Micro abrasion-corrosion of ferritic stainless steels

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ABSTRACT

The synergistic effect between abrasion and corrosion has been widely investigated and debated, where according to some works this synergy accentuates wear, and for others attenuates it. Despite the considerable effort to understand the synergy between abrasion and corrosion, little progress has been made to understand this phenomenon for ferritic stainless steels. This paper analyses the micro abrasion-corrosion performance of ferritic stainless steel with different chemical compositions (11%wt Cr with and without Ti stabilization; 16%wt Cr with and without Nb stabilization) and, for comparative purposes, austenitic stainless steel (18%wt Cr − 8%wt Ni) and carbon steel (0.2%wt C). The specimens were tested for corrosion (turbulent and aerated environment), micro abrasion and micro abrasion-corrosion. For the corrosion tests, a 1 N H_2SO_4 solution was used, a 10%wt mixture of SiO_2 in distilled water for the micro abrasion tests, and an abrasive-corrosive environment of 10%wt SiO_2 in 1 N H_2SO_4 for the micro abrasion-corrosion tests. In the micro abrasive wear tests there was not a clear trend between the different materials tested, despite differences in their chemical composition, mechanical properties and microstructure. On the other hand, their performance was ruled by their chemical composition, in particular the Chromium content, under abrasion-corrosion conditions. This indicated the predominant role played by corrosion in abrasive-corrosive environments in this particular tribo-system. For all materials tested, micro abrasion wear coefficients were higher ($4\times$) than those measured under abrasion-corrosion conditions. Friction coefficients could also be measured by a 3D load cell strategically positioned in the specially developed micro abrasion-corrosion device, showing a strong reduction ($2\times$) in friction coefficient under abrasion-corrosion conditions when compared with solely abrasion conditions. This was attributed to the formation of a corrosion product, mainly constituted of iron sulphate (identified via FTIR), which has lubricant properties.

1. Introduction

In various engineering applications, mechanical components are simultaneously subjected to a combination of mechanical wear and corrosion [1,2]. Due to their high corrosion resistance, stainless steels could be interesting candidates, despite their relatively low mechanical resistance when compared to other hard wear-resistant materials. For example, in conditions of moderate corrosion in combination with mechanical wear, such as in the initial stages of sugar cane plants for ethanol production, a previous work proved an exceptional performance of inexpensive ferritic stainless steels at low cost-benefit ratios [3].

In systems where corrosion and mechanical wear occur simultaneously, phenomena such as plastic deformation influence mechanical failure by wear, but also lead to the removal of passivating layers present in the metal surface. Exposed metal surfaces may be highly reactive to the environment, which can accelerate corrosion [4]. Moreover, the presence of stresses changes the electrochemical response of mechanical components and structures [5].

Typically, corrosion and abrasion are investigated separately. However, attempts to include the influence of a corrosive environment on wear via a mathematical approach have incurred in great dispersion and considerable errors [6]. According to Wood et al. [7], these errors may be reduced for tests that impose the combined effect of corrosion and wear "in situ". In this case, the mechano-electrochemical results dispense the mathematical approach for the synergistic effects. The combined effect between abrasion and corrosion, the so-called synergistic effect, has been widely debated in the literature. According to some authors, abrasion accentuates corrosion [2,6–11], whereas for others abrasion attenuates it [9,10]. However, even if considerable effort has been done to understand the synergy between abrasion and

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corrosion, little progress has been made to quantify this phenomenon for stainless steels [6].

The corrosion resistance of stainless steels is attributed to the formation of a protective passivated layer and they are generally regarded as materials that are easily repassivated. The dynamics involving removal of the passive layer by mechanical action and repassivation plays an important role on the abrasion-corrosion resistance of stainless steels. The complex tribochemical mechanisms of stainless steels depend on the microstructure and chemical composition of the material surface, the solution pH, the abrasive (size, type and concentration), and the imposed electrochemical conditions [7].

Bello et al. [6] performed abrasion-corrosion tests for AISI 304, AISI 316 and duplex stainless steel using SiC (diameter $\phi = 4.5\ \mu m$) abrasive in a 3.5%wt sodium chloride solution in distilled water. The abrasion corrosion tests showed higher passivation current densities than pure corrosion tests and this was attributed to the removal of the passive layer.

Another point regarding abrasion corrosion tests of passivating materials such as stainless steels is that they usually show more dispersion of the electrochemical current than pure corrosion tests, which is partly attributed to competition between the removal of the passive layer and repassivation [7].

Several studies have measured abrasion-corrosion for biomaterials and various coatings [7,8,10], including CoCrMo alloys and duplex stainless steels, materials that are easily repassivated. Those works showed higher current densities under abrasion-corrosion conditions when compared with pure corrosion conditions, due to removal or damage of the passive layer.

