemical compositions of the starting materials

Material	Chemical composition (wt%)						
	C	Cr	Si	Mn	P	S	Fe
High-chromium alloy powder	2.70	27.21	1.44	0.12	0.028	0.016	Bal.
Steel band	0.10	–	0.21	0.30	<0.04	<0.04	Bal.
Hadfield steel	1.12	–	0.81	12.91	<0.04	<0.04	Bal.

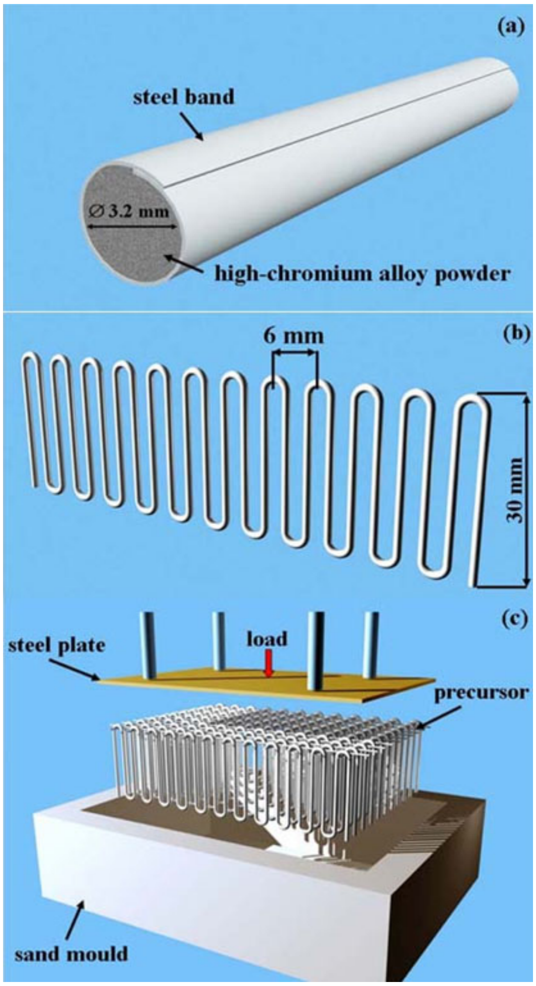


Fig. 1 Schematic illustrations of the flux-cored welding wires (**a**), preform (**b**), and fabrication process (**c**)

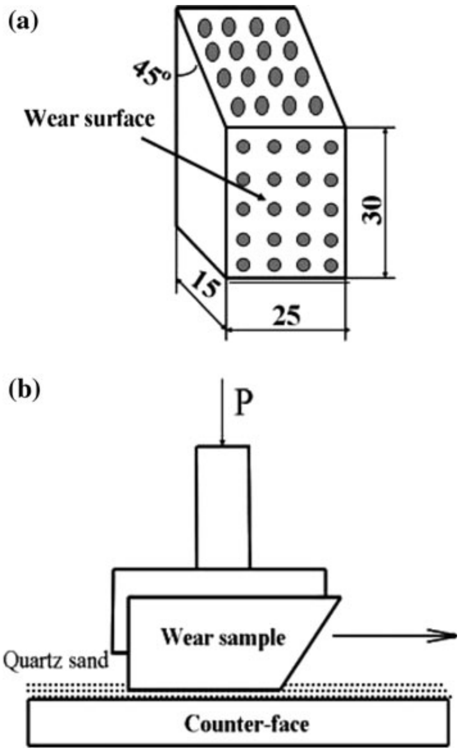


Fig. 2 Geometry of the sample (**a**) and schematic representation of three-body wear test (**b**)

