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High-temperature cyclic impact abrasion testing: wear behaviour of single and multiphase materials up to 750 °C

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Abstract. The aim of this work was to find correlations between selected microstructural parameters such as hardness, content of hard phases and coarseness of microstructure and the wear resistance at high temperatures. Two materials with different microstructures, showing promising high-temperature wear performance, were investigated under combined impact abrasion conditions at enhanced temperatures using novel high-temperature cyclic impact abrasion testing apparatus. Results indicate that the wear rate increases with the increase of the test temperature. In multiphase materials, the matrix ability to bind hard phases at high temperatures as well as the matrix stability at high temperatures strongly influence the wear resistance. The test results indicate that at higher temperatures the ability to form compound layers may have a positive effect on wear performance.

Key words: high-temperature wear testing, combined impact abrasion, mechanically mixed layer.

1. INTRODUCTION

In many fields of industry, erosion, abrasion and impact at high operating temperatures are the dominant wear mechanisms restricting the lifetime of costly machine parts such as crushers, hammer bars or cutting edges. Abrasive particles with their specific mechanical and geometrical properties are getting in contact with the wearing surfaces with certain energy under different angles of attack causing abrasion and surface fatigue. Hardfacing of bulk materials is one of the methods to modify surfaces and the tribological performances without changing the bulk properties of the components. Important hardfacing alloys are based on the systems Fe-Cr-C and Fe-C-B [1–3]. In this method of surface modification, both the coating and the substrate material is melted giving rise to a good metallurgical bond between the coating and the substrate. Rapidly solidified fine crystalline microstructure, containing finely distributed hard carbide phases, can exhibit an excellent combination of hardness and toughness [4]. To achieve high impact resistance of carbide reinforced materials, good ductility and sufficient interfacial carbide-matrix bonding is necessary [1]. For high abrasion resistance, coarse hard phases and high hardness are important, especially while the hardness of the hard phases and of the matrix are higher than the hardness of the abrasive [5–7]. The materials removal mechanisms by erosion and abrasion at elevated temperatures are superposed by the effect of oxidation [8]. The state-of-the-art of erosive wear at elevated temperature has been reviewed comprehensively in [9]. Materials with high temperature resistance and oxidation resistance are reported in [10,11] to have high alloyed matrix, especially austenites, which behave well.

In view of the above, a novel Fe-Cr-C-B complex hardfacing alloy has been investigated under combined impact/abrasion at elevated temperatures with the aim to understand the wear mechanisms on a basic level. Wear behaviour has been compared to a high alloyed austenitic stainless steel for clarification of the influence of hardness and hard phase content on wear behaviour.

2. EXPERIMENTAL

Within this study, a Fe-Cr-C-B complex alloy (fine microstructure with high hardphase content) and a standard austenitic stainless steel (1.4841, Böhler H525) have been investigated. Chemical composition and hardness of these materials are summarized in Table 1. Typical microstructures of the materials are presented in Fig. 1. Characterization of the microstructure was performed by optical microscopy after etching and scanning electron microscopy (SEM + EDS). Hardness measurements were carried out with a standard Vickers hardness technique HV5. To determine the hardness of each phase in the microstructure, e.g. hard particles and metallic matrix, micro-hardness HV0.1 was used.

The austenitic steel (Fig. 1a) has a heat resistant microstructure at a C-content of 0.08%, Cr-content of 25% and 20% Ni. Hardness of this material was determined as 175 HV5. Austenitic stainless steels have high ductility, low yield stress and relatively high ultimate tensile strength when compared to typical carbon steel. The hardfacing alloy, produced as flux cored wires on iron basis,

Table 1. Summary of the chemical composition and hardness of the materials investigated

Material	Hardness	Chemical composition, wt%						
		C	Cr	Ni	Nb	B	Others (Mo, V, W)	Fe
Austenitic stainless steel 1.4841	175 HV5	0.08	24.8	19.8	–	–	–	base
Fe-Cr-C-B complex alloy	1020 HV5	1.3	15.4	–	4.2	4.2	11.5	base

