



Three-body abrasive wear of carbide-free bainite, martensite and bainite-martensite structure of similar hardness

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ABSTRACT

The three-body abrasive wear behavior of three ferrous alloys with different microstructures but similar hardness has been investigated using a standard dry-sand rubber wheel test (ASTM G65-16). Although the hardness of the alloys was similar, the abrasion rates are radically different owing to differences in abrasion mechanisms in their microstructures. A carbide-free bainitic steel having fine bainitic laths exhibited better abrasion resistance owing to the strain-induced transformation of austenite into martensite. Nano-scaled martensitic laths that formed on the surface resisted plastic deformation during abrasion and thereby increased the abrasion resistance. The microstructure containing bainitic ferrite undergoes extensive plastic deformation associated with a large quantity of dislocations, which in turn accommodates the strain of abrasion. The steel with a blocky-martensitic microstructure had the least wear resistance. In that case, fragmentation and chipping comprised the prominent abrasion mechanism. The degeneration of a martensitic structure and its subsequent tempering radically reduces the hardness at the surface and makes it more susceptible to abrasion. Steel containing a mixture of bainite and martensite had intermediate abrasion resistance relative to the other two alloys.

1. Introduction

The equipment used in various industries such as mining, transport and agriculture undergoes severe abrasive wear during the service life. The cost of abrasive wear to the national economy is estimated to be about 1% of the gross national product, and it can compromise with the safety and reliability of engineering components [1]. The mechanism of wear during three-body abrasion is highly complex in nature and depends on various factors like the properties of material involved in the process, contacting environment, the shape and size of the abrading particles. Mostly abrasion-resistant steels are made of quenched and tempered martensitic microstructure, because the high hardness of the steel intuitively matters in determining the wear resistance. However, the exact relationship between hardness and wear resistance is often quite dubious [2–4]. Hardness resists the penetration of abrasive particles at the onset of wear, whereas, the toughness inhibits the formation of cracks and subsequent material removal at the later stages of wear. In this context, it has been observed that the deformation of the surface region and extent of work hardening of the material beneath plays a significant role in material detachment [5]. Vingsbo *et al.* reported that once steady-state abrasive wear is achieved, the structure and properties of the abrading surface and underlying material vary considerably

relative to the bulk of material. It is the properties of this active layer which controls the abrasion resistance of the steel rather than those of the unaffected bulk material [6]. Richardson *et al.* first reported that bainitic microstructure has better resistance for abrasion than martensitic steel of similar hardness and composition [7] due to its combination of high ductility and hardness [8]. However, the contradictory views exist [9–11], where martensite has been found to exhibit better abrasion resistance compared to pearlite and bainite owing to its high hardness, which were again contradicted under different experimental conditions [8,12–14]. Martensitic steel with higher carbon (C ~ 0.65 – 1.2 wt%) has been found to possess higher wear rates compared to low carbon martensite (C ~ 0.16 – 0.37 wt%) owing to its relatively low toughness [15]. Under rolling-sliding wear condition, carbide free bainite microstructures were found to exhibit excellent wear resistance property as it has high capability of accommodating strain of deformation [16–20]. Wang *et al.* [21] studied the dry sliding–friction wear resistance of nanostructured bainite steel and reported that the dry sliding friction induces the transformation of retained austenite into carbon-supersaturated fine α -phase (~ 3 nm) in the top friction surface. Yang *et al.* and Leiro *et al.* [3,4] investigated the rolling/sliding wear resistance of several carbide-free bainitic steels for the application of rail. The nanostructured bainitic steels with chemical composition

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0.83C–0.81Cr–1.56Si–1.37Mn–0.87W–1.44Al–0.012P–0.0053S (wt%) developed by the isothermal treatment at 220 °C, 240 °C and 260 °C for different hours exhibit significantly better specific wear resistance to that of bainitic steels transformed at higher temperatures with similar hardness values. Bakshi et al. [22,23] conducted experiments in a novel steel of composition 0.83 C – 2.28 Mn – 0.011 P – 0.008 S – 1.9Si–0.044Al– 0.12Cu– 1.44Cr– 0.24Mo– 0.11V– 1.55Co– 0.019Sn– 0.023 Nb. The nanostructure bainite is obtained by isothermal transformation at 200 °C of hardness 622 ± 13 HV30. The same steel was heat treated to produce fine pearlite of hardness 378 ± 9 HV30 and untempered martensite of 739 ± 7 HV30. The three steels were investigated for wear resistance under three body abrasion [22] and rolling-sliding wear [5,23] conditions. Untempered martensite steel suffers fragmentation of the wear track, whereas, bainitic steel has significant plastic deformation at the wear surface with good adhesion of the damaged steel material akin to pearlite. Nanostructured bainite of this composition exhibited one of the lowest specific wear rates of any carbide-free bainite investigated previously under similar circumstances [24,25]. The lowest specific wear rates of nanostructured carbide-free bainite is due to the presence of fine scale of (35 nm) of the bainitic lath structure together with considerable amount (27%) of meta-stable retained austenite in form of thin films. This provides a mechanism of work hardening that leads to an increase in hardness in the active surface area [23].

