

ABRASION-CORROSION: A REVIEW

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ABSTRACT

The abrasion-corrosion wear mechanism is characterized as an important part in the failure of tribological systems, and the total loss of material, which in this case is configured by the synergistic combination of the abrasion and corrosion processes. Abrasion-corrosion occurs in different working environments such as metalworking, sugar-alcohol, oil-gas, biomechanics, among others, and therefore, a more in-depth knowledge of this process is important. In this context, the objective of this work was to perform a state of the art on the synergy involved in the wear mechanism of a material subjected to abrasion-corrosion. Some techniques found in the literature focused on the study of the abrasion-corrosion process and results that the authors had from their respective researchers in the area were discussed. At the end of this work, it is concluded that the synergy between the abrasive and corrosive process promotes a more severe mass loss in a body that is subjected to both processes simultaneously, than the body subjected only to wear by corrosion or abrasion.

Keywords: Synergy, Abrasion, Corrosion.

INTRODUCTION

In the failure of tribological systems, the abrasive-corrosive process plays an important role in many engineering and bioengineering applications. Pumps and valves in oil and gas processing and in the naval industry, metal surgical implants for bone replacement in the human body, and equipment in the production of biofuel - ethanol, are examples of systems subjected to the phenomena of abrasion and corrosion simultaneously [1, 2, 3]. When there are applications involving relative movements between materials, such as that occurring in abrasion, and electrochemical processes, such as corrosion, there is a process called abrasion-corrosion [4].

The interactions between mechanical and corrosive processes are very complex, and the failure of materials by the synergistic action of these two distinct processes still requires a more in-depth understanding and a more detailed investigation. Currently, there have been efforts aimed at creating diagrams that identify the synergism between the process of corrosion and tribological [4, 5, 6].

There are studies that study abrasion and corrosion separately, through mathematical modeling and experimental research, in order to evaluate the interactions between mechanical and corrosive damages and, thus, to try to understand the influence of the corrosive environment, however, they present great dispersion and many errors, since the final effect promoted by the simultaneous action of the two processes is not the same effect that is calculated simply by summing the effects of each analyzed in isolation [4, 7]. Therefore, test apparatus for simulating an abrasive-corrosive medium should promote a combination of these processes and provide data during the joint action [6]. Material selection and surface design should be done in such a way as to provide a correct balance between the corrosion resistance of the material and the ability of the material to form a passive layer in the corrosive working environment while also being subjected to abrasive wear, which can prevent complete passivation of the surface, always leaving areas vulnerable to corrosion [2].

In this context, the deepening of the subject related to the combination of abrasive and corrosive wear is relevant for many areas of engineering.

MATERIALS AND METHODS

A review of the literature was carried out regarding the processes of abrasion and corrosion when they occur simultaneously, giving origin to a unique synergetic wear mechanism, called abrasion-corrosion. For this, concepts and basic notions of each term were approached, as well as some forms of tests, parameters analyzed and results of these tests.

RESULTS AND DISCUSSION

Synergistic effect of abrasion-corrosion

A thorough understanding of the subject of abrasion-corrosion cannot be achieved without synergy. The synergistic effect of abrasion and corrosion can lead to more severe wear. The value of the sum of the loss of material due solely to corrosion and abrasion is only less than the value of the loss of material promoted by the abrasive-corrosive process, meaning that the synergy is a combined effect of these two processes when acting simultaneously. Corrosion can aid in the rate of abrasive wear, in the same way, that abrasive action can improve corrosive attack, and consequently lead to a synergistic relationship between mechanical and chemical interactions. The corrosive action favors the formation of the passive film on the surface that participates in the abrasion process [5, 8, 9].

There are corrosion resistant metal materials depending on a surface oxide film or film to provide corrosion protection. However, under stress applied externally during the wear process, this film can be removed and, a flow of electric current between worn areas and non-worn areas begins, thus indicating the beginning of the corrosive process, which will progress until the movie will recompose itself [2].

Stainless steels, for example, have this oxide film, or passive film, for corrosion resistance, and damage to this layer caused by wear processes, such as abrasion or sliding between the steel surface and a counter body, normally result in localized and accelerated corrosion. Damage or fractures occurring in the passive layer are also known as depassivation [4].

