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Comparisons of the two-body abrasive wear behaviour of four different ferrous microstructures with similar hardness levels

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ABSTRACT

The abrasive wear resistance of four distinct metallurgical steel microstructures – bainite, pearlite, martensite and tempered martensite, with similar hardness levels was investigated. A pin-on-disc tribometer was used to simulate the two-body abrasive condition (i.e. the metallic surface abrading against the silicon carbide abrasive particles) and evaluate the specific wear rate of the microstructures. Each microstructure had a unique response towards the abrasion behaviour and this was largely evident in the friction curve. However, the multi-phase microstructures (i.e. bainite and pearlite) demonstrated better abrasion resistance than the single-phase microstructures (i.e. martensite and tempered martensite). Abrasion induced microstructural changes at the deformed surfaces were studied using sub-surface and topographical techniques. The properties of these layers (i.e. surface profile measurements) determined the amount of material loss for each microstructure. These were directly linked to the single-wear track analysis that highlighted a marked difference in their mode of material removal. Ploughing and wedge formation modes were dominant in the case of bainite and pearlite microstructures, whereas the cutting mode could be attributed to the higher material loss in the single-phase microstructures. The combination of brittle and ductile phases in the multi-phase microstructure matrix could be one of the driving factors for their superior abrasion resistance.

1. Introduction

Abrasive wear is an undesirable material removal phenomenon occurring in most mineral and mining processing machinery or equipment. The material removal process takes place when hard particles indent or abrade a relatively smooth material surface and move relative to it [1–4]. Sliding abrasion involves dissipation of frictional energy into heat. A major part of the frictional energy is expended towards the metallic surface (i.e. microstructure). In this context, the amount of frictional energy consumption has a major influence in determining the amount of material removal, which in turn, defines the abrasion resistance of the alloy. Moreover, it has been shown that there is a marked difference in the friction energy consumption of steels due to the distinct characteristics of the microstructural constituents [5–7].

Studies have shown that a linear relationship exists between bulk hardness and abrasion resistance of microstructures with similar metallurgical structures but with different chemical compositions [8,9]. However, it must be noted that the microstructural constituents significantly influence the bulk properties of steels such as hardness, flow stress and fracture toughness. It, is therefore, difficult to neglect the effect of the microstructural constituents in abrasion, as they influence the material removal mechanism in the microstructures [8,10–14]. Literature reports that a eutectoid steel heat-treated to different pearlitic structures (i.e. lamellar pearlite and spheroidized structure) produced different abrasive responses [21]. A significant difference in the abrasion resistance of commercial tool steels AISI D2 and O1 heat treated to similar hardness has also been observed due to the carbide morphology (i.e. plate-like and blocky ones) [22]. This emphasises the fact that the metallurgical structures can play a role in determining the abrasion resistance of a material.

Moreover, in a two-body sliding abrasive system, dynamic changes occur both in the material (i.e. microstructure) and the abrasive particles (i.e. deterioration of abrasive particles) [15,16]. Abrasion induces several morphological changes in the abraded surface, ultimately leading to a difference in its mechanical properties (i.e. hardness and fracture toughness). Thereby, the properties of the abraded or deformed regions are of tribological interest, as they affect the wear mechanism [6,17–20]. Despite substantial studies on the behaviour of microstructures under abrasive wear [11,23–26] limited investigations have been conducted to investigate the tribological system as a whole. This has

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motivated the current study that involves simultaneous examination of the microstructural behaviour (i.e. material removal mechanism) with respect to dynamically changing abrasive conditions (i.e. particle deterioration mechanism and efficiency).

The entire study on the dynamic two-body sliding abrasive system has been dealt in two parts. The effect of microstructures and the role of abrasive particle characteristics in abrasive wear behaviour has been investigated separately. Work in progress at this writing has found that the abrading efficiency of the abrasive particles largely depended on their size and density. Meanwhile, this part of the work focuses on the impact of four distinct steel microstructures, namely bainite, pearlite, martensite and tempered martensite with similar hardness levels on abrasive wear. An attempt has been made to analyse the sub-surface and topographical regions of the deformed microstructures. In addition, single-wear track investigation of microstructures has been undertaken, to understand their mode of material removal.

2. Experimental methods

The materials used in the current investigation consisted of three different steel alloys (Table 1). These steels were subjected to different heat treatment routes to produce distinct microstructures, namely bainite, martensite, tempered martensite and pearlite all with similar hardness levels. Steels A and B were received as ingots and subjected treatment at 1400 °C for 24 h in an argon gas atmosphere. Steel A was then austenitized at 1000 °C for 30 min, followed by austempering in a salt bath furnace at 300 °C for 5 h to obtain a bainitic microstructure. To produce a tempered martensitic microstructure, the fully austenitized structure of Steel A was initially subjected to rapid water quenching resulting in a fully martensitic structure. The sample was reheated (i.e. tempered) at 500 °C and held for 3 h to produce a tempered martensitic microstructure. Steel B was austenitized at 900 °C for 5 min, followed by rapid water quenching to obtain a fully martensitic microstructure. Steel C was used in the as-received condition and had a fully pearlitic microstructure.

