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Enhanced wear resistance of nanotwinned austenite in higher Si nanostructured bainitic steel

Binggang Liu, Xianwen Lu, Wei Li*, Xuejun Jin*

Institute of Advanced Steels and Materials, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

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A B S T R A C T

The role of a highly-deformed layer and higher Si content on the impact-abrasive wear of nanostructured bainitic steel was investigated. Using an impact-abrasion testing machine, it was demonstrated that nanostructured bainitic steel containing 3 wt% Si had the best wear resistance compared with Hardox550 steel and carbidic austempered ductile iron (CADI). During the abrasion of the high-Si nanobainitic steel, a hardened layer can be created from the formation of nanoscale twinning bundle and an austenite transformation. Twinning can act as an intermediate phase preceding martensite formation under cyclic wear conditions that are dominated by plastic deformation. The formation of lamellar twinned austenite and martensite in nanobainitic steel can effectively enhance its impact-abrasive wear resistance. It was also found that micro-cracks nucleated on the bases of abrasive craters were blunted. That mechanism could be attributed to nanoscale twin formation and transformation-induced crack arrest.

1. Introduction

Bainitic steel austempered at a low temperature exhibits better wear resistance than pearlitic steel or Hadfield's austenite steel under rolling/sliding wear and shows great potential application in rails [1–3]. Recently, nanocrystalline bainitic steel with fine bainite ferrite lath and high-carbon-film austenite has attracted attention because of their exceptional mechanical properties. It has been discovered that its ultimate tensile strength could reach 2.3 GPa with a hardness of 700 HV30 [4,5]; this is due to the fine bainite ferrite, which is 20–50 μm in thickness. It presents exceptional wear resistance in terms of sliding/rolling and abrasive wear [6–9]. Wang [6] and others reported that the sliding wear resistance of nanostructured bainitic steel is better than that of tempered martensite microstructure, which results from the ultra-fine lathy bainitic ferrite and retained austenite. Leiro [10] found that nanostructured steel had superior wear resistance compared with other bainitic steels transformed at high temperatures. The higher wear performance was attributed to its excellent mechanical properties provided by the finer microstructure. In addition to the fine structure in nanobainite steel, the retained austenite also plays a key role during abrasion. Xu [11] showed that bainite steel has a high toughness that can bear severe plastic deformation and impact. Hodgson [12] and others conducted two-body abrasive wear studies and concluded that the retained austenite morphology was changed from film + blocky to film with a decrease in the transformation temperature, and the wear resistance was also greatly enhanced by the microstructure refinement. The blocky retained austenite, which has lower mechanical stability than filmy austenite, is more prone to form martensite during wear, and coarse fresh martensite is more vulnerable to crack initiation. Koyama [13] found that arrest of fatigue cracking takes place at the boundaries of austenite films because of the transformation-induced crack termination (TICT) mechanism. Therefore, the excellent wear resistance in nanostructured bainitic steel can be attributed to its fine microstructure and austenite transformation due to shear stress in the surface layer.

Recently, nanoscale twins have led to a significant improvement in fracture toughness in nanotwinned copper, and show excellent fatigue crack growth resistance [14,15]. Furthermore, twin boundaries can efficiently strengthen materials without ductility reductions and work hardening. The deformation twinning of Fe-Mn austenitic steel with nanoscale twins predominates over plastic training, and exhibits high crack resistance as well as hardness [16,17]. Thus, the twinned structure could be introduced into nanobainite steel by adjusting the addition of alloying elements to obtain enhanced wear resistance performance. However, the formation of a nanotwinned structure is closely related with stacking fault energy and is promoted if the stacking fault energy is between 18 and 30 mJ m^{-2} [18].

Typical wear mechanisms are divided into four categories: abrasive, adhesive, fatigue, and corrosive wear [19]. However, they are complex and often interact with each other during the wear period. In particular, the mining and minerals industries use equipment such as ore loading

* Corresponding authors.
E-mail addresses: weilee@sjtu.edu.cn (W. Li), jin@sjtu.edu.cn (X. Jin).

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Table 1
Chemical composition of three steels, wt%.

Sample	C	Si	Mn	Cr	Mo	Nb	Ni
Nanostructured bainitic steel	0.95	2.90	0.75	0.52	0.25	0.03	
Hardox550	0.37	0.50	1.30	1.40	0.60		1.40
CADI	3.31	1.80	0.66	0.54	0.43		0.38

and moving buckets and crushers, which means that the surfaces of components are often damaged by heavy impacts and scratches by hard ores [12,20,21]. Most research has concentrated on the wear behavior of nanostructured bainitic steel in terms of sliding/rolling wear; few studies have focused on impact abrasive wear behavior. Besides the effect of nanoscale bainite ferrite, the influence of retained austenite in impact abrasive wear has not been emphatically discussed and remains unclear. In this paper, high carbon (0.95 wt%) and silicon (2.9 wt%) were designed to increase mechanical stability and stacking fault energy in retained austenite [18,22]. Thus, the deformation behavior of retained austenite and its role during wear is discussed. Furthermore, the mechanism of impact abrasive wear and the relation between material microstructure and wear behavior were also studied.

2. Materials and methods

The chemical compositions of nanostructured bainitic steel, Hardox550, and CADI are listed in Table 1. It was industrially manufactured in an intermediate frequency furnace and electroslag furnace, and annealed at 1143 K (870 °C). The ingot was reheated to 1423 K (1150 °C), and hot rolled to a 40 mm × 40 mm × 1500 mm bar. Afterwards, the bar was slowly cooled in sand molds. The size of the specimens was 60 mm × 100 mm × 15 mm; they wear austenitized at 1223 K (950 °C) for 30 min, followed by austempering in a salt bath furnace at 523 K (250 °C) for 24 h before quenching in water.