Thus, the accelerated corrosion process in an abrasive-corrosive process has two important ones, the first one related to the amount of protective material during the abrasion and the second related to an amount of metal that needs to be oxidized to a depassivated area return to have a passive layer of protection [10].

Mechanism of abrasion-corrosion

Using simple definitions to establish the ratio of the contribution of abrasion to the contribution of corrosion, abrasion regimes are defined in aqueous conditions as [11]:

- a) $K_c/K_a \leq 0,1$ (abrasion);
- b) $0,1 < K_c/K_a \leq 1$ (abrasion-corrosion);
- c) $1 < K_c/K_a \leq 10$ (corrosion-abrasion);
- d) $K_c/K_a > 10$ (corrosion).

In which, K_c is the total corrosion rate and K_a is the total abrasion rate, both given generally in grams.

Regarding the characterization of the effect of the abrasion-corrosion process, it can be separated into two parts: increased corrosion due to abrasion and increased abrasion due to corrosion [9], according to Eq. 1:

$$\Delta m_S = \Delta m_T - (\Delta m_A + \Delta m_C) = \Delta m_A/C + \Delta m_C/A \quad (1)$$

In that, Δm_S is the mass loss ($\text{mg/h}\cdot\text{cm}^2$) due to the synergistic effect; Δm_T is the total mass loss due to abrasion-corrosion; Δm_A is the mass loss ($\text{mg/h}\cdot\text{cm}^2$) due to abrasion only; Δm_C is the mass loss ($\text{mg/h}\cdot\text{cm}^2$) due to corrosion only; $\Delta m_A/C$ is the mass loss ($\text{mg/h}\cdot\text{cm}^2$) due to the effect of abrasion on corrosion and $\Delta m_C/A$ is the mass loss ($\text{mg/h}\cdot\text{cm}^2$) due to the effect of corrosion on abrasion.

Thus, the existence of a synergistic effect between abrasion and corrosion means that the total damage caused by the abrasion-corrosion process is greater than the sum of the damages caused by abrasion only or corrosion only [9], according to Fig. 1.

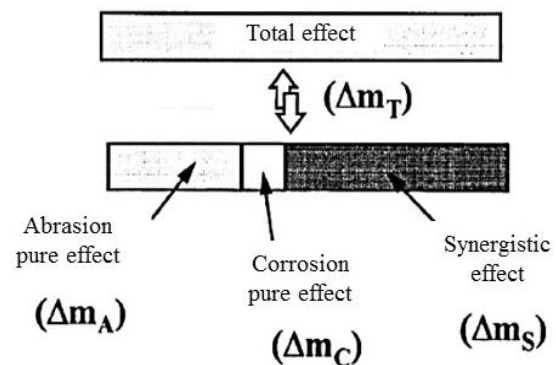


Figure 1. Representation of the contributions of damages during the abrasion-corrosion process [9].

Important parameters in abrasion-corrosion

Effect of the relative velocity between the bodies in contact

The relative velocity of sliding between two bodies in contact has an influence on abrasive wear and the synergistic effect of abrasion and corrosion. In the work of García, Drees and Celin [12], this

event is tested, where an abrasion-corrosion test apparatus is used consisting of a disc made of AISI 316 stainless steel that rotates in contact with a sphere of the material harder than that of the disc, causing it to wear out (Fig. 2). The disc rotates in several frequencies with different loads.

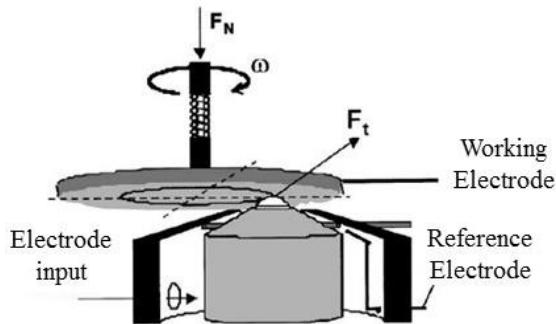


Figure 2. Schematic of a ball-and-disc abrasion-corrosion test [12].

As can be seen from Fig. 3, the mean anodic current, which indicates the progress of a corrosive process, recorded during abrasion-corrosion tests with two sliding bodies, increases linearly with the rotational frequency of the disk [12].

