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Wear reducing effects and temperature dependence of tribolayer formation in harsh environment

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ABSTRACT

Certain materials show a tribolayer formation especially at enhanced temperatures in abrasive environment, building a wear protection layer with the abrasive on the surface. Three materials with different microstructures were tested in three-body abrasive and impact/abrasive environments at temperatures up to 700 °C to investigate tribolayer formation. Optical and electron microscopical methods were used for wear qualification. Furthermore, hot hardness tests were performed up to 700 °C to investigate the influence of hardness drop on tribolayer formation.

It was shown that no significant tribolayer formation occurs on grey cast iron, whereas other materials form tribolayers. Generally, tribolayer formation increases with increasing testing temperature, especially for austenitic and ferritic materials. This entails a self-protecting effect and thus superior wear resistance in abrasive environment.

1. Introduction

Abrasive wear during high temperature applications causes increased damage to materials, which leads to the loss of operability and causes downtimes. To reduce abrasive wear, it is crucial to understand the mechanisms in the tribological three-body abrasion and impact/abrasion contact at various working temperatures. It is known that materials' chemical composition and the microstructure have the main influences on their resistance against abrasion [1–3]; mechanisms can change with increasing temperature [4–6]. Brittle or hard phase rich materials tend to be more wear resistant than ductile ones [7,8]; however, at elevated temperature, mechanisms can change [9,10]. Generally, it can be said that matrix softening at high operating temperature causes reduced wear resistance especially for metal matrix composites [11,12]. Ductile materials, e.g. austenitic steels, can form tribolayers, which reduce wear. This tribolayer formation is affected by temperature, counterpart material, abrasives and other parameters [5,13]. Three different layers can be formed in a tribological contact: (i) transfer layers are built up when the worn surface shows the same chemical composition as that of the mating surface where oxidation does not take place; (ii) mechanically mixed layers are formed when the chemical composition of the debris is a mixture of the wearing and the mating materials, and no oxidation takes place; (iii) composite layers build up in combination with wear and oxidation at higher temperatures. These layers consist of both mating and wearing materials with mixed oxides [5].

The main objectives of this study are the investigation of the formation of tribolayers and the wear mechanisms according to the microstructure of different materials at different temperature levels and loading conditions for casting alloys. In addition to the wear results and the qualitative characterisation of the materials investigated, hot hardness tests provide some information about materials softening with increasing temperature. The investigation shows the performance of different microstructures in impact–abrasive and high stress three-body abrasive conditions at elevated temperatures for a comprehensive understanding of tribological phenomena.

2. Fundamentals of abrasive wear phenomena

Abrasive wear conditions are present especially in mining, earthmoving and minerals processing [14], but also occur in high temperature applications, e.g. pig iron and steel industry, coke production or refuse incineration cf. [15]. Generally, abrasive wear is classified [14,16–18] as follows (i) Gouging abrasion, which occurs when large abrasives, e.g. chunks of rock, are crushed or handled, where, high stress levels dominate when sharp rock edges are cut to tear the material. (ii) High stress abrasion appears when abrasive particles are compressed between two solid

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surfaces i.e. in grinding mills. Following definition is given by Bhushan (editor [14]): "High-stress abrasion is sometimes referred to as three-body abrasion, although two-body, high stress conditions can sometimes exist. High-stress abrasion implies that the abrasive particle is fractured and broken apart during the wear process." (iii) In low stress abrasion generally abrasive forces are so low, that hard phases of the microstructure are not fractured or micro-spalled. This typically occurs when dealing with slurries. (iv) Erosion corrosion in corrosive environments with abrasives in a slurry, where removal of oxide layers and material by abrasives, in addition to accelerated corrosion, takes place due to the removal of the protective passivation layer [19].