For carbon steels, current density increases with the applied normal load, showing the abrasive effect on the passive film [2].

For WC-metal composites tested using basic slurries, the metallic matrices that formed passive layers showed higher resistance under abrasion-corrosion conditions when compared with pure abrasion conditions, i.e., a negative synergy between abrasion and corrosion. On the other hand, for the matrices where corrosion resulted in the loss of matrix support for the carbides, resistance decreased under abrasion-corrosion conditions, showing a positive synergy between abrasion and corrosion [9].

Most studies about abrasion-corrosion resistance of stainless steels are mainly focused on more traditional materials, such as AISI 304 and AISI 316 stainless steels, and, more recently, on AISI 2205 duplex stainless steels. The investigation of cost effective ferritic stainless steels for those applications is often neglected. Despite this, they have found an important application niche in the biofuel industry [3], which certainly involves abrasion and corrosion. Within ferritic stainless steels, it is relevant to investigate the effect of Cr content on tribocorrosion, as well as the effect of stabilization. The cheapest stainless steel is 11Cr (DIN 14003) and it has vast application in the sugar-cane biofuel industry. 11CrTi (ASTM S40910) is also a low-cost ferritic stainless steel stabilized with Ti, largely used in automobile exhausts systems. 16Cr (ASTM S43000) steels are slightly more expensive ferritic stainless steel, mainly used in the cutlery industry, but they are still cheaper than austentic steels. 16CrNb (ASTM S43000) is the same stainless steel stabilized with Nb, used in cutlery and stamping. On the other hand, austenitic stainless steels, such as 18Cr8Ni (AISI 304), present higher cost, but are extremely versatile in their use, with high corrosion resistance, good formability and weldability.

This paper analyses the micro abrasion-corrosion performance of ferritic stainless steel with different chemical compositions:

- 11%wt Cr with (11CrTi) and without Ti (11Cr) stabilization;
- 16%wt Cr with (16CrNb) and without Nb (16Cr) stabilization;
- For comparative purposes, one austenitic stainless steels with 18%wt Cr and 8%wt Ni (18Cr8Ni) and one carbon steel with 0.2% wt C (ASTM A36).

The specimens were characterized in terms of corrosion, micro-abrasion and micro-abrasion-corrosion. For all materials tested, friction coefficients were measured by a 3D load cell.

2. Methodology

2.1. Materials

Four ferritic stainless steels were selected for this work and were compared with one austenitic stainless steel for its great versatility in terms of use. The ferritic stainless steels had different Cr contents and were tested both in stabilized (with Ti or Nb) and non-stabilized conditions. All the stainless steel specimens were used after industrial hot rolling and annealing (see hot rolling temperatures and annealing conditions in Table 1). The stainless steels were also compared with a commercial low carbon steel, ASTM A36, in the hot rolled condition, due to its low cost and large applicability in engineering applications.

Their chemical composition, which was evaluated by different techniques [infrared absorption, (Leco, *CS444*®), thermo conductivity (Leco, *TC436*®), X-ray fluorescence spectrometry (Thermo ARL, 9900) and optical emission spectrometry (Thermo ARL, 4460)] is presented in Table 2.

The specimens were thoroughly characterized in terms of mechanical properties [tensile tests (Instron, 5583) and Vickers hardness (Instron Wolpert, *Testor 930*®)] and microstructure, details can be found in [12]. Table 3 summarizes the main mechanical properties of the materials tested.

For each material, samples were cut into coupons with dimensions of 35x25 × 5 mm^3 and then sanded (grit sizes of 220 and 600). After this step, they were subjected to ultrasonic cleaning in acetone for 15 min and dried. All materials were tested for pure corrosion, pure microabrasion and microabrasion-corrosion.

2.2. Corrosion tests

A standard 2 cm^2 of active area for the corrosion and abrasion-corrosion tests was obtained using nail varnish and wax. A copper wire bonded by a silver glue established the electrical contact. To ensure the solidification and fixation of the wax on the specimen and consequently the reproducibility of the results, the entire preparation process occurred at least 8 h before each test.

The electrolyte was a 1 N H_2SO_4 (F. Maia Ind. e Com. Ltda - Brazil) solution in distilled water. A platinum gauze was the

Table 1
Industrial hot rolling and annealing conditions.

Specimen	11Cr DIN 14003	11CrTi ASTM S40910	16Cr 16CrNb ASTM S43000		18Cr8Ni AISI 304
Final hot rolling temperature (°C)	1000 + 50	950 + 50	1000 + 50	950 + 50	1100 + 50
Annealing soaking temperature (°C)	760 + 50	950 + 30	780 + 20	930 + 20	1040 + 20
Annealing time	8 h	30 s	8 h	30 s	30 s