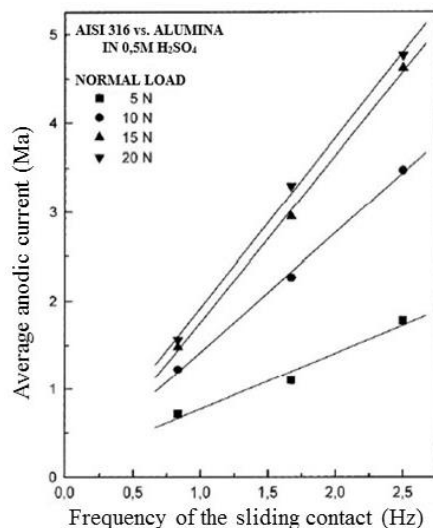


Figure 3. Schematic of a ball-and-disc abrasion-corrosion test [12].

This linear increase indicates that the current is proportional to the number of activation events per unit time. An activation event is a moment that the hard asperities or hard particles of a surface touch another surface while they are in a relative sliding motion, removing material. In other words, each activation event is every moment that the abrasion process occurs. Thus, each small abrasive event is the beginning of a new corrosive process. In this context, the size of the worn out area, and the amount of metal required that needs to be oxidized to form a new passive layer in the depassive area are important

factors that will define the speed of wear when there is a corrosive process after an abrasive event [10].

Effect of the concentration of abrasive particles

In the work of Bello, Wood, and Wharton [4], abrasion-corrosion (Abr-Corr) and pure abrasion (PA) tests are shown for three types of stainless steels, according to Fig. 4.

The specific wear rate, k , increases with increasing volumetric fraction of abrasive for both PA and Abr-Corr tests for the three stainless sheets of steel. In Fig. 4 it can be seen that a linear relationship exists between k and the volumetric fraction of abrasive between the values of 0.03 and 0.135 (two-three-mixed-three-bodies). This range represents an increase in the concentration of abrasive sludge and consequently an increase of k by a factor of greater than 6.2 for tests of Abr-Corr and 7.0 for PA. This suggests that at these concentrations the wear rate is not directly related to the number of abrasive particles being introduced into the contact (assuming these are proportional to the volume fraction of mud), but also to the fact that the three-body abrasive mechanisms are more efficient at removing material than two-bodies or two-three-bodies-mixed. Clearly, these results suggest that when the mechanism changes wear two-bodies, with risk formation, to three-bodies, with the formation of multiple notches, the damage is more severe. But an important point to note is that above a mud concentration of 0.135, the change in k was minimal. This tendency is probably due to the reduction in contact severity because of the reduction of the load per abrasive particle [4].

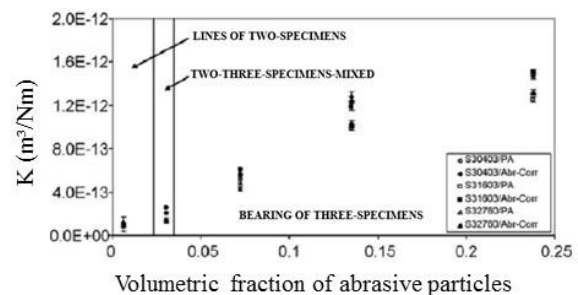


Figure 4. Specific wear rates for abrasion and abrasion-corrosion tests on UNS S30403, S31603 and S32760 and a sliding distance of 180 m [4].

Tests for the study of abrasion-corrosion

As motivation of this work is to serve as a research source for future work, in addition to the tests already shown, we will briefly present other important types of tests found in the literature for the study of the abrasive-corrosive process.

It is known that researchers use different systems of tribocorrosion tests since each one is based on a specific target of study and, consequently, they have different parameters of influence. The

contact configurations, type and movement of the sliding surface and the very nature of the test system influence the results generated [13]. So some other test systems are provided:

a) Pin/ Sphere in contact with the spinning disc (in one direction): the one-way slide of a ball or pin against a metal disc [14];

b) Sphere (pin) in contact with the disc (reciprocal movement): In this system, a ball or pin (fixed by a vertical support) is sliding back and forth, using the same line / wear mark on the moving disc. This is the most commonly used tribocorrosion arrangement [10, 14];

c) Microabrasion test system (ball in contact with disc): in a microabrasion test system the ball is rotated relative to an axis against a vertical disc and allows the insertion of third bodies [11, 15];