High temperature abrasion is investigated by a few authors. Fischer [20] studied high temperature three-body sliding abrasion up to 750 °C. Especially at high testing temperatures, the formation of tribolayers with the abrasive, which strongly adhere to the surface, could be observed. These tribolayers protect the surface against abrasion and lower wear rates. Venkatesan et al. [21] studied abrasion in hot forging dies, using a ring-on-disc model test with abrasives in between, from room temperature (RT) to 600 °C. In this three-body setup the authors found tribolayer formation for soft materials, but also oxidation could be observed. Two-body low stress abrasion at 650 °C was investigated by Liu et al. [22] for a hypereutectic cast alloy with high amounts of hard phases and a conventional 25Cr cast alloy. At this low stress testing, no tribolayer formation could be observed. Antonov and Hussainova [23] also investigated two-body abrasion at high temperature up to 900 °C, but concentrated on ceramics. Nevertheless, one major finding concerning the stainless steel reference AISI 316 is that the corrosion taking place is negligible compared to the abrasive wear loss. Antonov et al. [24] investigated steel and cermets using a new test setup with sample heating system based on the ASTM G65 three-body abrasion testing standard. The main difference is a steel ring instead of rubber where two load regimes were investigated: three-body low stress abrasion, where no significant abrasive breaking takes place, and high stress abrasion. The reference steel material is also AISI 316, and the temperature range in this study is up to 450 °C. A well-developed mechanically mixed layer which includes the abrasives could be found on the surface at high stress conditions and the majority of the abrasive particles in contact are broken. Combined impact/abrasion testing at high temperatures was studied in the work of Zikin et al. [25], Winkelmann et al. [11] and Varga et al. [12]. Composite layer formation could be observed for alloys with low hard phase content, especially austenite. Also oxidation could be found for several Fe-based alloys and tungsten carbides. Zikin et al. [25] concentrated on the wear behaviour of reinforced Ni-based alloys with different types of hard phases. They observed the formation of mechanically mixed layers in the matrix zones with broken abrasives as well as broken hard phase particles. Also, oxidation was observed, albeit very thin layers.

Table 1
Chemical composition of the materials investigated.

Chemical composition [wt%]	A—austenitic stainless steel	B—stainless casting steel	C—grey cast iron
C	< 0.08	0.9–1.3	3.2–3.5
Si	< 1.0	< 2.0	2.5–2.7
Mn	< 2.0	< 1.0	0.5–0.8
Cr	16.5–18.5	33.0	–
Ni	10.5–13.5	–	–
Mo	2.0–2.5	–	–
Ti	5 × C–0.7	–	–
Fe	Base	Base	Base

Taking these investigations into account, it can be expected that tribolayers will form preferentially on soft materials, increasing with temperature. Furthermore, oxidation may take place at high testing temperatures, but plays only a subordinate role dealing with highly alloyed steels. Nevertheless, investigations on cost-efficient cast materials are rare and wear phenomena cannot be predicted reliably yet.

3. Experimental

3.1. Materials and characterisation

Three materials were investigated: Material A, an austenitic steel, which has low hardness and is predestined to form tribolayers in abrasive environment [11,23,24] and is used as a reference material; Material B, a stainless casting steel with precipitated carbides, which should lower wear and stabilise the ferritic matrix against wear cf. [26]; and Material C, a grey cast iron with lamellar graphite and a ferritic–perlitic matrix. Grey cast iron tends to break at graphite lamella and deforms. The cementite, as a hardphase in the perlitic structure, gives matrix stability [27]. These materials were chosen because previous studies mainly concentrated on costly hard phase reinforced materials and cermets, while cost-efficient casting production was mostly neglected.

The chemical composition of the materials is given in Table 1; the cross-sectional analysis is shown in Fig. 1. Material A (Fig. 1a) reveals an austenitic microstructure with twin grain boundaries after etching with V2A reagent (100 ml HCl conc., 10 ml HNO_3 conc. and 100 ml aqua dest.) for 50 s. The homogeneous structure shows no significant precipitations. Average grain size of this steel is 25–50 μm; hardness measurements average ~160 HV10. Material B was etched with Marble's reagent (20 g $CuSO_4$, 100 ml HCl conc. and 100 ml aqua dest.) for 180 s (Fig. 1b) and shows typical dendritic ferritic microstructure with homogenously dispersed chromium carbides at the grain boundaries in the regions solidified last during casting. Due to the carbides, the material's macrohardness is ~420 HV10. Material C (Fig. 1c) was etched with 1%

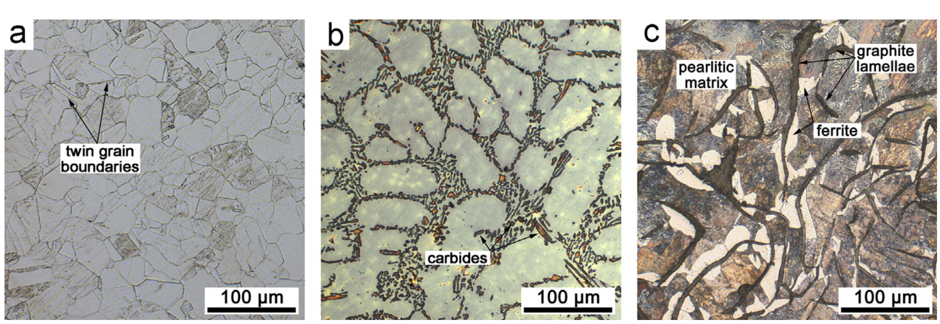

Fig. 1. Cross-sectional analysis of the materials investigated (a) Material A: austenitic stainless steel; (b) Material B: stainless casting steel with high Cr-amount; and (c) Material C: grey cast iron.