Hardness measurements were carried out at 0.01 N with a dwell time of 15 s using a Struers, DuraScan micro-hardness machine. Ten hardness measurements were carried out for each microstructural condition (i.e. before and after the wear test) and an average was taken. Scanning electron microscopic (SEM, SUPRA 55VP operated at 20 kV with a SE2 detector) techniques were employed for microstructural characterisation. The samples were prepared using standard metallographic techniques and etched in a 4 vol% nital solution. To measure the volume fraction of retained austenite in the bainitic microstructure, the polished sample was further chemically treated using a solution of 80% hydrogen peroxide, 5% hydrofluoric acid and 15% water to minimise residual stress and avoid any phase transition during sample preparation. The volume fraction of retained austenite was then measured using the direct comparison method between the integrated intensities of $(200)_\gamma$, $(200)_\alpha$, $(220)_\gamma$ and $(220)_\alpha$. X-ray diffraction was undertaken using a Philips PW 1130 diffract metre with graphite monochromatic CoK_α radiation at 40 kV and 30 mA in the 2θ range of 30–120° at a rate of 0.02°/6 s.

Table 1
Chemical composition of the steels (in wt%).

Alloys	C	Si	Mn	Cr	Mo	Ni	Al	Co
Steel A	0.261	1.61	3.51	1.05	0.275	1.69	0.78	0.49
Steel B	0.046	0.264	1.84	0.0078	0.251	0.0087	0.0702	0.0066
Steel C	0.844	0.27	0.67	0.02	0.006	0.04	0.002	0.004

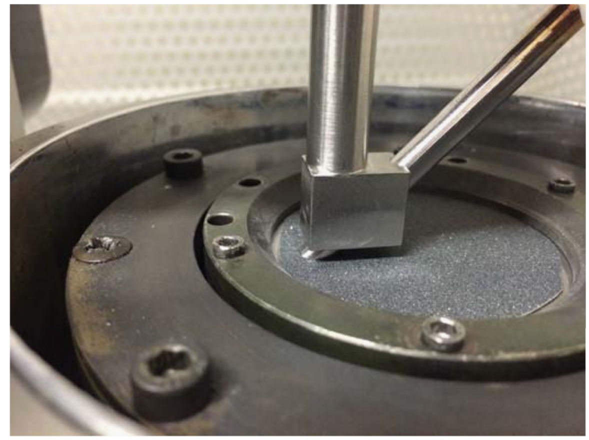

Fig. 1. (a) Pin-on disc tribometer simulating a two-body abrasive environment.

A CSM high temperature tribometer was used to study the abrasive wear behaviour of the microstructures (Fig. 1a). The heat treated samples were machined using an electron discharge machine into the form of a pin 60 mm long and 6 mm in diameter (Fig. 1b) for the abrasive wear tests. The tip of the pin was chambered to 45°, as the pin holder was inclined at 45° to the disc. Therefore, the pin contact (i.e. the cross sectional area of the sample) remained constant throughout the test. A silicon carbide abrasive grit paper was stuck to the disc by an industrial glue (Fig. 1c). In the current study, silicon carbide abrasive grit papers of different particle sizes (i.e. 58 µm, 25 µm and 12 µm) were employed. Subjecting the stationary pin to abrade against the abrasive disc simulates a two body abrasive environment. The tests were conducted in an unlubricated condition with a constant speed (i.e. 200 mm/s), load (i.e. 9 N) and sliding distance (i.e. 300,000 mm). Before and after each test, the pin was ultrasonically cleaned in ethanol to minimise the presence of debris attached to the wear grooves. This was followed by the weight loss measurements. The specific wear rate and friction coefficient of the microstructures were calculated based on weight loss data. At least four tests were performed for each testing condition and an average specific wear rate was presented in the current study.

To clearly understand the mechanism of material removal in the different microstructures, a single-track wear test was performed under controlled testing conditions. The chambered tip surface of the pin was initially subjected to the standard metallographic technique. The pin was mechanically polished further using Oxide Polishing Suspensions (OPS). This led to a light etching of the surface enabling the observation of the interaction of the microstructural constituents with the abrasive particles. The pin was subjected to a minimal traverse (i.e. sliding distance of 20 mm at a sliding speed of 20 mm/s) so that the wear tracks were not overrun by more than one particle. In other words, each wear track was created by a single abrasive particle. The nature of material displacement and the groove characteristics were investigated using scanning electron microscopy.

The topography of the abraded pin surface (i.e. surface roughness and groove characteristics) of different microstructures was studied three-dimensionally using an Alicona-Infinite Focus, optical profligate. The surface roughness and the groove characteristics were analysed using optical 3D measurements. The modular software aided in defining the region of interest using a point selection technique, thereby producing the desired scans or surface profile measurement. The surface profile of the abraded surfaces was quantified based on the characteristics of the peaks and valleys. R_a and R_q (also known as root mean square or RMS) represent the arithmetic and geometric average roughness, which