d) The cylinder in contact with bar: in this system, the cylinder moves against the bar [16];

e) Disc contact ring: In this system, the discs are fixed and the rings are rotating. The electrochemical interaction is reached as in other systems [17];

f) Special devices: some research laboratories have developed special arrangements for tribocorrosion experiments to simulate practical applications. For example, an apparatus made by Geringer, Forest and Comrade [18] to study events of tribocorrosion of the femoral stem of the hip joint and cortical bone. Hallab et al. [19] developed the special triboroprosthesis (vibration-corrosion) system for conical hip joint joints. Vieira et al. [20] developed a special arrangement for tribocorrosion testing for dental applications.

For each test, a summary of the methods, materials used and results produced is summarized.

Ball-type test on plate

In the work of Santos et al. [6], we have a test apparatus that was specially designed for the study of these authors. A schematic view of the equipment is shown in Fig. 5. This test device can be divided into four parts: movement and load measurements; electrochemistry; image acquisition and processing; and abrasive slurry preparation. Fig. 5 shows the parts of the test equipment such as the abrasive slurry preparation system, the digital camera for wear mark measurement, the deadweight lever arm system or an electromagnetic actuator for load application (in detail in Fig. 6a), and the electrochemical cell (in detail in Fig. 6b, Fig. 7a and Fig. 7b), within which are located the sphere and the test sample immersed in an electrolyte. The applied load and the rotational speed of the ball can be varied. The samples were of stainless steel AISI 304 and 430 in rectangular plate format and the rotating sphere was of zirconia. On one side of the electrochemical cell was a flexible membrane (Fig. 7b), through which it was possible to pass the rod to charge transmission [6].

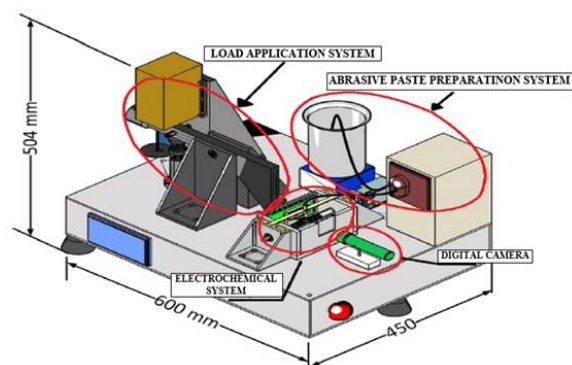


Figure 5. Schematic drawing of the test apparatus [6].

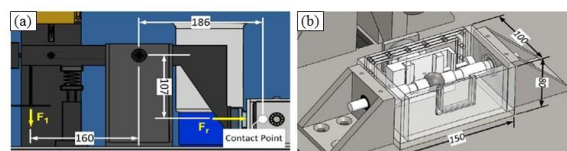


Figure 6. Details of the test apparatus: (a) force application system by the lever; and (b) electrochemical cell [6].

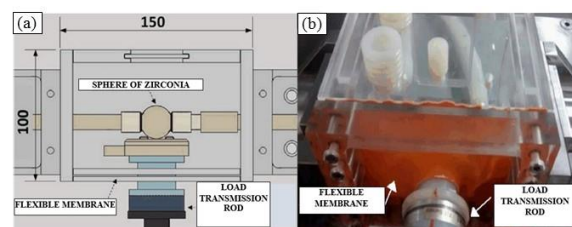


Figure 7. (a) Schematic arrangement of the load cell and the flexible membrane; and (b) the actual condition of the membrane [6].

In the work of Santos et al. [6], independent tests of pure abrasion, pure corrosion and combined abrasion-corrosion tests were carried out for eventual comparison of data. The abrasive used was a paste consisting of 10% by weight of SiO_2 in distilled water and the electrolytic solution was composed of 1 N H_2SO_4 . For all corrosion and abrasion-corrosion tests, the system solution was aerated.

Results of the ball-type test on plate

Comparing the pure corrosion bias curves as shown in Fig. 8 and the abrasion-corrosion tests as shown in Fig. 9, it is evident that the abrasion action increases the passive current density, as shown in Fig. 10. Other tests, in which the normal load was varied during the passivation, were performed. Fig. 11 shows a typical polarization curve obtained under the test conditions already described. The normal charge decreased from 1.3 N to 0.5 N, which induced a decrease in current density from 0.12 mA/cm^2 to 0.06 mA/cm^2 , which may be associated in principle with the lack [6].

