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High temperature abrasive wear of metallic materials

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ABSTRACT

Abrasive wear at high temperatures (HT) is a serious issue that limits the lifetime of many industrial components, e.g. in steel production, the cement or the chemical industry. Various forms of abrasion like three-body abrasion, gouging, impact-abrasion or solid particle erosion degrade surfaces.

In order to study abrasive wear behaviour, three different abrasion modes were investigated experimentally up to 700 °C using prospective HT alloys. The wear modes were high-stress three-body abrasion, impact-abrasion and solid particle erosion to investigate the material response to these very different forms of abrasion and to further identify the critical temperatures for the materials. Various temperature- and wear-resistant metallic alloys were compared: materials with low hard phase content (~15%) and Fe-, Ni- and Co-based matrix against a high-alloyed Fe-based hardfacing with a hard phase content >50%.

It was found that the in-situ formation of mechanically mixed layers (MML) with the abrasive provides excellent HT wear protection in many abrasion modes. Hence the mechanisms of MML formation were studied in greater detail, in order to predict the effectiveness of this MML formation in abrasive applications.

1. Introduction

Abrasion is a serious issue in many fields of industry. Especially in mining and earth-moving abrasion is most severe, leading to substantial economic loss [1]. This is further exacerbated, when elevated temperatures are present, like in steel production or cement industries [2,3].

As this work deals with various types of abrasion, which may occur in different components of plants, this discussion will start with a short review on the classification of abrasive wear. The most general classification is based on the constraint of the abrasive and distinguishes two- and three-body abrasion. Two-body abrasion is present when the abrasive is fixed, while for three-body abrasion the abrasive can freely roll between the counter-bodies [4,5]. Though three-body abrasion does not necessarily need a counterface, forces can also be created by the abrasive itself [4,6]. Further classification by the severity of the contact is reasonable. Four abrasion modes are generally differentiated and displayed in Fig. 1 [1,4,7]. Gouging abrasion is present at very high stress levels, e.g. at the manipulation of sharp rocks. High-stress abrasion also implies high stress levels, entailing breakage of the abrasive. This first two, severe forms of abrasion may also be classified as two-body abrasion, as the abrasive particles are locally fixed and acting like a sharp indenter [1]. Low-stress abrasion generally entails no fracture of particles, e.g. an unconstrained flow of abrasive. In solid particle erosion wear is solely caused by the inertia of the abrasive particle alone [6]. For more details of classification of abrasive wear the work of Gates [4] is recommended.

Although wear of material is a serious economical factor, it cannot be linked to individual bulk material properties so far, as it is always a response to the present conditions of the tribosystem [9]. Nevertheless, certain material groups are known to withstand special modes of wear. Often a certain hard phase content is added to improve wear resistance [10,11]. This work concentrates on metallic alloys with chemical compositions leading to the precipitation of hard phases, entailing metal matrix composites (MMCs). A detailed review of MMCs mechanical and wear behaviour is given by Berns in [12]. Here the focus should be placed on the high temperature (HT) behaviour of such materials. Of special interest is the diverging temperature behaviour of metal matrix and hard phase precipitations. While the hardness of most hard phases of technical alloys is not significantly affected in the temperature range where MMCs are commonly implemented, their matrices suffer softening. Fe-based matrices significantly loose

Abbreviations: bal., balance; BSE, Back scattered electrons (SEM); EDX, Energy dispersive X-ray diffraction (SEM); GMAW, Gas metal arc welding; HT, High temperature; HT-CAT, HT-continuous abrasion test; HT-CIAT, HT-cyclic impact-abrasion test; HT-ET, HT-erosion test; MMC, Metal matrix composite; MML, Mechanically mixed layer; OM, Optical microscopy; PTA, Plasma transferred arc (welding); RT, Room temperature; SE, Secondary electrons (SEM); SEM, Scanning electron microscopy; wt%, weight %; XRD, X-ray diffraction

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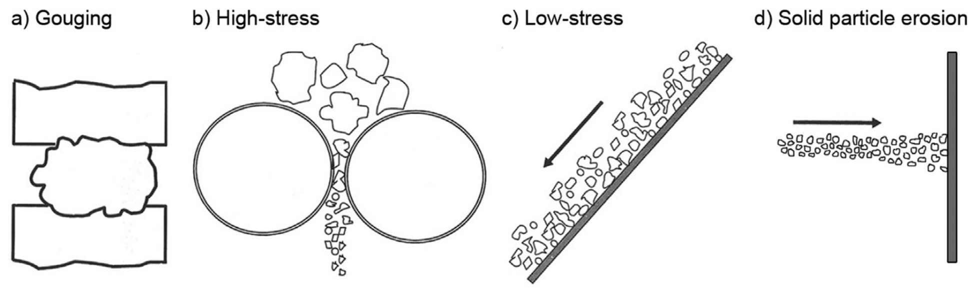

Fig. 1. Schematic of typical abrasion processes: a) gouging [8]; b) high-stress abrasion [8]; low-stress abrasion [8] and solid particle erosion.

hardness in the typical range of 500–650 °C, while for Ni- and Co-based alloys this unbeneficial behaviour is shifted to higher temperatures [12,13]. This matrix softening also can impair the hard phases, entailing pronounced breakage due to failing matrix back-up [14].

