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Erosion–corrosion resistance of various stainless steel grades in high-temperature sulfuric acid solution

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ABSTRACT

Two austenitic stainless steel grades, 316L and 904L, and three duplex stainless steel grades, LDX 2101, 2205, and 2507, were erosion–corrosion tested as impeller blade materials for hydrometallurgical applications. Samples were attached to the pressure and suction sides of an impeller and were tested in 50 g/l H₂SO₄ and 0.5 g/l Fe₂(SO₄)₃ for 72 h at 80 °C and 95 °C in a small-scale reactor using quartz sand slurry. The results showed that under lower erosion intensity the ranking of the grades was similar to that in pure erosion. Under higher erosion intensity the ranking of the grades changed completely: lean alloys LDX 2101 and 316L suffered from the highest mass losses followed by 2205, 2507, and 904L. To clarify this behavior, the ability of the grades to repassivate was investigated with scratch tests. It was found that the ranking could be explained by the repassivation rates. The only exception was that 2507 showed a similar repassivation rate to 904L but its erosion–corrosion mass loss under higher erosion intensity was larger. One contributing factor to this was found to be the selective dissolution of the austenite phase of all the tested duplex grades. The prerequisites for the galvanic coupling between the phases that was responsible for the selective dissolution are discussed.

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1. Introduction

Global trends of declining ore grades, more complex raw materials, and the increasing use of secondary resources have promoted the use of hydrometallurgical processing techniques for the treatment of non-ferrous metals. The hydrometallurgical processing route is a versatile one. It typically involves leaching stages, solution purification stages, and recovery stages [1]. The processing conditions, especially in leaching, are aggressive: sulfuric acid solutions at elevated temperature are often employed [2]. As a result, the corrosion properties of the construction materials are of paramount importance [3,4]. The efficiency of hydrometallurgical unit processes is governed by the reaction kinetics. Effective mixing of constituents is required to ensure high process performance [5,6]. In the leaching stage, solids and sometimes also gases are mixed with the process solution. Consequently, the construction materials are subjected not only to corrosion, but also to solid-particle erosion giving rise to a damage mechanism called erosion–corrosion.

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Erosion–corrosion leads to higher metal wastage rates than the sum of the respective wear rates of pure erosion and flow corrosion. The term synergy has been coined for the difference. It can be expressed by Eq. (1) [7,8]

$$S = T - (E + C) \quad (1)$$

where T is the total wear rate due to erosion–corrosion, E is the wear rate due to pure erosion and C is the material loss rate due to flow corrosion and S is the additional wear rate due to the synergistic interaction between erosion and corrosion. Both the erosion enhanced corrosion rate (ΔC) and the corrosion enhanced erosion rate (ΔE) contribute to the synergism:

$$S = \Delta E + \Delta C \quad (2)$$

In high-temperature acidic environments, erosion can enhance corrosion by:

- Removing the protective passive film and exposing the underlying metal surface to the corrosive medium [7–11] or by creating less protective surface films with embedded particles [12].
- Generating strain-induced martensite in the metastable austenitic alloys or a strain hardened layer that dissolves more readily [13–16] or forms micro galvanic cells on the surface [12].

Table 1

Nominal chemical composition in percentage by weight of the stainless steel grades and the pitting equivalent number calculated from the alloy composition. E–C refers to the samples used in the erosion–corrosion tests and S to the samples used in the scratch tests.

Grade	EN	Micro-structure	C	N	Cr	Ni	Mo	Others	PRE
316L (E–C)	1.4432	Austenitic	0.02		16.9	10.7	2.6		25
316L (S)	1.4404		0.02	0.06	17.7	11.4	2.1		25
904L (E–C)	1.4539	Austenitic	0.01		20	25	4.3	1.5Cu	34
904L (S)			0.009	0.06	19.8	24.3	4.3	1.6Cu	35
LDX2101 (E–C)	1.4162	Duplex	0.03	0.22	21.5	1.5	0.3	5 Mn	26
LDX2101 (S)			0.014	0.22	21.4	1.6	0.3	0.3 Cu 5.0 Mn 0.3 Cu	26
2205 (E–C)	1.4462	Duplex	0.02	0.17	22	5.7	3.1		35
2205 (S)			0.01	0.18	21.9	5.7	3.0		35
2507 (E–C)	1.4410	Duplex	0.02	0.27	25	7	4		43
2507 (S)			0.02	0.29	24.7	6.9	3.7		41

- Increasing the mass transfer coefficient by creating turbulent conditions or by creating a rough surface [17,18].