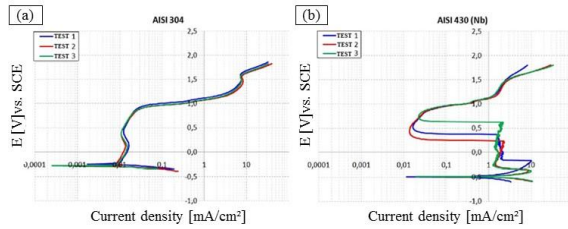


Figure 8. Typical polarization curves with the partially submerged specimen in a 1 N H₂SO₄ solution. (a) AISI 304; (b) AISI 430 (Nb) [6].

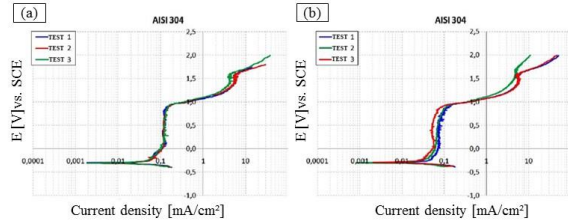


Figure 9. Effects of normal force on the polarization curve during an abrasive-corrosive test on AISI 304 steel. (A) $F_n = 1.23 \pm 0.12$ N; (b) $F_n = 0.49 \pm 0.1$ N [6].

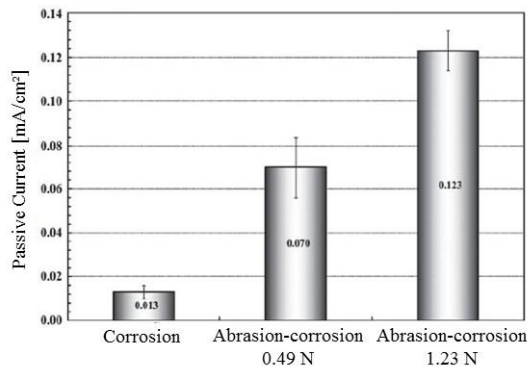


Figure 10. Average passive current density [6].

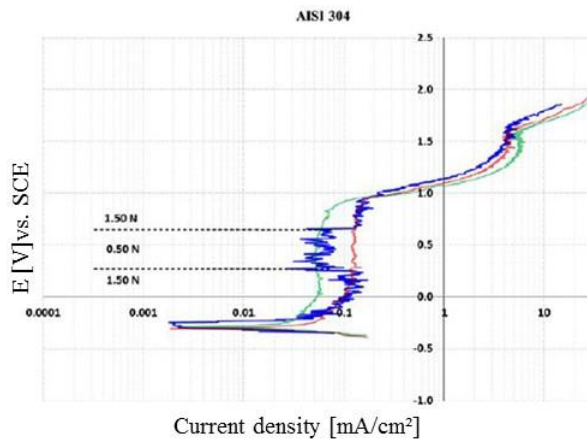


Figure 11. Polarization curves for an abrasive-corrosive test with the sample under variable normal load and partially submerged in a solution of 1N H₂SO₄ + SiO₂ abrasive [6].

The wear rates and friction coefficients for the abrasion test were higher than for the abrasion-corrosion test under the same conditions (Fig. 12). In contrast, corrosion alone had lower passive current densities when compared to abrasion-corrosion tests. In addition, the abrasion-corrosion tests were shown to be influenced by the normal load imposed. Higher loads induced higher passive current densities and slightly higher wear rates. It appears that there is a strong correlation between contact forces (mechanical wear) and passive film formation and stabilization [6]

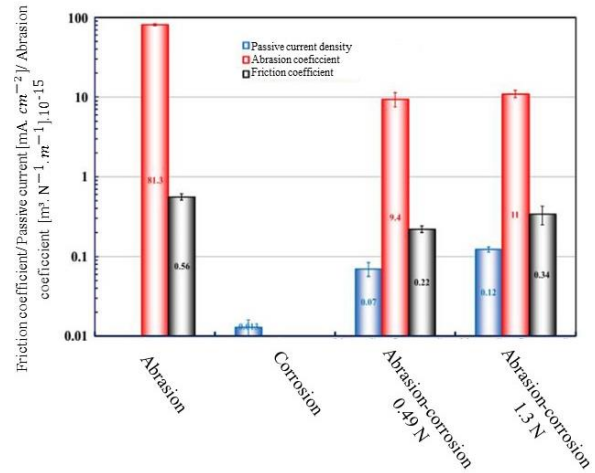


Figure 12. The coefficient of friction, passive current density, and wear rate for abrasion, corrosion, and abrasion-corrosion tests [6].

