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Experimental study on the behavior of wear resistant steels under high velocity single particle impacts

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ABSTRACT

High velocity solid particle erosion may cause severe damage and high wear rates in materials used for wear protection. An experimental work on the behavior of wear resistant steels, including three high-strength martensitic alloys and a carbide-reinforced metal matrix composite, was performed in high rate single impact conditions. Characterization of the mechanical behavior of the materials at high strain rates was conducted using the Hopkinson Split Bar technique to identify the effects of strain rate on strain hardening and the prevailing failure mechanisms. The high velocity impact experiments using spherical projectiles were carried out at various impact angles and projectile velocities. The effects of impact energy and impact angle were studied and discussed. Wear was analyzed as volume loss from the surface, but it was also presented in a more precise way by taking into account the actual energy spent on the plastic deformation and wear. In-situ high speed photography and post impact characterization of the impact craters were used to reveal the prevailing failure and wear mechanisms. Depending on the impact angle and impact energy, different wear mechanisms of plastic deformation, cutting, shear banding and fracture were identified. The martensitic steels exhibited adiabatic shear banding in the microstructure at high strain rates and impact velocities, which may accelerate the wear. The carbide reinforced steel was found susceptible to catastrophic fracturing especially at high impact angles.

1. Introduction

In the mining industry, protection of machinery against wear is a challenging task due to the harsh loading conditions. Materials are exposed to both heavy abrasion and high energy impacts when, for example, large amounts of rock material is handled, crushed and transported. From the economical point of view, high wear rates or even premature failure of the machinery can become very costly. Also the environmental aspects are becoming more and more important, and therefore materials that can better resist various types of wear are needed. In heavy industrial components, the capability to bear the high traction loads occurring during scratching and the capability to absorb energy during solid particle erosion are of primary importance. The stress states produced by the different loading types, however, have a different dynamic nature, which is a great challenge for most materials. The use of coatings and composites has in many cases proven useful, but when heavy impacts are considered, steels are still the most widely used materials in wear-prone applications. Lighter structures can be achieved for example by reducing the component wall thicknesses, but to withstand heavy loadings and to retain the component functionality, materials with improved mechanical properties must be developed. In fact, some newly developed high strength steels have in the laboratory scale [1] been shown to provide excellent properties against impact-abrasion type loadings. It is, however, also important to understand their behavior under solid particle erosion and abrasive conditions in order to improve them further.

The theoretical background of solid particle erosion is summarized in various monographs and text books from many different perspectives, including contact mechanics by Johnson [2] and Engel [3], wear and microstructure by Zum-Gahr [4] and Levy [5], and wear testing by Kleis and Kulu [6]. The dynamic nature of impacts exposes the material to high rate deformation, where also inertia

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effects are considerably affecting the material behavior. Dislocation motion during deformation is a rate dependent property of the microstructure, but also the additional thermal effects have to be accounted for. For example, failure mechanisms that are not observed at quasi-static strain rates may be activated during impacts due to deformation induced heating and nucleation of fracture from defects. The regions subjected to high rate shear deformation may also undergo localization to thin shear bands, known as adiabatic shear banding (ASB) [7]. The ASBs have been reported to be responsible for example for fragmentation [8], damage [9,10] and ballistic failure [11,12] in metallic materials. In high strength steels the adiabatic shear bands are generally divided into deformation shear bands and transformation bands. The transformation bands are also known as white etch bands due to their particular white appearance when etched. The white shear bands have been disputed over the years as to what is their microstructural evolution during loading. According to Dodd and Bai [13], the deformed bands can act as precursors for the harder transformed bands, in which the fractures tend to initiate. What is especially important for the wear behavior of the currently investigated steels is whether or not they exhibit strain rate dependent formation of adiabatic shear bands that can act as precursors for damage and fracture.

In an oblique angle impact, energy is consumed in directions both normal and parallel to the surface. The large shear deformations occurring near the surface region result from the parallel stress component, while compressive deformations result from the normal direction component. Hence the material is required to withstand different stress states that occur depending on the impact direction, friction, and the particle properties. Initially Finnie [14] and Bitter [15,16] proposed a model that has been modified over the years for different purposes in the analytical and numerical models for erosion [17]. Most models accept that wear is related to the energy consumed in the cutting and plastic deformation of the material. The impingement angle [18] has been observed to have a great effect on the erosion rate, which is clearly related to the energy dissipation and failure mechanisms. To properly understand the varying behavior of materials under erosion [19], the exact wear mechanisms and their relation to the failure mechanisms need to be studied in more detail.