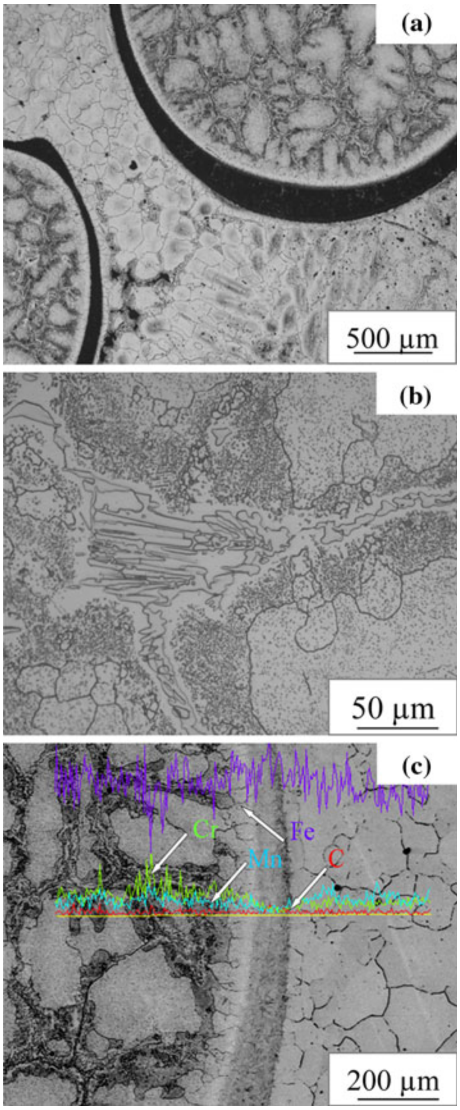


Fig. 3 SEM morphologies of the water-quenched Hadfield steel matrix composite reinforced with oriented high-chromium cast iron bars (**a**), high-chromium cast iron bar (**b**), and interface scanning analysis (**c**)

Results and discussion

Microstructure

Figure 3a shows the SEM micrograph of the water-quenched Hadfield steel matrix composite reinforced with oriented high-chromium cast iron bars. As can be seen, alloy powders inside the flux-cored welding wires were melted by the heat of Hadfield steel melt and transformed into high-chromium cast iron bars by tightly joining to the matrix; their center distances are 6 mm in the horizontal and 4 mm in the vertical directions. The microstructure of the reinforcement phase within the composite is shown in Fig. 3b. It is a typical microstructure of high-chromium cast iron bars structured with proeutectic austenite dendrites and interconnected eutectic cells composed of carbides [$(Fe,Cr)_7C_3$], and austenite [9]. After the composite was water quenched, no cracks could be found between the high-chromium cast iron bars and steel bands as well as between the steel bands and the Hadfield steel matrix. Figure 3c shows SEM micrograph of the diffusion layers between the Hadfield steel matrix and high-chromium cast iron bars. It indicates that the thickness of the two diffusion layers is in the range of about 10–20 μm. The results of EDS analysis obtained from the interface area of the matrix and cast iron bars reveals the presence of four elements: carbon; chromium; manganese; and iron, indicating the metallurgical bonding, which is essential in improving mechanical properties of the Hadfield steel matrix composite. In order to confirm the reinforcement phases present in the composite, X-ray diffraction analysis was performed. As can be seen from Fig. 4, austenite and $(Fe,Cr)_7C_3$ carbides are predominant phases in the reinforcement bar of the water-quenched composite. This is the evidence that the retained austenite in the reinforcing cores provides higher work hardening that leads further to an increase in hardness of the composite. Surface hardening can also be the result of work hardening by the multiplication and entanglement of dislocations, repetitive twinning, and both ε and α' martensite formation [10].

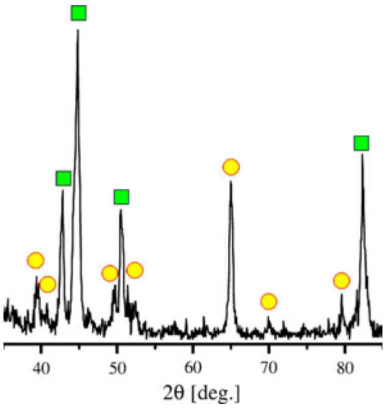


Fig. 4 XRD pattern of the reinforcement bar of the water-quenched composite. *Key*: *filled square* austenite and *filled circle* $(Fe,Cr)_7C_3$