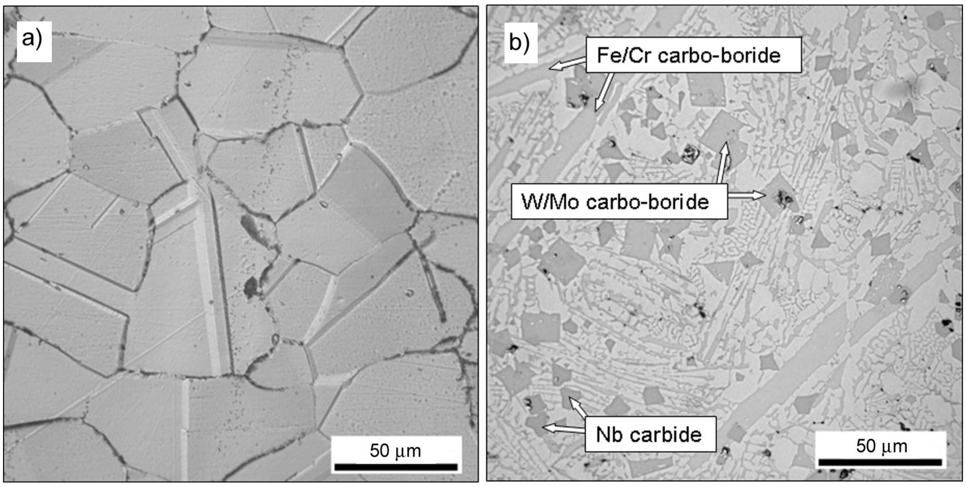

Fig. 1. Microstructure of the materials investigated: a) austenite; b) Fe-Cr-C-B complex alloy.

was welded onto mild steel plates (DIN 1.0038) with dimensions of 150 × 100 × 6 mm. Welding parameters are optimized, related to the welding behaviour in practical welding procedures performed [2]. The Fe-Cr-C-B complex alloy shows a dense and uniform distribution of very hard complex carbides and carbo-borides (Fig. 1b) with hardness values between 1200 and 1900 HV0.1. The hard phases were identified by SEM + EDS as Fe/Cr carbo-borides with a volume content of 52% and a size of 10–100 µm, and Nb carbides and Mo/W carbo-borides with a volume content of approximately 5% in blocky shape [2]. The hardness of the matrix is very high, 1020 HV5. To understand the material removal mechanism, the morphologies of the worn samples are examined with scanning electron microscopy (SEM). Cross-section images of the worn surfaces were investigated with the aim to understand the subsurface deformation and the mechanisms of formation of various coatings.

The high-temperature cyclic impact abrasion testing apparatus (Fig. 2a) was constructed and established at the Austrian Competence of Centre for Tribology (AC²T) to determine the behaviour of materials in cyclic impact abrasive environment at elevated temperatures. Test principle is based on potential energy, which is cyclic, turned into kinetic energy by free fall. The samples are fixed at 45° and get cyclic hit by the plunger, while a constant abrasive flow is running between the sample and the plunger as shown in Fig. 2b. The plunger material used for these tests was a Co-rich high-speed steel. Detailed description of the testing device can be found elsewhere [12]. The testing parameters are summarized in Table 2. Impact energy, angle of impact and frequency were chosen as 0.8 J, 45° and 2 Hz, respectively. The total number of testing cycles was fixed to 7.200 which correlate to a testing duration of 1 h. The abrasive material used for 3-body-contact was fine silica sand at angular shape which can be observed in Fig. 2c. The experiments were carried out at temperatures up to 750 °C with an abrasive flow rate of 3 g/s.