In the current work, solid particle erosion was studied with a novel high velocity particle impactor (HVPI) device [20]. The main aim of the work was to elucidate the high strain rate response of high strength steels to oblique impacts in a controlled environment.

2. Materials and methods

The studied materials comprise three commercial hot-rolled wear resistant high strength low alloy (HSLA) plate steels and one carbide reinforced wear resistant steel. One of the HSLA steels is commonly used in abrasion applications, in this paper referred to as Abrasion Resistant Steel (ABRS). The second one, Impact Resistant Steel (IRS), is typically used in impact wear related applications. The third one is a higher strength still laboratory grade steel intended for similar applications, here referred to as Advanced Impact Resistant Steel (AIRS). Table 1 shows typical as-received macrohardness values for the studied steels. Table 2 presents the nominal compositions and Fig. 1 the etched microstructures of the steels. Regardless of the similar surface hardness of the tempered martensitic steels, they have different amounts of untempered martensite in the microstructure, appearing white in the etched micrographs, which increases the strength but can be expected to reduce the toughness. Similarly, the effect of martensite morphology and its high angle boundaries affect the mobility of dislocations, which very likely affects the strength and failure properties of the steels. The AIRS has the finest grain size, whereas ABRS and IRS have larger grain sizes but different amounts and distributions of untempered martensite.

For a comparison, a high strength chromium carbide (Cr_7C_3) reinforced steel, the 'composite steel' (COMP), was investigated for its suitability for impact conditions. The reinforcing particles are known to increase the abrasion resistance, but they may also increase the susceptibility to crack initiation from stress concentrations in the microstructure, which could result in a low service lifetime in high energy impact conditions.

2.1. Low and high strain rate mechanical testing

The mechanical testing at low strain rates was performed with an Instron 8800 servohydraulic materials testing machine. All tests were carried out at room temperature using strain rates from 10^{-3} to 10^{0} 1/s. The sample dimensions are presented in Table 1. A thin layer of MoS_2 grease (Molycote) was placed between the tungsten carbide hard metal compression platens and the sample to minimize friction. All mechanical testing on the HSLA steels was performed perpendicular to the rolling plane of the plate. The diameter of the samples was selected based on the strength of the materials and the capacity of the testing machine. The length-to-diameter ratio of all specimens was close to one (see Table 1).

The dynamic properties of the test materials were determined using the compressive Hopkinson Split Bar technique at strain rates ranging from 700 to 3600 1/s. Detailed descriptions of the HSB devices and techniques used at DMS/TUT can be found for example in Ref. [21]. The set-up used in this work consisted of 22 mm diameter maraging incident, transmitted and striker bars. High strength steel inserts were placed on both sides of the actual cylindrical sample to prevent deformation and damaging of the incident and transmitted bar ends. The three millimeter thick inserts were changed after every test. To reduce friction and thus the possibility of barreling of the sample, a thin layer of MoS_2 was used between the sample and the inserts. Copper pulse shapers were placed between the striker and the incident bar to smoothen the incident pulse. As usual, the stress, strain and strain rate in the sample were calculated from the three measured stress pulses (i.e., incident, reflected and transmitted pulses) using Equation (1). For the pulses, a dispersion correction was applied following the method originally presented by Gorham [22].

$$\sigma_E(t) = \frac{A_b E \varepsilon_T(t)}{A_s}, \varepsilon_E(t) = \frac{2C_0}{L_s} \int_o^t \varepsilon_R(t) dt, \dot{\varepsilon}(t) = \frac{2C_0 \varepsilon_R(t)}{L_s} \quad (1)$$

Table 1
The studied wear resistant steels and their sample sizes in mechanical tests.

Material designation	Microstructure	Surface hardness (HV10)	Compression sample size in mechanical testing
ABRS	Tempered martensite (Hot rolled)	500–510	d = 6 mm, L0 = 5 mm, L0/d = 0.83
IRS	Tempered martensite (Hot rolled)	490–515	d = 6 mm, L0 = 7 mm, L0/d = 1.17
AIRS	Tempered martensite (Hot rolled)	540–565	d = 6 mm, L0 = 6 mm, L0/d = 1.0
COMP	Chromium carbides & martensitic matrix	740–760	d = 5 mm, L0 = 6 mm, L0/d = 1.2