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Slurry pot investigation of the influence of erodent characteristics on the erosion resistance of austenitic and duplex stainless steel grades

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ABSTRACT

The erosion resistance of several austenitic and duplex stainless steel grades was investigated with slurry pot tests using erodents with different size fractions and properties. Ranking of the studied stainless steel grades was rather systematic despite the type and properties of the erodent. The results revealed that, on average, duplex stainless steel grades showed better erosion resistance in aqueous slurries than austenitic grades whatever the erodent. Out of the austenitic grades, 316L had higher erosion resistance than that of 904L when tested with high wear-inducing erodents. Regarding the duplex grades, superduplex grade 2507 had the best erosion resistance. The kinetic energy of the erodents explained a substantial amount of the measured erosion mass loss, but chromite for instance was more wear-inducing than expected on the basis of kinetic energy due to the angularity of the particles. Wear surface features of the austenitic grades differed from those of the duplex grades. Reasons for the observed behavior are discussed.

1. Introduction

Wear caused by solid particle erosion has received significant attention amongst researchers in recent years, due to the severity of the problems caused by this phenomenon to components in service, e.g. in the mining and metallurgical industry [1–7]. Mechanical damage to a surface is possible when particles are suspended and/or entrained in a fluid flow that impinges on the surface. The general expression for erosion rate W has been established empirically and can take the form [2]

$$W \propto \dot{M}_p \, K \, f(\alpha) \, v^n \tag{1}$$

where $\dot{M}_p$ is the mass of particles impacting the surface per unit time, v is the particle velocity on impact, α is the particle impact angle, and K and n are constants assumed to be dependent on the characteristics of the erodent/target materials involved. The constant n is commonly reported to adopt values between 2 and 3 [8], leading to a strong dependence of the erosion rate on particle velocity. This can be rewritten for a constant temperature:

$$V_u = E_k^m \, f(\alpha) C_v \, A \tag{2}$$

where V_u is the erosion rate (material loss per impact), E_k is the particle kinetic energy, m is the energy exponent, C_v is the volume fraction of the particles, A is a constant, and $f(\alpha)$ is as in Eq. (1). If particles are assumed to be spherical, the kinetic energy of the particles is

$$E_k = \frac{\pi \, \rho \, D^3 v^2}{12} \tag{3}$$

where D is the particle diameter and ρ is the density of the particles.

The erosion rate of ductile materials typically peaks at a particle impact angle of 30–50° [9], as confirmed for 304 eroded with silica sand [10–12], alumina, and quartz [12]. The dependence of the erosion rate on the impact angle can be ascribed to angular variation of the efficiencies of different erosion mechanisms. At low angles, microcutting is responsible for erosion damage. However, at angles close to the normal impact, another mechanism is active. Originally Bitter proposed that, at 90°, erosion is caused by deformation wear [2]. Hutchings [8] postulated that any unit volume of the target material is lost when it reaches a critical fracture strain. Later modifications [13–18] describe that the formation of an extruded lip (or platelet) and its removal during subsequent impacts in the form of thin platelets is mainly responsible for material loss during normal impacts. Certain studies assume that it is lip formation rather than lip fracture that controls the erosion rate [15]. Regardless of the different opinions on the rate controlling stage in the lip formation and fracture the studies emphasize the importance of the resistance of the target material to the localization of deformation, which is not solely governed by its hardness.

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According to Eq. (1), the erosion rate exhibits power-law dependence on particle velocity. This has been supported by the experimental results for UNS S31603 stainless steel eroded in a slurry pot with sand in a particle velocity range of 5–9 m/s [19]. Eq. (2) demonstrates that the erosion rate depends linearly on the concentration of the erodent. For dilute slurries of 1–3% solids concentration, this dependence is in line with the experimental observations [19]. For more concentrated slurries, the erosion rate does not increase linearly with the solids concentration [20,21]. This can be attributed partly to the decrease in particle kinetic energy due to particle–particle collisions, partly to the blanketing effect, and partly to the decrease in particle rotation [22].

Based on the energy approach, increasing particle size conveys an accelerated erosion rate which has been reported in the literature. The relation between the erodent size and weight loss can show a threshold value, a nearly linear range which then saturates at a certain value [23–26] depending on the experimental conditions. It is known that the slurry pot test arrangements [27,28] typically employed in erosion tests are incapable of detecting the effect of particle size on the erosion rate as an independent parameter because slurry flow and particle impact conditions are too complex and particle-size dependent. This means that the results obtained with different particle sizes, even under the same nominal test conditions, are not directly comparable [29–31]. In addition, there is experimental evidence that particle shape also varies with particle size within a certain erodent [26]. Different target materials can nevertheless be compared.

