Wear 376-377 (2017) 468–483

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Mechanisms of severe sliding abrasion of single phase steels at elevated temperatures: Influence of lattice structure and microstructural parameters

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form
23 December 2016
Accepted 11 January 2017

Keywords:
Ferritic steels
Austenitic steels
High temperature two-body abrasion
High temperature hardness
Wear mechanisms
X-ray diffraction and line-profile analysis
Rietveld analysis

ABSTRACT

Due to the complex influence of elevated temperatures on the characteristics of a tribological system, severe high temperature sliding abrasion of single phase metals is a unique type of wear. The mechanisms of high temperature sliding abrasion (indentation and grooving of metallic surfaces) are strongly governed by the temperature-dependent interaction between the bulk metal and the abrasive during the wear process. This interaction can be correlated with the metal physical and microstructural parameters of the worn metal, which consequently greatly influence abrasive wear processes.

In this context, the present study deals with the influence of microstructural aspects of single phase steels on the mechanisms of high temperature abrasion. Investigations focus on the aspects of abrasion by performing high temperature hardness and sliding wear experiments (two-body, ceramic counter body) on bcc and fcc steels. Results confirm a clear lattice-structure dependence of the abrasion behavior of steels. Major differences exist in the stability of the mechanical and tribological properties of the bcc and fcc materials investigated. Hardness and work hardening of bcc steels decrease above 500 °C, leading to non-stationary wear. In contrast, fcc steels show a steady decrease of mechanical properties, avoiding instabilities. Accordingly, wear experiments and investigations of the wear scars (surface and subsurface regions) show a higher wear resistance and more favorable mechanisms of high temperature abrasion of fcc steels (e.g. pronounced micro-ploughing). Further, the microstructural elements of fcc steels high temperature abrasion resistance are investigated in more detail using X-ray diffraction. Microstructural analysis using diffraction-line broadening (Rietveld analysis) is used to determine the degree of plastic deformation (microstrain) and the phase fraction of α'-martensite of the austenitic wear scars. These parameters are related to the present mechanisms of abrasion, explaining the high temperature wear properties of fcc steels.

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1. Introduction

High temperature abrasive wear of steel occurs in various industrial applications. A variety of harsh environments in the processing and transporting of solid fuels and related waste for new energy production processes cause severe wear and consequently incur extremely high maintenance efforts. Therefore, abrasive wear is one of the most damaging and costly issues for the energy industry. In particular, the transport of hot solids results in very high maintenance costs and production losses, because the severe interactions between the equipment and the hard solids take place at elevated temperatures [1]; for example, the wear processes of the construction materials of a circulating fluidized bed (CFB) combustion reactor can be pointed out. CFB burnings are mainly used for the combustion of a combination of pulverized coal and solid biomass in a solid state fermentation reactor [2]. These reactors use a fluidized bed, formed by a carrier material (SiO_2 particles), to burn the fuel while floating with a high efficiency. Nevertheless, the combination of high temperature processes and abrasive constituents of the CFB medium leads to abrasive wear of the construction materials used [3]. In this example, severe two-body sliding abrasion of steels takes place by the impact of ceramic particles (Al_2O_3, SiO_2, etc.). These particles act as individual abrasives or as part of a multiphase medium consisting of a hot carrier gas and abrasive particles. In both cases, the abrasive flows over the surface of the metallic base material at elevated temperatures, which leads to severe high temperature abrasion [2,3].

The abrasive wear behavior of Fe-based materials consisting of

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http://dx.doi.org/10.1016/j.wear.2017.01.043
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a metal matrix and different types of hard phases differs greatly between room temperature and elevated temperatures [4]. In addition to the role of high temperature oxidation on the abrasion processes, the pronounced role of thermal softening mechanisms changes the requirements of material properties to resist abrasion [5]. For temperatures above 500 °C, the indentation of particles into the surface of metals cannot be prevented by the established room temperature mechanisms such as the martensitic hardening of steels [4,6]. Thus, the mechanisms of interaction between the bulk material and the abrasive particles, in correlation with the microstructure and microstructural properties of the bulk material, gain higher importance. A key issue in achieving stationary and better wear resistance of a material is the stability of the wear-generated surface zone [7–9]. In this context, it is necessary to distinguish between the roles of the metal matrix and the hard phases during the abrasive wear process. The metal matrix of multiphase steels has a more pronounced influence on the high temperature abrasion resistance than the hard phases. This is due to the fact that the stability of the high temperature wear behavior is mainly determined by the properties of the metal matrix [4,7,10]. Pronounced thermal softening of the metal matrix leads to a sharp increase of removed material, which occurs almost independently of the amount and structure of the hard phases [4,7,8]. Reasons for this behavior can be found in the loss of support and integration of the wear-affected surface region by a softened matrix [4,7,10]. Therefore, an unsteady and sharp decrease in the matrix properties leads to degradation of the entire microstructure of metallic materials during abrasive wear. Due to this degradation, the abrasive wear behavior of single phase Fe-based metal matrices is of major interest for the analysis and improvement of the high temperature abrasive wear resistance of Fe-based materials. During abrasive wear, the metal matrices are severely plastically deformed. Therefore, the analysis of the abrasive wear behavior of the materials has to concentrate on their responses to high degrees of deformation. A high wear resistance against severe abrasive indentation and scratching of single phase Fe-based materials is achieved by a matrix material with a high resistance against the relative motion of the abrasive counter body (fracture energy) [11]. Elements of the resistance of a material against a dynamic, abrasive stress are the tensile strength, hardness, and amount of work-hardening during deformation of the material [4,11]. In particular, the deformation characteristics of a material are of high importance for severe high temperature abrasive wear, because pronounced strain-induced work-hardening during deformation can counteract the thermal softening processes at elevated temperatures [12]. The mentioned parameters and the dominant micro-mechanisms of abrasion, according to Zum Gahr [13], are influenced by the lattice structure and microstructural parameters (e.g. such as the stacking-fault energy in a material) of single phase Fe-based materials. By evaluating these characteristics, it is possible to correlate the deformation behavior of a material with the abrasive wear characteristics and the states of the worn microstructures.