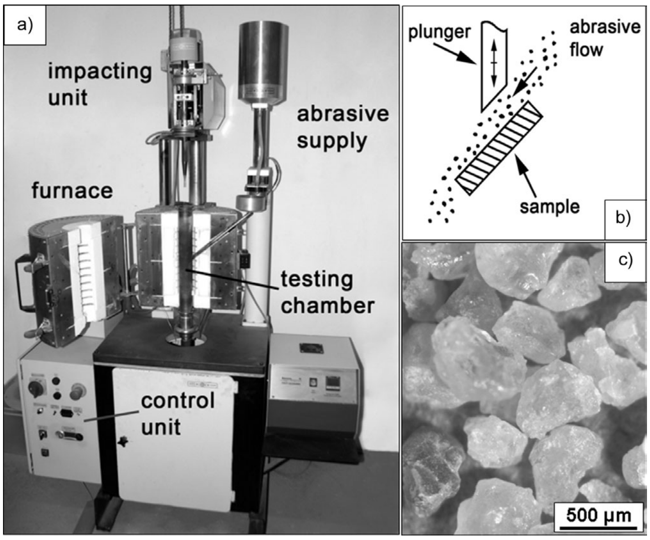

Fig. 2. High-temperature cyclic impact abrasion test (HT-CIAT): a) view of the tester; b) testing principle; c) micrograph of abrasive particles.

Table 2. Summary of testing parameters used in HT-CIAT

Parameter	Value
Impact energy	0.8 J
Impact angle	45°
Frequency	2 Hz
Testing cycles	7200
Abrasive material	Silica sand; 0.4–0.9 mm; angular
Abrasive flow	3 g/s
Testing temperature, °C	500, 600, 650, 700, 750

Characterization of wear behaviour was done by measuring the weight loss of the samples (accuracy 0.1 mg), by standard optical microscopy and SEM. Also cross-section images of the worn specimen area have been made to analyse the predominant mechanisms, e.g. carbide breaking, cold work hardening, composite layer formation and changes in the matrix, caused by high temperature.

3. RESULTS AND DISCUSSION

The dependence of the CIAT mass loss of both materials, investigated at the test temperature, is shown in Fig. 3. In general, it can be observed that the CIAT mass loss of both materials increases with testing temperature. This behaviour can be explained by softening effects, which become dominant at higher temperatures. A good correlation of CIAT mass loss and material hardness can be detected at room temperature, where the softest austenite (175 HV) with a

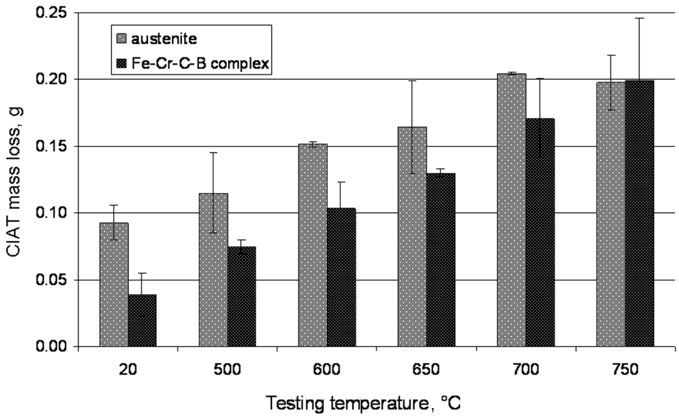

Fig. 3. Dependence of the mass loss of the materials on the testing temperature in HT-CIAT.

lack of hard phases in the microstructure shows higher mass loss compared to the harder Fe-Cr-C-B complex (1020 HV), which behaves best.

The predominant wear mechanisms for the austenite can be observed in Fig. 4. There it can be seen that the materials behaves very ductile by room