Microhardness

Figure 5 displays the microhardness values of the water-quenched sample measured across the transition region from the center of the reinforcement bar to the matrix. It is visible in the micrograph (Fig. 5a) that the diagonal lengths of the indents change according to the phase exist in the area. Figure 5b shows that the microhardness of the matrix is about 302 kgf/mm^2 (dotted area), further increases to 633 kgf/mm^2 in the transformation area (dotted-dashed area), and ultimately reaches 1233 kgf/mm^2 in the center of the reinforcement bar (dashed area) with a fluctuation due to the simultaneous presence of austenite and $(Fe,Cr)_7C_3$ carbides, which possess slightly different microhardness values compared to each other. The higher hardness was achieved by the presence of a large number of $(Fe,Cr)_7C_3$ carbides in the center of the reinforcement bars. The exact mechanism for the formation of the high-chromium cast iron bars remains unclear. We can speculate on the basis of the obtained results in the present work. When precursor was inserted into the Hadfield steel melt, high-chromium flux-cored welding wires could be instantaneously converted into the high-chromium cast iron hypoeutectic melt by the heat effect of Hadfield steel melt. A hypoeutectic solidification formed the $(Fe,Cr)_7C_3$ carbides as eutectic phase (a mixture of $(Fe,Cr)_7C_3$ and austenite) after the formation of proeutectic austenite dendrites; consequently, the eutectic phases surrounded the austenite dendrites. In most cases, the $(Fe,Cr)_7C_3$ carbides are disconnected and presented as a network morphology [11]. Due to in situ solidification of hypoeutectic melt, the high-chromium cast iron bars could be formed in the Hadfield steel matrix.

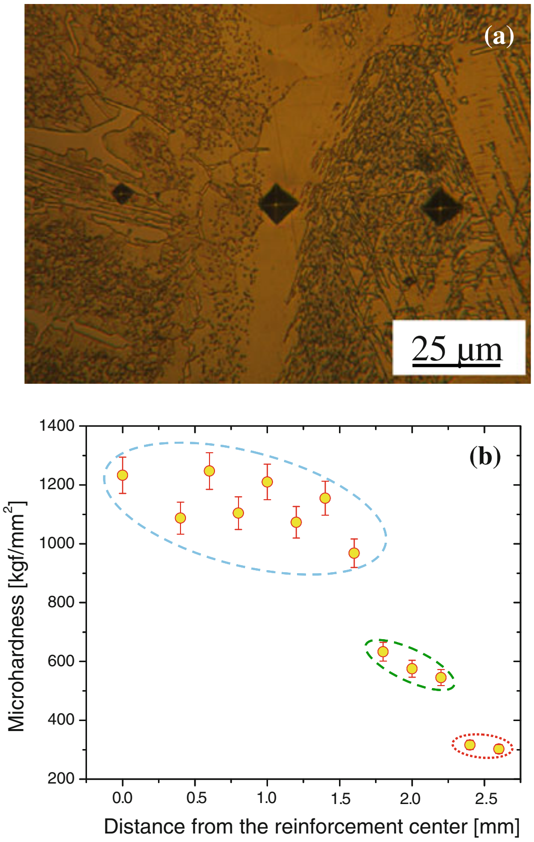
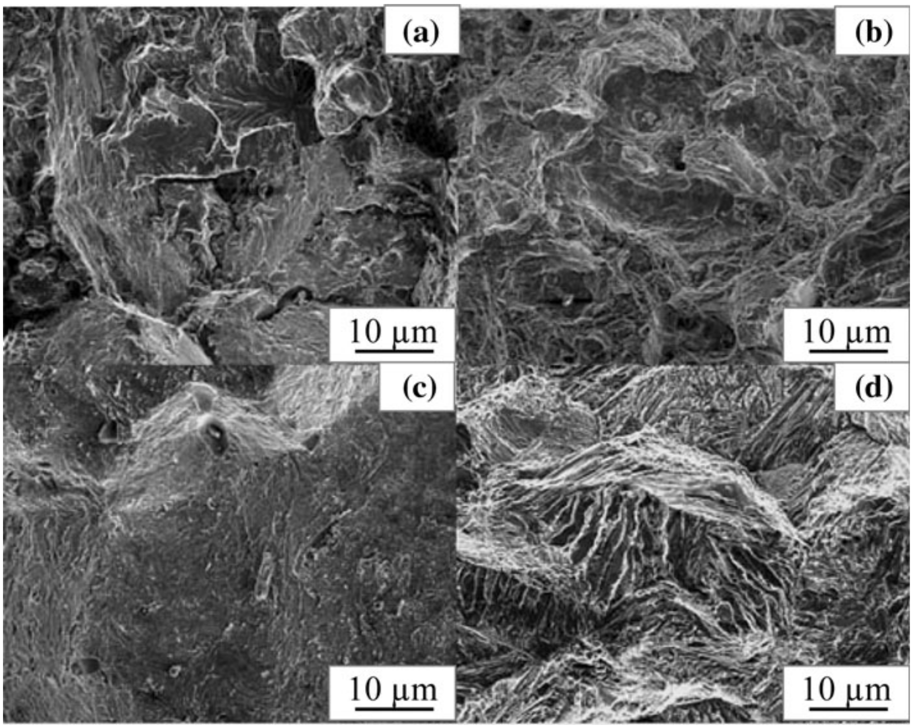


