



The effects of particle angularity on low-stress three-body abrasion-corrosion of 316L stainless steel



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ABSTRACT

This study investigates the effects of particle angularity on the tribo-electrochemical behaviour of 316L stainless steel under low-stress three-body abrasion–corrosion conditions. Different angularity particles were delivered to the interface between the samples and a rotating rubber counterface, while changes in current with time were potentiostatically monitored. Based on a linear relationship existed between tribological factors (load and speed) and the average current evolved, an empirical correlation is proposed and possible underlying mechanisms are discussed. The effects of particle angularity on the surface and sub-surface damage are also demonstrated. It was found that increasing particle angularity improved their depassivation efficiency.

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1. Introduction

Superior corrosion resistance of stainless steels is due to the presence of a nano-scale passive film on their surface [1–3]. The passive film is, however, prone to localised breakdown as a result of chemical [4–6] and/or mechanical attack [7–9], leading to accelerated corrosion. Tribocorrosion, defined as the conjoint action of tribological wear (mechanical damage) and corrosion (electrochemical dissolution), is a frequently encountered cause of the passive film breakdown [10,11]. Over the past two decades, various tribo-electrochemical methods have been successfully applied to elucidate how mechanical abrasion or erosion accelerate corrosion of passive stainless steels [12–19].

Tribocorrosion is usually divided into two distinct categories: i) erosion-corrosion, and ii) abrasion-corrosion [10]. In erosion-corrosion, the particles (entrained in a flowing solution) disturb the integrity of the passive film by impacting the surface. Published results revealed the following critical mechanical factors that determine the severity and rate of erosion-corrosion: impact angle [8,20–22], kinetic energy of the particles (affected by particle size, density and impact velocity) [23–27], particle hardness [28], shape and the shattering strength [29].

Abrasion-corrosion, the second category of tribocorrosion, is further divided into two contact types: i) two-body; where two solid bodies slide against each other, and ii) three-body; where abrasive particles are trapped between two surfaces in relative motion. In both cases the surfaces are loaded and the motion occurs in a corrosive environment.

Fundamentals of the *dynamic* two-body abrasion-corrosion of passive materials have been studied by several research groups, e.g. Refs [15,30–33]. It was shown that in a two-body abrasion-corrosion contact (reciprocating or pin-on-disc) where an inert counterface slides on a passive metal, the depassivated area is generated at a rate that depends on the sliding velocity, v , and the applied normal force, F .

Three-body abrasion-corrosion, involving interactions between loosely held coarse abrasive particles forced against the passive film, is yet to be well understood. The particles (third bodies) trapped between two surfaces under load, abrade the passivating material (which could be one or both of the surfaces) by rolling or sliding across the interface. Studies published so far either quantified the synergy between three-body abrasion and corrosion [34,35], or investigated the interactions between three-body abrasion and electrochemical corrosion [19,36]. Under identical electrochemical conditions, the damage to the passive film in three-body abrasion-corrosion can be affected by several interconnected variables such as the load exerted on the particles, frequency of particle-surface interactions, load-bearing ability of the passive

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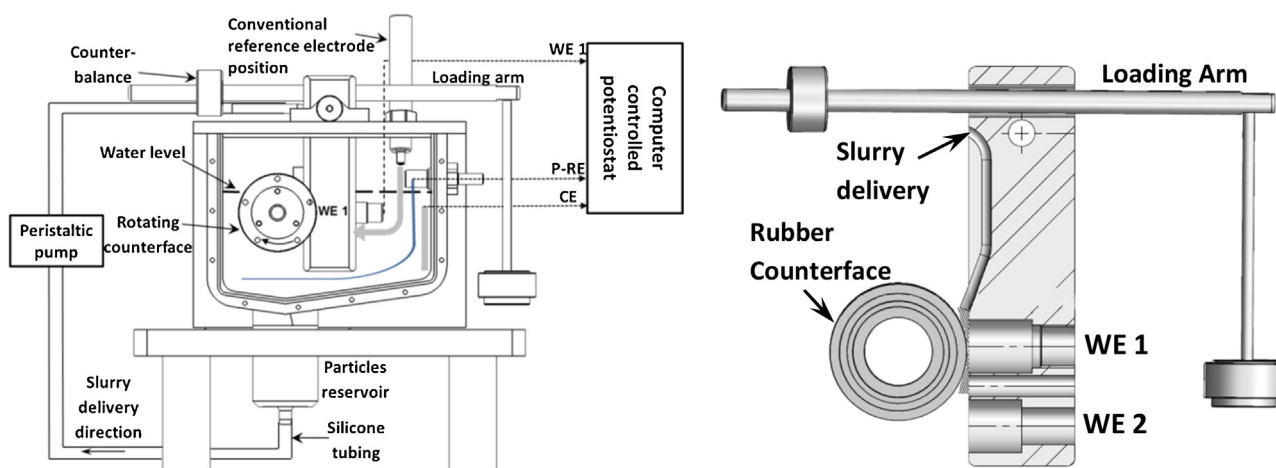


Fig. 1. Tribo-electrochemical test rig used in the three-body abrasion-corrosion experiments.

film, hardness of the counteracting surfaces, and particles characteristics such as hardness, size and angularity.

