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Effect of particle characteristics on the two-body abrasive wear behaviour of a pearlitic steel

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ABSTRACT

The specific wear rate and friction coefficient of a pearlitic microstructure subjected to different abrasive environments (i.e. SiC and alumina) were examined. A CSM high temperature pin-on-disc tribometer was used to simulate the two-body abrasive condition (i.e. the metallic surface abrading against the abrasive particles). The characteristics of the abrasive particles (i.e. particle size and density) revealed a significant impact on the amount of material loss. The specific wear rate of the pearlitic microstructure decreased with a reduction in the abrasive particle size, irrespective of the particle type. In addition, distinct particle deterioration mechanisms were observed during the abrasion process, which was largely determined by the abrasive particle size. Attrition, shelling and fracture were some of the dominant particle deterioration mechanisms occurring in both of the abrasive environments. SEM and EDX analysis on the wear debris displayed a unique metallic chip formation with respect to the particle type. Furthermore, the abrading efficiency (i.e. threshold level) of the abrasive particles was identified by means of interrupted abrasive wear tests. The dense packing nature of the alumina abrasive particles resulted in a significantly higher material removal rate than the SiC abrasive environment.

1. Introduction

Abrasive wear is a serious issue that occurs invariably in many industrial applications, such as mining, agricultural and mineral processing equipment. This commonly occurring wear mechanism involves severe material loss, leading to a significant rise in the operation and maintenance cost of industry. The process of material removal appears when hard (i.e. abrasive) particles indent on a relatively soft surface of a material and move relative to it [1–4]. In this context, the characteristics of the abrasive particles (i.e. the freedom of movement, morphology, orientation, distribution etc.) play a pivotal role in affecting the amount of material loss [5–10]. Extensive research and several theories have been postulated based on the investigations of the abrasive environment.

The process of abrasive particle indentation and their mechanism of material removal is based on the particle size and morphology. Literature reports that there is a transition in the mode of material removal based on the particle morphology (i.e. rounded or sharp tips). Round or polyhedral particles can cause a progressive abrading action, whereas, sharp tips can easily cut through the material [11–13]. This can eventually lead to a difference in the characteristics of the wear debris generation and mechanism of particle deterioration. Moreover, in a two-body abrasive system, the efficiency of the particles and the active wear loss over a defined sliding distance is often debatable. This is due to the restriction in their freedom of movement and repeated traversals induces significant particle deterioration during abrasion [12–14]. This emphasises the fact that the abrasive environment is quite dynamic and undergoes appreciable changes during abrasion.

Concurrently, abrasion induced microstructural changes and wear modes are of primary importance in determining the abrasion resistance of a microstructure [11,15–18]. To tackle the problem of abrasion, an in-depth understanding of the multiple variables (i.e. metallurgical factors of a material and abrasive particle characteristics) that co-exist in a tribological system is required [19–20]. Earlier, investigations were performed to understand the abrasion wear behaviour of pure metals and alloys towards different abrasive characteristics (i.e. particle size and type) [13]. However, the materials that were compared had contrasting mechanical properties such as bulk hardness and the study had more emphasis on the characteristics of abrasive particles on abrasive wear [13]. Therefore, the current study aims to address the aforementioned issues through simultaneous investigation of the major components of the tribological system (i.e. microstructure and abrasive environment).

This paper focusses on the effect of abrasive particle characteristics on the process of material removal during abrasion. An

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attempt has been made to understand the efficiency of the abrasive particles during the abrasion process through interrupted abrasion tests. Topographical analysis and EDX analysis were performed to understand the abrasive particle deterioration mechanism and wear debris for different abrasive environments (i.e. particle size and type). The outcome from the combined study of both the systems (i.e. microstructure and abrasive environment) can aid us in understanding the tribological model and in designing better steel microstructures to combat abrasion.

2. Experimental method

The steel used in the current study with a composition of 0.84% C, 0.27% Si, 0.67% Mn and 0.02% Cr (in wt%) had a fully pearlitic microstructure (Fig. 1b). The steel sample was mechanically polished using standard metallographic techniques, followed by etching in a 4 vol% nital solution for microstructural characterization. Friction and abrasive wear experiments were conducted on a CSM high temperature tribometer compliant to ASTM G99 standard (Fig. 1a). A pin sample (approx. 6 mm Ø and 50 mm long) with an angular orientation of 45° was made to slide against an abrasive disc. The angular orientation of the pin ensured that the contact mechanics and the cross sectional area of the pin remained constant during the wear process. Different abrasive environments including silicon carbide (SiC) and alumina were employed by sticking industrial grade abrasive papers to the disc. ImageJ (i.e. Image processing and analysis in Java) software was used to measure the size of the abrasive particles (i.e. particle size). Five measurements were conducted for each condition and an average value was taken. The abrasive wear tests were performed at room temperature in an unlubricated condition with a constant speed of 200 mm/s, a load of 9 N and a sliding distance of 300 m. Friction coefficient measurements were based on lever deflections using a linear variable differential transformer (LVDT) sensor on the tribometer. Before each test, the pin was ultrasonically cleaned in ethanol and weighed on a precise weighing balance to carry out the weight loss analysis after the wear test. The specific wear rate was computed based on the obtained weight loss data.