Fig. 5 Micrograph of the indented sample (**a**) and microhardness of water-quenched composite as a function of distance from the reinforcement center (**b**)

Impact toughness

The impact toughness of the water-quenched composite is 80 J/cm^2, which is lower than that of the reference sample (121 J/cm^2) and higher than that of the as-cast composite (42 J/cm^2). The obtained values can meet the requirements for impact toughness of the steel in industrial applications. It is known that the mechanical properties of the steel composites directly correlate with their microstructures. In this context, to better explain the fracture mechanism, the SEM micrographs of the as-cast and water-quenched composites with higher magnification are shown in Fig. 6. In terms of the steel matrix, the fracture surface of the as-cast composite (Fig. 6a) was characterized by river patterns and cleavage facets with cracking along the grain boundaries, indicating the brittleness of the fracture mode. After water quenching, however, the fracture surface (Fig. 6b) presents some large and small dimples, revealing ductility during the impact test. The large dimples can be nucleated on the primary carbides or inclusions. Moreover, dynamic strain aging phenomenon may be the reason for the development of large dimples from the small ones. Probably, the tearing has not occurred for void coalescence, and shear rupture does not involve as is common in the neck of ductile materials [12]. In terms of high-chromium cast iron bar reinforcement, the fractured feature of the as-cast reinforcement (Fig. 6c) displayed brittleness, resulting in

Fig. 6 SEM fractographs: matrix zones of the as-cast (**a**) and water-quenched (**b**) composites, reinforcement zones of the as-cast (**c**), and water-quenched (**d**) composites



the formation of planes of fracture for the water-quenching condition (Fig. 6d); river patterns and fiber could be observed among the cleavage facets, showing that the mixed ductile–brittle fracture mode [13]. Generally, the fracture mechanism of the composites is very complicated considering not only the difference between Hadfield steel and high-chromium cast iron bars but also the heat effect during thermal treatment.

Three-body wear performance

In abrasive wear, chipping of the harder material on a micro-scale occurs as a result of rubbing the softer material. If one of the in touch surfaces is enough rough and hard, it chips the other surface due to relative motion or touching forces. This wear is so-called two-body abrasive wear [14]. If there are free particles between two bodies, the wear is called three-body abrasive wear. As shown in Fig. 7, the wear rate of the water-quenched composite is low among the three samples tested under various applied loads ranging from 0.3 to 1.2 kg. As the load increases, the wear rates of all samples increase. When the applied load was 0.3 kg, the corresponding values were 1.23, 187, and 2.75 mg/h m^2 for water-quenched, as-cast, and reference samples, respectively. The same tendency continues up to highest load; i.e., when the applied load was 1.2 kg, the wear rate of the water-quenched composite was 2.93 mg/h m^2, i.e., much lower than that of the as-cast composite (4.21 mg/h m^2) and reference sample (5.12 mg/h m^2). Although applying different loads, the water-quenched composite still shows better wear resistance. It must be noted that the loads are not only the factor which is important in varying the wear rate, and heat treatment can also play a key role on the wear rate variation.