The microstructure of CADI is identical to graphite nodules, dispersed carbides, and ausferrite matrix with high hardness and wear resistance. The microstructure of Hardox550 steel is only martensite, and is often used in wear ribs, crushers and other sever wear situations.

Microstructures were characterized using a scanning electron microscope (SEM; VEGA3, TESCAN, Czech Republic) and metallographic microscope (OM; Imager A1m, ZEISS, Germany) after mechanical polishing and etching in 4% nital solution. The ultrafine microstructure was investigated by a field emission high resolution transmission electron microscope (TEM; JEM-2100F, JEOL, Japan) operated at 200 kV using the 3 mm diameter samples electropolished in 7% perchloric acid solution at room temperature until perforation occurred. The volume fraction of retained austenite was measured by a polyfunctional X-ray diffractometer (XRD; 3 kW/*D8 ADVANCE Da Vinci, BRUKER, Germany) with monochromatic Cu_Kα radiation at 40 kV and 40 mA, and a scanning speed of 5°/min. In order to study the depth of the deformed area in the subsurface, micro-Vickers hardness was measured by a hardness tester (1600–6406, Zwick/Roell, Germany) at a loading of 50 g. Tensile tests were conducted with a gauge length of 16 mm in a Zwicks universal testing machine (BTCT1-FR020 TN.A50, Zwick/Roell, Germany). Impact testing was performed with dimensions of 10 × 10 × 55 mm^3 with no notch on an impact test machine (PTM2000, Suns, China) at room temperature.

Wear tests were conducted on an impact abrasive wear machine (MLD-10, Zhangjiakou integrity test equipment manufacturing co. LTD, China), as shown in Fig. 1(a) and (b). It consists mainly of a hammer, test sample, and lower-counter specimen. During wear testing, the test sample was placed in a clamping chuck connected with the hammer. The impact energy, which could be adjusted by the height of the 10-kg hammer, was set at 4 J. The hammer impact frequency was 50 times/min. The abrasives (5–7 mesh quartz sand particles) were fed between the test sample and lower specimen at approximately 360 g/min. The Hardox550 steel lower specimen was rotated by a motor at a rate of 200 rpm. The test sample size was 10 mm × 10 mm × 30 mm, and two samples were prepared in each condition. The surface of the test samples was metallographically polished to 7–10 µm prior to the tests. The round lower specimen was 50 mm in diameter and 10 mm thick.

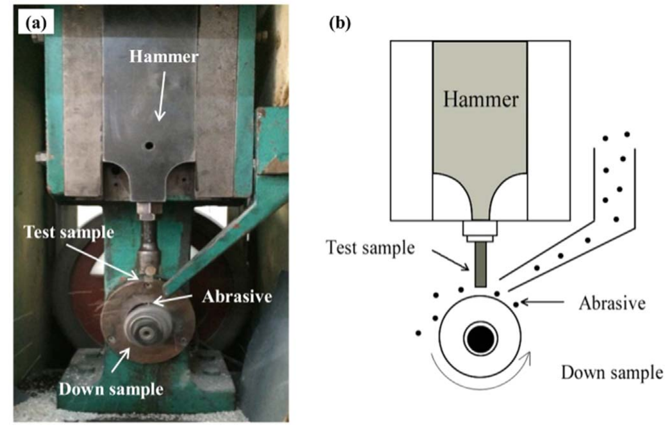

Fig. 1. (a) Photograph of MLD-10 wear machine; (b) schematic of MLD-10 wear machine.

3. Results

3.1. Wear resistance of three steels

The wear mass losses were measured after 2000 and 5000 impacts. As shown in Fig. 2, either 2000 or 5000 impacts, the nanostructured bainitic steel exhibited the least mass loss and excellent wear resistance. In terms of wear resistance, the nanostructured bainitic steel was the best, Hardox550 was second, and CADI was the worst.

3.2. Microstructure of the three steels

Fig. 3 shows that the microstructures of the three steels are completely different. As shown in Fig. 3(a), CADI mainly consists of graphite, carbides, and matrix. In addition, it has the highest hardness value (872 ± 10 HV) compared with others in Fig. 4. It is observed that the microstructure of Hardox550 is only martensite in Fig. 3(b). Nanostructured bainitic steel includes bainite ferrite and retained austenite. The thickness of the lath-like bainite ferrite is less than 100 nm, and the morphology of the retained austenite is mainly film shaped (Fig. 5). Although 550 steel and nanostructured bainitic steel have different structures, they have almost the same hardness value of 630 ± 10 HV, as shown in Fig. 4. Furthermore, the mechanical properties and volume fraction of the retained austenite in the

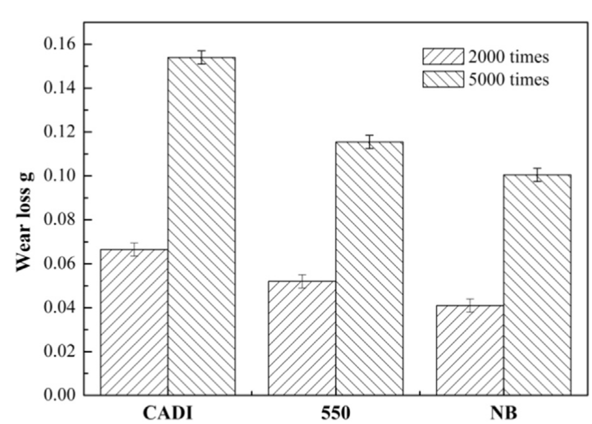

Fig. 2. Wear mass loss of CADI, Hardox550 (550), and nanostructured bainitic steel (NB).