For the characterization of the abrasive papers, they were gold coated using a high vacuum coater, LEICA EM ACE600 operated at 40 mA for 100 s, to enhance the conductivity for electron microscopic investigations. The characterization of abrasive particles and the microstructure was investigated using scanning electron microscopy (SEM, SUPRA 55VP scanning electron microscope) with a SE2 detector operated at 10 kV and 20 kV for abrasive paper and microstructure characterization, respectively. EDX was also employed to analyse the chemical composition of the debris particles generated during abrasion. AZtec software was used to conduct the EDX analysis and map elements over a defined region. The topography of the deteriorated abrasive particles was investigated using an optical profilometer, Alicona-Infinite Focus by generating three-dimensional contrast rich images. Modular software supplemented the microscopic studies to produce the desired scans using the point selection technique and rendering optical 3D measurements based on depth profiles.

Tests undertaken in the current study concentrated on the influence of the characteristics of the abrasive particles (i.e. particle size and type) on the abrasive wear phenomenon. Therefore, two different types of wear tests were performed, namely: (i) linear or progressive abrasive wear tests and (ii) interrupted abrasive wear tests. In the linear wear test, the specific wear rate of the microstructure was calculated at the end, i.e. after the pin had completed its total sliding distance (i.e. 300 m) on a fixed track diameter. Meanwhile, in the interrupted abrasive test, the material loss of the microstructures was obtained at regular intervals (i.e. each 60 m) under identical test conditions (i.e. same track diameter). It must be noted that the wearing surface of the microstructure was ultrasonically cleaned in ethanol, to eliminate the effect of clogging (i.e. accumulation of debris). This test was a valuable tool in revealing the extent of cutting efficiency of abrasive particles during the abrasion wear phenomenon. The specific wear rate of the pearlitic steel at different abrasive environments was calculated from the weight loss of the pins. The specific wear rate (K) was determined by the volume of the material loss (V), sliding distance (S) and normal load (P). Specific wear rate is given by the equation, $K=V/(P^{*}S)$ (mm^3/N m) [31]. A minimum of four abrasive wear tests were performed for each testing condition (i.e. normal and interrupted abrasive wear tests) to ensure repeatability in the current study.

3. Results

The fully pearlitic microstructure consisted of ferrite and cementite lamellae with an interlamellar spacing of approximately 0.1 μm (Fig. 1b). The currenty study dealt with the evolution of abrasive particle characterisitcs during the abrasive wear behaviour of the pearlitic microstructure. A uniform cross-section ($\sim$500 μm × $\sim$500 μm) of the abrasive papers was analysed to measure the average abrasive particle size for different abrasive environments (i.e. silicon carbide and alumina papers, Fig. 2). SiC abrasive particles a displayed non-uniform morphology (i.e. particle size and shape) and were relatively less densely distributed than the alumina particles over a defined area (Fig. 2d and e). For SiC, the packing density (i.e. particle distribution over a defined area of $\sim$ 500 μm × $\sim$500 μm) was measured as 1×10^{-4}, 1.68×10^{-4} and 8.4×10^{-4} (particles/μm^2) for the particle size of 58 μm, 26 μm and 15 μm, respectively (Fig. 2a–c). Similarly, the packing density of alumina was 2.68×10^{-4} and 6.68×10^{-4} (particles/μm^2) for the particle size of 41 μm and 20 μm respectively (Fig. 2d–e).

The abrasive particle size revealed a significant effect on the specific wear rate of pearlitic microstructure for both abrasive environments (Fig. 3). In general, the specific wear rate decreased with a reduction in the particle size. For SiC environment, the specific wear rate was measured as $(2\pm0.15)\times10^{-4}$, $(1.6\pm0.07)\times10^{-4}$, $(1.2\pm0.07)\times10^{-4}$ (mm^3/N m) for the particle size of 58 μm,

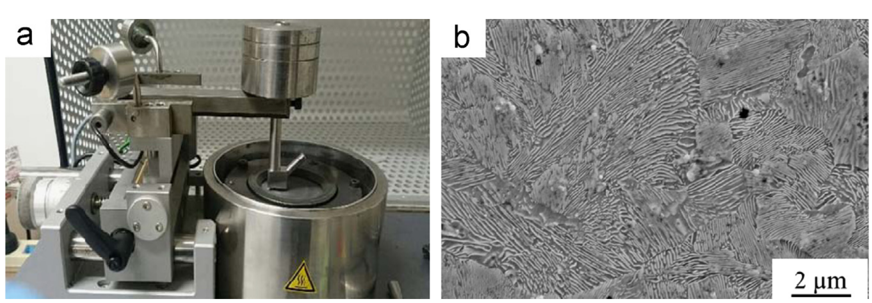

Fig. 1. (a) CSM high temperature tribometer and (b) pearlitic microstructure.