The wear track surfaces of the water-quenched composite, abraded with 40 μm abrasive particles at 1.2 kg load, are shown in Fig. 8. Some wear marks/grooves can be seen in the reinforcement zone of the high-chromium cast iron bars as well as in two diffusion layers (Fig. 8a, b). The micro-cutting mechanism might be the main reason for

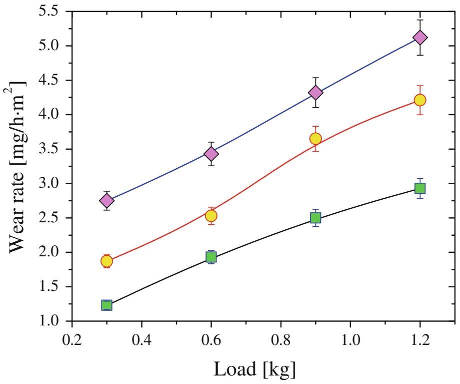


Fig. 7 Wear rates of the as-cast (*filled circle*), water-quenched (*filled square*) composites, and reference sample (*filled diamond*) as a function of load

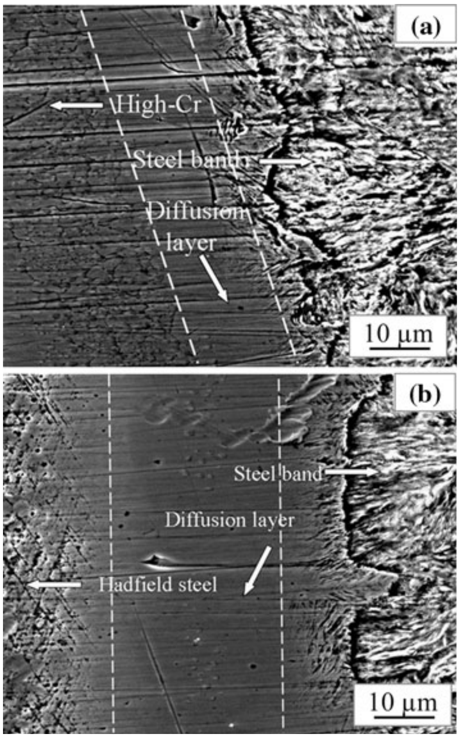


Fig. 8 SEM morphologies of the worn surface of the water-quenched composite at 1.2 kg load: diffusion layers between steel matrix and reinforcement bar (**a**) and between steel matrix and steel band (**b**)

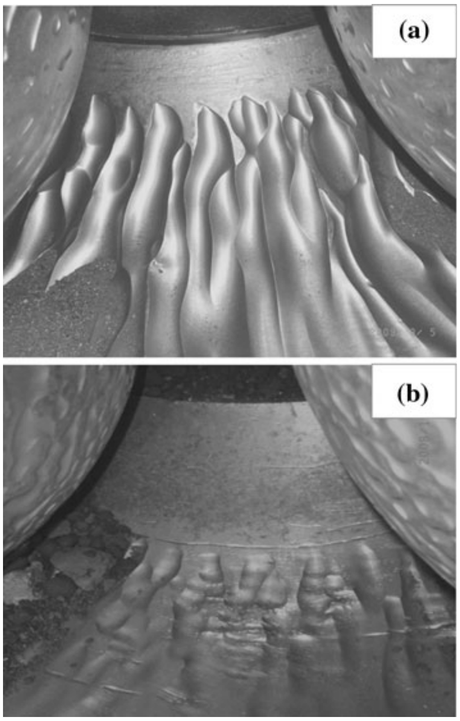


Fig. 9 Micrographs of pulverizer plates prepared from Hadfield steel (**a**) and water-quenched composite (**b**) after 95 days 22 h usage

weight losses in the composite. The marks/grooves are interrupted through the steel band zone, and some concave wrinkles also appear due to the fatigue wear mechanism in the steel band zone. It is assumed that the larger amount of dislocation is present in the zone of the Hadfield steel matrix. The similar observation was explained by the formation of plastic deformation, high density of dislocation, and strain twins in the surface layer, leading to surface work hardening [15, 16]. When the Hadfield steel was exposed to the lower load (0.3 kg), the work-hardened layer did not form, and the wear resistance was mainly affected by high-chromium cast iron bars. Therefore, the modified wear resistance of the Hadfield steel matrix composites was related not only to the higher hardness of high-chromium cast iron bars but also to the excellent work-hardening ability of the Hadfield steel matrix.