In abrasive environments the formation of tribolayers with the abrasive can occur. So called mechanically mixed layers (MMLs) are formed through plastic deformation of the matrix and intermixing with the abrasive [15–17]. This is strongly dependent on the material's properties at application temperature, hard phase content and -distribution, abrasion mode, contact severity, type of abrasive, etc. [16,18,19]. Nevertheless the formation kinetics of MMLs are incomprehensively understood. Hence, the goal of this study is to elucidate the MML forming mechanisms at certain abrasive conditions and furthermore to predict the efficiency of such protective MMLs for abrasive applications. A special focus is laid on the temperature dependence of the MML formation. Thereto the different abrasive modes: high-stress abrasion, impact-abrasion and solid particle erosion will be investigated on prospective HT wear-resistant alloys.

2. Experimental

2.1. Materials

Four prospective materials for HT operation were chosen for investigation. Relative soft cast alloys were compared with a very hard hardfacing. As Fe-based materials show usually a worsened performance above 500–600 °C, a Ni-based and a Co-based material were also investigated. The chemical compositions of the materials are given in Table 1. FeCrC is a typical white cast iron with high amounts of Cr (27–30 wt%) and C (1.2–1.4 wt%). From the chemical composition a ferritic matrix with Cr-carbide precipitations was expected. Samples were taken from a casted rod.

To compare the Fe-based FeCrC with a more temperature stable material, NiCrW was chosen. This is a Ni-based material, also with high amounts of Cr (27–30 wt%) and C (0.35–0.55 wt%) with further W (4–6 wt%), hence Cr- and W-precipitations in an austenitic matrix were expected. Samples were taken form a casted block.

For even higher temperatures Co-based materials are in use. As example a welded CoCrWC overlay was investigated here. Comparable to the two aforementioned materials it also features high amounts of Cr (30 wt%) and C (1.8 wt%) to increase carbide precipitations. Samples were manufactured by plasma transferred arc (PTA) welding technology on austenitic steel plates in one-layered structure.

In contrast to this three previous materials, which were optimised for oxidation/corrosion resistance, a fourth material optimised for abrasion resistance in the form of a hard phase-rich Fe-based hardfacing was investigated. It contains comparatively large amounts of C and B (1.3 and 4 wt%) which were supposed to form carbo-borides with the high amounts of Cr, Nb and W. The hardfacing was deposited with gas metal arc welding (GMAW) technology onto austenitic substrate in a two-layered structure to avoid dilution with the substrate and to maintain purity and high hardness levels of the hardfacing.

Materials were analysed by optical microscopy (OM, Leica MEF4) and scanning electron microscopy (SEM, Zeiss Supra 55 VP) equipped with an energy dispersive X-ray diffraction device (EDX - EDAX). Phase analysis was done by X-ray diffraction (XRD - PANalytical Empyrean Θ-Θ diffractometer in Bragg-Brentano configuration). Quantitative image analysis was done with Leica QWin software for phase analysis [11,20,21]. For phase contrast in OM two etchants were used on the various materials: FeCrC: V2A; others: Murakami etchant. Hot hardness measurements were done up to 800 °C with the hot hardness test rig developed at AC2T research GmbH [22] with 10 kg load.

2.2. Abrasion testing

To investigate the material response to various forms of HT abrasion three different abrasion test rigs were utilised, which are summarised in Fig. 2 and the test parameters used in Table 2. High-stress abrasion which takes typically place e.g. in crusher applications was simulated by the HT-continuous abrasion test (HT-CAT, Fig. 2a). Impact-abrasion, which occurs when falling goods drop onto surfaces and subsequently begin to slide, was investigated by the HT-cyclic impact-abrasion test (HT-CIAT, Fig. 2b). Solid particle erosion was tested with the HT-erosion test (HT-ET, Fig. 2c), which simulates the impacting of small abrasives with no counterbody and is typically found e.g. in exhaust pipes.

The **HT-CAT** is based on an ASTM G65 apparatus [25] modified for HT usage. Thereto an inductive heating system for the samples was used. Further the rubber wheel was replaced by a Hardox 400 steel wheel. The test principle is shown in Fig. 2a*: a heated sample is pressed onto a turning steel wheel with abrasive flow in between. Due to the steel wheel the contact severity is much

Table 1
Chemical compositions [wt%] of the materials investigated (bal. = balance) and their production technology.

Material	C	Si	Mn	Cr	Nb	B	others [Mo, W, V]	Ni	Co	Fe	Technology
FeCrC	1.2–1.4	1.0–2.5	0.5–1.0	27–30	–	–	< 0.5	–	–	bal.	Cast rod
NiCrW	0.35–0.55	1.0–2.0	< 1.5	27–30	–	–	4.0–6.0	bal.	–	15	Cast block
CoCrWC	1.8	1	0.4	30	–	–	< 12.9	–	bal.	< 3	PTA
FeCrNbBWC	1.3	0.5	0.2	15.4	4	4	< 11.5	–	–	bal.	GMAW