A significant factor in controlling three-body abrasive wear rate is angularity (or sharpness) of the abrading particles. This study investigates how the particle angularity affects the electrochemical corrosion of 316L stainless steel at different normal loads and counterface tangential speeds, under low-stress three-body abrasion-corrosion. It is believed that understanding the relationship between the mechanical factors and the current evolved is instrumental in developing a semi-mechanistic model for three-body abrasion-corrosion contacts.

2. Experimental

2.1. Test rig and materials

Schematic of the tribo-electrochemical test rig is illustrated in Fig. 1 while the details are described in Refs [19,36,37]. As shown in Fig. 1, the test rig incorporates three electrodes necessary for electrochemical testing, i.e. 316L stainless steel (SS316L) working electrode (WE1), platinum (Pt) counter electrode (CE) and Pt pseudo-reference electrode (P-RE). A rubber ring counterface (10 mm wide and 40 mm in diameter) rotates against a loaded flat wear sample (WE 1) while the abrasive slurry is delivered to the contact interface. This contact configuration was found to simulate low-stress three-body abrasion-corrosion, i.e. the particles remain relatively intact [36].

Three types of abrasive particles were used: glass beads (GB), silica sand (SS), and alumina (AO). Particle average size, Vickers microhardness, and angularity (A_{SPQ}) of each abrasive type are given in Table 1. Representative secondary electron SEM images in Fig. 2a illustrate shape differences of the particles while the particle size distribution, measured by laser diffraction, is shown in Fig. 2b.

It is generally accepted that the particle-size effect on abrasive wear rate becomes pronounced for particles smaller than about 100–150 μm , and for larger particles abrasive wear is rather independent of grit size [38,39]. This size effect was confirmed for wear samples with different hardness and for different applied loads. Therefore, small differences in the average sizes between the three particle types (Table 1) are deemed not significant in affecting three-body abrasion-corrosion. On the other hand, the particle shape, characterized in this study in terms of particle angularity, is very important. For a given load on a particle, particle angularity affects the groove area and the contact pressure.

The particles angularity (A_{SPQ}) was quantified using a ‘spike parameter-quadratic fit’ (SPQ) method, developed by Hamblin and Stachowiak [40]. For each particle, the method isolates the boundary features protruding outside the average-radius circle of the particle. These protrusions, called ‘spikes’, are most likely to cause abrasion. Quadratic segments are then fitted to both sides of each spike and differentiated; the cosine of half the apex angle, called ‘spike value’ (SV), is used as a measure of the spike’s angularity. The SPQ value for a particle is averaged over all individual SVs [41]. For each type of abrasive particles used the SPQ values of at least 50 particles were calculated and the average value is denoted as A_{SPQ} .

Particle hardness, another parameter considered in abrasion-corrosion, significantly affects the wear rate only when the ratio r of particle hardness to wear sample hardness is between 0.8 and 1.5 [42,43]. Since in all tests the ratio r was higher than 2 (the hardness of SS316L was 210 HV), the abrasive wear rate is presumed to be independent of the particle hardness. Therefore, any differences in the wear rates, or abrasion efficiency, between the three types of particles used should be affected predominantly by the differences in their angularity. The low-stress abrasion conditions were selected to avoid fracture of the loaded particles that would alter their original angularity values.

The SS316L wear samples, mounted in an epoxy resin, were ground using SiC papers to a 1200 grit finish, resulting in an average surface roughness R_a of 0.03 μm . Prior to testing, the samples were rinsed with ethanol and ultrasonically cleaned for 3 min in deionised water. A nominal surface area of 1.13 cm^2 was exposed to 1.5 L of an open-to-air 3.5 wt% NaCl electrolyte. Temperature of the solution was 24 (± 2) $^\circ\text{C}$. Unbuffered solution (pH 6.2) was used for the tests. It was found, however, that the presence of GB increased the pH of the unbuffered solution from 6.2 to 11. To investigate the effect of pH change on the current evolved, verification tests were conducted where the solution pH was buffered at 8.35 (± 0.03) by adding 0.01 M sodium bicarbonate. No significant differences in the current evolved were found between the buffered and unbuffered solutions indicating that the GB effect on the solution pH did not change the tribo-electrochemical results.

2.2. Tribo-electrochemical tests

The tribo-electrochemical tests were conducted potentiostatically while potential of the sample was monitored against a long Pt wire used as a pseudo-reference electrode (P-RE) [44,45]. Prior to selecting Pt wire as the pseudo-reference (P-RE), its potential in 3.5 wt% NaCl was measured against a double junction Ag/AgCl

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