In a chemically aggressive environment, erosion may accelerate corrosion as the protective passive layer is continuously removed [2,32,33]. This erosion–corrosion may result in high metal wastage rates, e.g. in the hydrometallurgical industry, where stainless steels are extensively employed as construction materials. Appropriate material selection requires an understanding of these complex interactions as well as the erosion and corrosion behavior of the material. The corrosion properties of stainless steels are well established [34] but there is significantly less understanding of the erosion properties of these materials.

The erosion resistance of austenitic stainless steels, especially that of 304 and 316, has been investigated. Less research activity has, however, been dedicated to more corrosion resistant grades, like 904L, in pure erosion. In the slurry pot experiments of Tsai et al. [27], the erosion resistance of austenitic grades 304 and 316L was found to be identical. For the duplex stainless steel family, the erosion resistance of relatively new lean grades is less well understood. Aribo et al. [19] compared the erosion resistance of various stainless steel grades under jet impingement. They concluded that the lean duplex grades LDX 2101 and 2304 had a higher erosion resistance than those of the austenitic 304 and duplex 2205 grades.

The aim of this work was to gain knowledge of the behavior of various austenitic and duplex stainless steel grades in pure erosion, by studying several grades with varying corrosion resistance and mechanical properties in combination with different erodents. This will provide a basis for understanding more complex erosion–corrosion phenomena experienced in the mining and metallurgical industry, e.g. in hydrometallurgical process equipment.

2. Experimental

Two austenitic stainless steel grades, 316L and 904L, and three duplex stainless steel grades, LDX 2101, 2205, and 2507, were tested in as-received condition. Samples of $35 \times 35x3\ \mathrm{mm}^3$ were laser cut from larger sheets for erosion tests. The chemical compositions of the grades are given in Table 1. The corrosion resistance of the tested grades varies widely. The pitting resistance equivalent (PRE) number, which roughly describes the resistance of a material against localized corrosion, is included in Table 1. It is calculated based on alloy composition:

$$\mathrm{PRE} = Cr\% + 3.3Mo\% + 16N\% \tag{4}$$

The higher the PRE number, the more resistant the alloy. It shows that the corrosion resistance of 316L roughly equals that of LDX 2101. Similarly, the corrosion resistances of 904L and 2205 are equal. Superduplex grade 2507 has the highest corrosion resistance. The mechanical properties of the tested grades are shown in Table 2. The duplex grades exhibit somewhat higher strength and hardness compared to the austenitic grades, but their ductility is slightly lower.

Several different erodents relevant to the metallurgical industry were investigated, either after sieving to a desired size fraction or as such. Quartz and chromite were studied in different size fractions. Other erodents were concentrate, ore, matte and tailings. Concentrate and ore are typical raw materials in the metallurgical industry, matte is an intermediate product in the metallurgical processing and tailings are left when all the valuable metals have been extracted.

Table 3 gives a summary of the densities and particle sizes of the erodents. Density values of the erodents were measured by a gas pycnometer (MicroMetrics Corp.). The particle size distributions were measured by sieving. D_{50} (mean particle diameter) and D_{80} (80% of the sample is finer) values were obtained from the measured distributions.

The quartz used as such had a nominal size fraction of 100–600 µm. The measured D_{50} and D_{80} values were 277 µm and 398 µm, respectively. Sieved quartz fractions 75–100 µm and 125–180 µm were produced using custom-made sieves and their particle size characteristics are given in Table 3. Fig. 1 presents scanning electron microscopy (SEM; Jeol JSM-6490LV) images of the quartz erodents. The low vacuum SEM allowed the examination of uncoated particles.

Chromite was divided by sieving into fine and coarse fractions. The D_{50} and D_{80} values of the fine chromite fraction were 29 µm and 68 µm and those of the coarse chromite fraction 56 µm and 117 µm, respectively. Fig. 2 shows the morphology of the fine and coarse chromite fractions.

Table 1
Nominal chemical composition in weight percent of stainless steel grades and the pitting equivalent number calculated from the alloy composition.

Grade	EN	Microstructure	C	N	Cr	Ni	Mo	Others	PRE
316L	1.4432	Austenitic	0.02		16.9	10.7	2.6		25
904L	1.4539	Austenitic	0.01		20	25	4.3	1.5Cu	34
LDX 2101	1.4162	Duplex	0.03	0.22	21.5	1.5	0.3	5Mn–0.3Cu	26
2205	1.4462	Duplex	0.02	0.17	22	5.7	3.1		35
2507	1.4410	Duplex	0.02	0.27	25	7	4		43

Table 2
Typical mechanical properties of the stainless steel grades given by the supplier.

Grade	Proof stress [N/mm^2]	Tensile strength [N/mm^2]	Elongation A_5 [%]	Hardness HB
316L	280	570	50	165
904L	260	330	45	150
LDX 2101	570	770	38	230
2205	620	820	35	250
2507	590	900	30	265