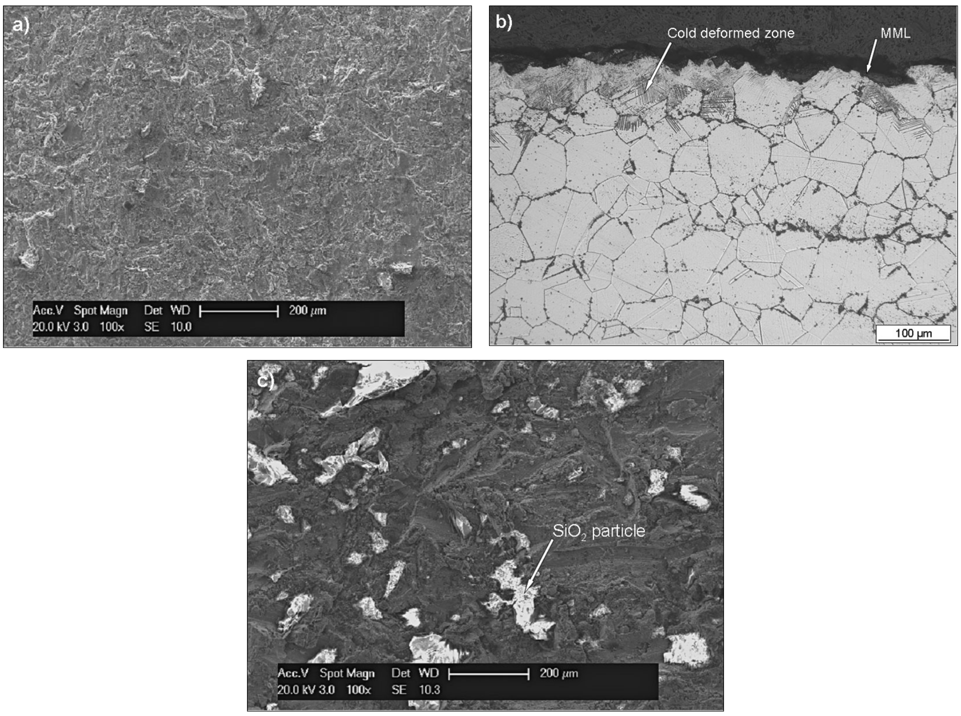

Fig. 4. Worn surfaces of austenite in CIAT: a) SEM of wear mark after testing at room temperature; b) cross-section image after testing at room temperature; c) SEM of wear mark after testing at 700 °C.

temperature testing where a high degree of plastic deformation combined with abrasive grooves are present (see Fig. 4a). This is in good agreement with the observations in the cross-section image, where cold deformed zones are present in the near-surface regions, which can be identified by significant twin formation in the austenitic grains. An increase in hardness by approximately 100 HV can be detected up to a maximum depth of 100 µm (Fig. 4b). With the increase in testing temperature, the plastic behaviour of the austenite is more pronounced.

The wear behaviour of the austenite is governed at higher testing temperatures by the formation of a mechanically mixed layer (MML), where abrasive SiO_2 particles are embedded into the highly plastically deformed near-surface zone and form a MML. This *in situ* formation of the MML strengthens the austenitic surface and protects the materials against wear. This effect gets more dominance at higher temperature and furthermore explains the non-increasing CIAT mass loss at the temperature exceeding 700 °C (Fig. 3). The SiO_2 particles, embedded into plastically deformed surface regions, can be seen very clearly in the SEM image in Fig. 4c. At high temperatures, when the matrix starts softening, a certain amount of coarse hard phases are necessary to withstand grooving and therefore keep the wear on a low level.

The wear mechanisms for the Fe-Cr-C-B complex alloy are illustrated in Fig. 5. It can be observed that the very high wear resistance at room temperature