Corrosion can enhance erosion by several mechanisms:

- Corrosion can weaken the platelets or lips formed during particle impingement, making them more vulnerable to detachment by successive impingements.
- Dissolution of the surface can eliminate the work hardened surface layer and, consequently, particles can penetrate deeper into the material leading to more severe erosion damage.

Erosion–corrosion “maps” are often used to give a visual representation of these interactions and to isolate regimes, in terms of flow parameters, where various mechanisms dominate [19,20].

Quite a number of erosion–corrosion studies have been aimed for marine applications. For example, erosion–corrosion in NaCl environments has been studied using stainless steels [7,21–23], carbon steels [7], cast iron [20], and stellite [20]. Other environments where the synergistic effects have been systematically examined include for instance NaOH and HCl [7]. Meng et al. [22] reported that both austenitic stainless steel grades UNS S31603 and UNS S32760 responded to changes in test conditions in the same way but the better corrosion resistance of UNS S32760 translated into lower mass losses in a NaCl environment. For 316L stainless steel grade, positive synergy has been reported in 0.3 M HCl whereas in 3.5% NaCl, 0.1 M NaOH, and 0.1 M HCl, synergy was negative [7]. It has been reported for 316L that the synergy increased when the relative contribution of erosion decreased [24]. The reason for that could be the fact that under mild erosive conditions corrosion has more time to attack the material surface.

Tribocorrosion (unidirectional sliding) of 316 has been studied in ambient temperature in a sulfuric acid environment [25]. However, studies on the erosion–corrosion behavior of various stainless steel grades in high-temperature sulfuric acid environments are lacking. The aim of this work was to gain knowledge on the behavior of various austenitic and duplex stainless steel grades in high-temperature sulfuric acid solutions, i.e., environments relevant to the hydrometallurgical processing of ores and concentrates. This work is a continuation of investigations where these materials were investigated under pure erosion, i.e., in water [26,27]. In the course of the erosion–corrosion tests, the repassivation properties of the grades became relevant. As no experimental data was found to cover the repassivation rates of all the grades in high-temperature sulfuric acid solution, complementary scratch tests were carried out in the same environment.

2. Experimental

Two austenitic stainless steel grades: 316L (EN 1.4432) and 904L (EN 1.4539), and three duplex stainless steel grades: LDX 2101 (EN 1.4162), 2205 (EN 1.4462), and 2507 (EN 1.4410), were tested in the as-received condition. Samples of $35 \times 35 \times 3 \text{ mm}^3$ were laser cut from the larger sheets for erosion tests. The cut edges were protected by the sample holder so that they were not exposed. Table 1 displays the chemical compositions of the grades together with the values of a Pitting Resistance Equivalent number (PRE). This value is calculated from the alloy composition by

$$\text{PRE} = \text{Cr} [\text{wt}\%] + 3.3 * \text{Mo} [\text{wt}\%] + 16 * \text{N} [\text{wt}\%]$$

The PRE number roughly describes the uniform corrosion resistance of the grades in sulfuric acid based solutions [28]. The higher the value, the better the corrosion resistance is expected to be. Based on PRE considerations, one can expect 316L and LDX 2101 to show the lowest corrosion resistance and superduplex 2507 the highest.

Quartz sand (Nilsjö quartz from Sibelco Nordic) with a nominal particle size of 0.05–0.2 mm was used. The particle size distribution of the sand was measured by sieving and its D_{50} was 121 μm and D_{80} 277 μm . The density was measured to be 2.67 g/cm^3 . A scanning electron image of the sand is shown in Fig. 1. For comparison, one set of measurements was conducted using quartz sand (also Nilsjö quartz from Sibelco Nordic) with a larger particle size (0.1–0.6 mm). A more detailed characterization of this sand can be found in [26,27].

The testing device was a small-scale reactor (about 200 l) and the samples were attached to the impeller blades. The reactor vessel is made of 904 L stainless steel and the axle, impeller, and specimen holders were made of 316L. They were replaced periodically if they showed damage after the test. No galvanic effects were expected between the different stainless steel grades. A schematic picture of the device is given in [27]. A total of 12 samples were tested simultaneously. Six samples were attached to the pressure side of the impeller blades and the other six were attached to the suction side of the impeller blades. The impeller blades formed a 45° angle with regard to the impeller axis. The test temperature and rotation speed were continuously monitored during the tests.

It is well established that the erosion conditions on the pressure and suction sides differ [27]. Pressure side samples are subjected to more uniform erosion, whereas suction side samples are exposed to more turbulent flow conditions, as so-called ‘trailing vortices’ are generated behind the blades [29,30]. As a result, the suction side samples characterize the resistance of various materials against more turbulent conditions, i.e., localized wear

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