The present work was motivated from observations of the severe abrasion of steel in the buckets being used in the mining industries mainly in excavators and shovels [26]. Such components are made of medium carbon (0.20–0.25 wt% C) steels alloyed with Ni, Cr and/or Mo and are heat treated to either martensite or tempered martensitic condition to achieve bulk hardness of 390 ± 10 BHN [26,27]. It has been reported that the wear of martensite is not only subjected to its bulk hardness, but also depends largely on the size and distribution of alloy carbide precipitates that interacts with the abrading particles [26]. The purpose of present work is to study the exact mechanism involved in abrasion of martensitic steel under three-body abrasion and compare the specific wear rate against carbide free bainite and microstructure comprised of a combination of martensite and carbide free bainite. The study aims towards design and development of a bainitic steel of superior abrasive wear resistance with a probable scope of suitable replacement of the existing martensitic steel for high hardness used in certain components of the earthmoving and other mining components.

2. Experimental procedures

2.1. Alloy design

Alloy 1 and Alloy 2 has been designed to achieve bainite, martensite and retained austenite under the continuous cooling rate 0.1–0.5 °C/s after austenization. Following aspects were considered during designing of the alloys,

- i. Complete austenization achieved by soaking at 1250 °C and continuous cooling up to room temperature (27 °C) with the cooling rate of 0.5 °C/s to produce bainite and retained austenite [28].
- ii. Si and Al play a crucial role in alloy composition to encourage the retention of high carbon in austenite over precipitation of cementite, which is desirable to achieve high toughness in steel [29].
- iii. Avoidance of allotriomorphic ferrite, widmanstatten ferrite and pearlite formation by the addition of Mo and B [28].
- iv. With the indicated fine scale microstructure, hardness in the range of 380–400 BHN should be achieved.

2.2. Melting, forging and heat treatment

Alloys (Alloy 1 and Alloy 2) with the composition as shown in

Table 1, were prepared using a vacuum induction furnace to produce 40 kg ingots of dimension $100 \times 100 \times 500$ mm³. The section of ingot was then homogenized at a temperature of 1250 °C for an hour and forged to $70 \times 70 \times 100$ mm³ bars. The forged bars were then homogenized at a temperature 1250 °C for three hours and air cooled to room temperature (27 °C) to attain the desired microstructure. Chemical compositions were measured on specimen using Induced Couple Plasma (ICP) and LECO analysis for carbon and sulfur content (typical measurement uncertainty: 1–3% of stated value). Martensite steel (Table 1) is standard materials being used in the application of earthmovers and mining industries [27].

2.3. Abrasion testing

Dry sand rubber wheel tests were conducted as per ASTM G65-16 following type-“A” procedure using the specifications listed in Table 2 [28]. A deviation was taken in terms of duration of test in order to achieve appreciable wear, later, the weight loss was normalized against the load and distance traversed. Rectangular samples of dimension $25.4 \times 76.2 \times 12.7$ mm³ were machined from the initial block using electro-discharge machine (EDM). The broad faces of the samples were ground using 400 µm grit SiC papers to remove any damage caused by EDM prior to the testing and to achieve the desired surface roughness. The schematic of the equipment and the secondary electron image of the abrasive sand used for the testing are shown schematically in Fig. 1a) and b) respectively [22]. The rotating speed of the wheel and sand flow rate were kept uniform throughout the experiment. The experiment was conducted for ten minutes at the specified parameters, and the specific wear rate was calculated using weight loss after abrasion. The abrasion test was conducted on five samples to confirm and validate the repeatability of the results under the same experimental conditions. The specific wear rate (SWR) was averaged out and reported with statistical error.

2.4. Microstructural analysis

The heat treated samples were characterized using Field Emission Gun (FEG) assisted Scanning Electron Microscope (make: FEI Nova Nano SEM) and Transmission Electron Microscope (Jeol JEM 2200FS) for finer structural details. For secondary electron imaging the samples were ground and polished followed by etching with 2 vol% nital at room temperature. For TEM, thin slices were cut from the bulk specimen using electro-discharge machining (EDM). The thickness of sample was reduced to ~0.1 mm by manual grinding and coupons of $\phi 3.0$ mm diameter were produced by shear punching. For the sample preparation of abrasion track special care has been taken by reducing the thickness from opposite side of abrasion track. The coupons so prepared were electro-polished by single jet machine, with impingement of the electrolyte jet from the opposite side of the wear track to create electron transparent region. Electrolyte used was a mixture of 10% perchloric acid and 90% ethanol by volume at an electro-polishing bath temperature of – 30 °C operated at ~ 40 V.

2.5. XRD analysis

X-ray diffraction analysis (XRD) was done in Bruker's D8 advance at $0.020^\circ \theta$ step sizes in the range of $2\theta = 40 - 100^\circ$, 45 kV applied potential at 45 mA current with filtered Cu K_α radiation. The samples were ground and polished using emery papers with increasing fineness followed by polishing with 0.6 and 0.1 µm diamond pastes. Subsequently, the samples were electropolished to remove the strain produced during process of grinding and polishing. Electrolyte used was a mixture of 4% perchloric acid, 21% glycerol and 75% ethanol by volume at an electro-polishing bath temperature of – 30 °C operated at ~ 30 V. For sample preparation for abrasive track, sample of 1 cm³ was cut using electro-discharge machine from the abrasive regime. The sample is leveled

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