Wear test under industrial conditions

In this study, the wear behavior of the water-quenched composite was also obtained from an industrial testing in China Star Material Co. Ltd. (Tongchuan, Shaanxi, China) using a scaled-up version of the casting technique described above. The pulverizer plate based on the water-quenched composite has been used in the mining and mineral processing equipments in Tongling Nonferrous Metals Group Holdings Co., Ltd. (Tongling, Anhui, China). The wear behavior of the water-quenched composite-based pulverizer plate was compared with that of the standard Hadfield pulverizer plate under the same production conditions. Figure 9 displays the micrographs of the standard and water-quenched composite-based pulverizer plates taken out after the usage for 95 days and 22 h. The testing was performed by mineral pulverization (27 t/h); total amount of pulverized powders by these pulverizer plates were 56,430 t. After testing, the morphologies of the working surfaces of the two pulverizer plates were quite different. Some wear marks/grooves could be clearly seen in the standard pulverizer plate (Fig. 9a), displaying more material removal from the working surface. However, the wear marks on the water-quenched composite-based pulverizer plate surface are relatively smooth, indicating that the composite has better wear resistance. On one hand, the reinforcement of high-chromium cast iron bars has high hardness and is protruded to resistance matrix loss. On the other hand, Hadfield steel matrix has high impact toughness, better work hardening capacity, and decreases the abrasion loss. Further investigation ought to be carried out on the development of a Hadfield steel matrix composite implying a significant advance towards industrial application of a wear resistant material with high hardness and high toughness.

Conclusion

In the present work, Hadfield steel matrix composite was reinforced by oriented high-chromium cast iron bars. The mechanical behaviors of the as-cast and water-quenched composites were comparatively studied with Hadfield steel as reference. The experimental results showed that the alloy powder inside the flux-cored welding wires could be melted by the heat of Hadfield steel melt and became high-chromium cast iron bars. The impact toughness of the water-quenched composite was higher than that of the as-cast composite, but much lower than that of the Hadfield steel. The wear rate of the water-quenched composite was 1.23 mg/h m^2 at 0.3 kg and 2.93 mg/h m^2 at 1.2 kg, which was lower compared with those of the as-cast composite and Hadfield steel. The impact toughness and wear resistance of the water-quenched composite were related not only to the combining actions of the Hadfield steel matrix and high-chromium cast iron bars but also to the effect of heat treatment. The pulverizer plate manufactured by using the water-quenched composite showed better wear resistance after 95 days and 22 h usage compared to the standard Hadfield steel pulverizer plate.

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References

1. Hadfield RA (1925) Metallurgy and its influence on modern progress. Chapman and Hall Ltd., London
2. Srivastava AK, Das K (2008) Mater Lett 62:3947
3. Gnyusov S, Tarasov S, Ivanov Yu, Rothstein V (2004) Wear 257:97
4. Proskurovsky DI, Rotshtein VP, Ozur GE, Ivanov YuF, Markov AB (2000) Surf Coat Technol 125:49
5. You XQ, Ren H, Si TZ (2003) Foundry 6:1170
6. Tianfu J, Fucheng Z (1997) Mater Lett 31:275
7. Kambakas K, Tsakiropoulos P (2005) Mater Sci Eng A 413–414:538
8. Bedolla-Jacuinde A, Rainforth WM (2001) Wear 250:449
9. Matsuo TT, Kiminami CS, Botta Fo WJ, Bolfarini C (2005) Wear 259:445
10. Atamert S, Stekly J (1993) Surf Eng 9:231
11. Pero-Sanz JA, Plaza D, Verdeja JI, Asensio J (1999) Mater Charact 43:33
12. Abbasi M, Kheirandish S, Kharrazi Y, Hejazi J (2009) Mater Sci Eng A 513–514:72
13. Lou D, Hellman J, Luhulima D, Liimatainen J, Lindroos VK (2003) Mater Sci Eng A 340:155
14. Luo K, Bai B (2010) Mater Des 31:2510
15. Xu Y, Fang L, Cen Q, Zhu J (2005) Wear 258:537
16. Kim J-K, Kim G-M, Kim S-J (2001) J Nucl Mater 289:263