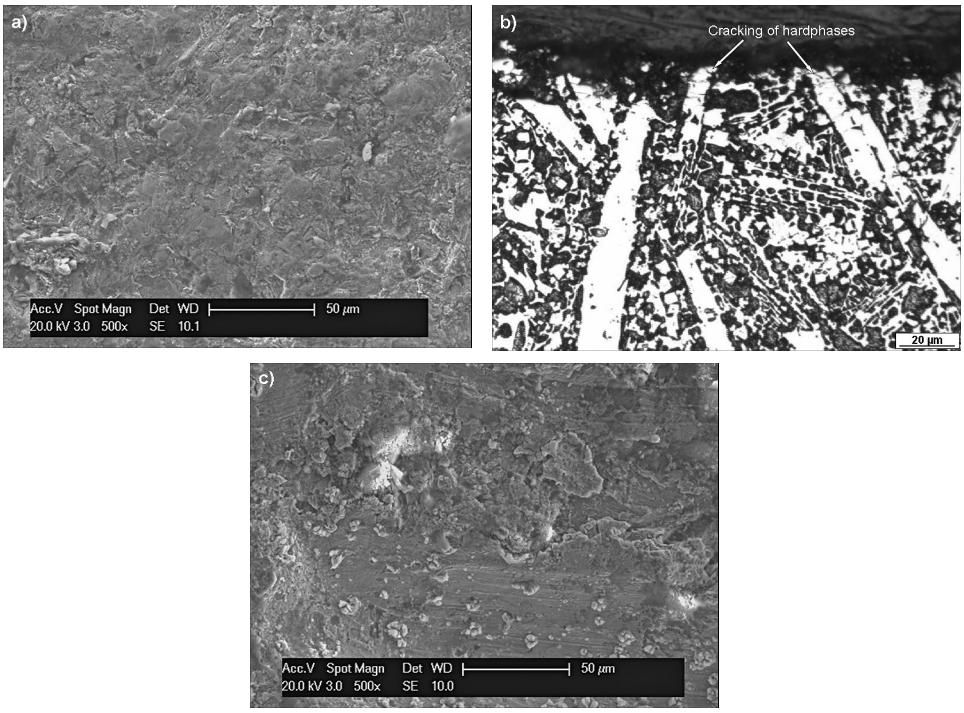

Fig. 5. Worn surfaces of Fe-Cr-C-B complex alloy in CIAT: a) SEM of wear mark after testing at room temperature; b) cross-section image after testing at 600 °C; c) SEM of wear mark after testing at 750 °C.

(see Fig. 3) is in good agreement with the worn surface, where no significant fracture and breakouts are present (Fig. 5a). Only very little grooving and some SiO_2 particle sticking can be detected. Slight increase in mass loss can be observed at 500 °C, whereas the wear resistance is still on a high level. Beginning at a testing temperature of 600 °C, the wear behaviour changes and abrasion marks and highly deformed areas can be detected. Protruding carbides also break at higher temperatures due to fatigue and by the worse matrix backing, which is due to the softening at higher temperatures (Fig. 5b). At the highest testing temperature of 750 °C, massive cracking of hardphases takes place and furthermore these broken hardphases form MML in combination with the deformed matrix and the SiO_2 particles (Fig. 5c).

4. CONCLUSIONS

The following conclusions can be drawn.

- Wear resistance generally decreases under combined impact/abrasion with an increases of the testing temperature in CIAT.
- Softening effects, which become dominant at higher temperatures, increase the formation of mechanically mixed layers.
- Cold deformation and massive grooving are dominating effects in single-phase austenitic microstructures. At higher temperatures a pronounced formation of MML takes place, which protects the material against wear.
- Breaking of coarse hard phases at high temperatures takes place in the Fe-Cr-C-B complex alloy due to fatigue effects and insufficient mechanical support by the matrix.

Summing up, it can be concluded that the high temperature cyclic impact abrasive wear testing device (HT-CIAT) is well suited to evaluate wear performance under combined impact/abrasive conditions.

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Kõrgetemperatuurne tsüklilise iseloomuga abrasioonkulumine: ühe- ja mitmefaasiliste materjalide kulumine temperatuuridel kuni 750 °C

Ewald Badisch, Horst Winkelmann ja Friedrich Franek

Töö eesmärgiks oli mõningate materjali mikrostruktuuri ja omadusi iseloomustavate näitajate – kõvadus, kõva faasi kogus, terasuurus ning kõrgetemperatuurne kulumiskindlus – vaheliste seoste väljaselgitamine. Uuriti kaht eksperimentaalset erineva mikrostruktuuriga materjali. Mõlemalt uuritavalt materjalilt eeldati suurt kulumiskindlust kõrgetel temperatuuridel. Kulumiskindluse uurimiseks kasutati uudse konstruktsiooniga löögilise toimega abrasioonkulumise uurimise seadet. Katsetulemused näitavad, et kulumise kiirus kasvab temperatuuri tõustes. Multifaasiliste materjalide korral mõjutab kulumiskindlust tugevalt maatriksi võime siduda kõva faasi osakesi ja maatriksi vastupanu oksüdeerumisele. Katsetulemuste põhjal võib väita, et kõrgetel temperatuuridel moodustuval reaktsiooniproduktide kihil on abrasiooni vähendav toime.