The present work investigates the mechanisms and microstructural aspects of high temperature severe sliding abrasion of single phase steels, which are suitable matrix materials for high temperature abrasion resistant Fe-based metal matrix composites. Issues discussed include the development of the abrasive wear behavior of steels as a function of temperature, as well as the influence of microstructural characteristics of the materials (such as lattice structure, phase stability, and stacking-fault energy) on the wear-affected subsurface structures. The experimental investigations of this study are structured into three main sections. The first section deals with the temperature dependence of the abrasive wear properties of the materials investigated. In the second section the surface microstructures of the wear-affected materials are analyzed. The objective of this investigation is to determine the dependence of wear mechanisms and microstructural effects on temperature and lattice structure. These investigations are discussed in more detail in the third section, which analyzes the wear-affected subsurface microstructures of fcc and bcc steels. The aim of the present study is to point out the differences in the high temperature abrasive wear behavior of austenitic and ferritic steels. Furthermore, additional analyses of the austenitic steels are used to highlight the influence of the austenitic alloying system on the microstructural wear mechanisms of austenitic steels.

2. Material and methods

2.1. Material, processing, and preparation

Four single phase steels were chosen to investigate their high temperature sliding abrasion behavior. The materials chosen were the austenitic CrNi(Mo)-steels AISI 304/ EN 1.4301 (X5CrNi18-8) and AISI 316L/ EN 1.4404 (X2CrNiMo17-10-2) and the ferritic Cr (Mo)-steels X1Cr17 and X1CrMo18-2.

The austenitic steels used were commercially available steel grades and are further indicated using their actual chemical composition measured by optical spark emission spectroscopy. The ferritic steels were produced as cast alloys in a vacuum casting furnace containing amounts of Cr and Mo comparable to the austenitic steels. Thereby, it was intended to generate two pairs of comparable austenitic and ferritic alloys, which mainly differ by their lattice structure and Ni content.

From the initial state (commercially available and as-cast), austenitic and ferritic steel round bars were round forged at 950 °C from a diameter of 42 mm to a diameter of 14 mm. The heat-treatment applied afterwards to the austenitic steel round bars consisted of solution annealing at 1100 °C for 2 h followed by water quenching. The ferritic steel round bars were solution annealed at 950 °C for 2 h followed by water quenching. The annealing temperatures and times were chosen to accomplish a homogeneous microstructure with a coarse grain size and without any precipitates. A grain size (>30 μm for the austenitic steels; >50 μm for the ferritic steels) was demanded to minimize the influence of grain size on the results of the wear and hardness testing. After the heat-treatment the steel bars were machined to a final diameter of 10 mm. The chemical compositions of the final states of the materials, determined by optical spark emission spectroscopy, are summarized in Table 1.

For hardness and wear experiments, samples with a thickness of 4 mm were cut from the steel bars. The preparation of the samples' surfaces for testing consisted of grinding with SiC paper followed by successive polishing with a diamond suspension with average grain sizes of 6, 3, and 1 μm. Final polishing was performed with oxide polishing suspension with an average grain size of 0.25 μm. Experiments were done with this surface quality to enable comparable experimental conditions.

After the wear testing, the wear scar surfaces were cleaned by ultrasonic cleaning in ethanol only. Microstructural surface analyses were performed without further preparation. Analyses of the

Table 1
Chemical composition of the materials investigated (in mass%) determined by optical spark emission spectroscopy; iron is the dependent substitutional element.

Material	C	N	Si	Mn	Cr	Ni	Mo	Fe
X5CrNi18-8	0.03	0.07	0.40	1.65	17.91	7.98	0.23	bal.
X2CrNi17-10-2	0.02	0.05	0.43	1.64	16.61	9.94	2.11	bal.
X1Cr17	0.01	–	0.23	–	17.39	0.02	0.01	bal.
X1CrMo18-2	0.01	–	0.31	–	18.40	0.03	1.94	bal.

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