Rubber wheel type test on the sample

The test apparatus used in the study of Gant, Gee, and May [21] is an adaptation of the apparatus used in the test method of ASTM G65-93 [22]. The test is widely used to produce three-body abrasion. Three-body abrasion occurs when the abrasive is free to rotate between the test apparatus and the sample, whereas in the case of two-body abrasion, the orientation of the abrasive particles is fixed relative to the test sample [10]. An overview of the test equipment is shown in Fig. 13.

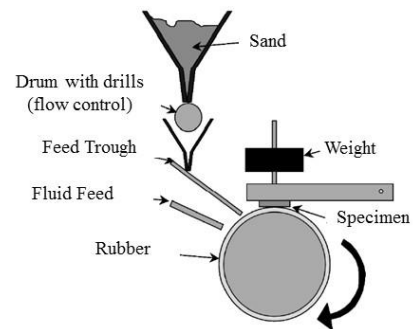


Figure 13. Modified ASTM G65-93 test apparatus used in current tests [21, 22].

In this test, the rectangularly shaped samples are pressed against a 210 mm diameter steel wheel with a 10 mm thick rubber ring glued over the circumference, giving a total diameter of 230 mm (Fig. 13). The samples were hard metals of tungsten carbide in various media, mostly with cobalt binders, but some samples had nickel or cobalt-nickel as the binder phase.

During the test, as shown in Fig. 13, a controlled flow of abrasive could be introduced into the system by means of the feed rail and, simultaneously, a flow of an aqueous medium could also be introduced, i.e., that apparatus allows the execution of only abrasive tests, only corrosive or a combination of the two. The tests were performed in basic media, neutral and acidic with the abrasive flow, and in acidic media only without abrasive flow, as shown in Table 1 [21].

Table 1. General description of the wear test program [21].

Test Condition	Atmosphere	Abrasive	Duration (min)	Load applied	Total slip distance during test (m)
1	pH H ₂ SO ₄	1.1 silica sand	50/70 20	130	345
2	pH H ₂ SO ₄	2.2 silica sand	50/70 20	130	345
3	pH 6.3 H ₂ O	50/70 silica sand	20	130	345
4	pH Ca(OH) ₂	13 silica sand	50/70 20	130	345
5	pH H ₂ SO ₄	1.1 -	20	130	345
6	pH H ₂ SO ₄	2.6 -	20	130	345

The abrasive used was rounded silica sand. Acid media were sulfuric, pH 1.1 and 2.6, the neutral medium was deionized water, pH 6.3, and the basic medium was a saturated solution of calcium hydroxide in deionized water, pH 13.0. Samples were weighed before and after the tests using a scale of 0 to 200 g. The same apparatus was also used to evaluate the density of the samples by the method of Archimedes [21].

Results of the rubber wheel type test

The volumetric wear loss data (in terms of HV30) and the microscopic examination of the wear surfaces by electron microscopy seemed to suggest that the acidic media are accelerating the wear process in the last instance by changing the step of the governing rate. In order to evaluate this, wear-corrosion synergism has been quantified according to the terminology found in ASTM G119-93 [22]. The ASTM standard allows the user to evaluate synergism using electrochemical corrosion; ASTM standard prescribes synergy assessment as [21]:

a) Electrochemical corrosion rate C : C_w is the rate of electrochemical corrosion during the corrosive

wear process, and the term C_0 indicates the rate of electrochemical corrosion when no mechanical wear occurs;

b) Mechanical wear rate W_0 : is the sample material loss rate when the electrochemical corrosion rate was eliminated by the cathodic protection during the wear test;

c) Total material loss rate T : is the rate of loss of sample material exposed to specified conditions, including the contributions of mechanical wear, corrosion and the interaction between these two;

d) Abrasion-corrosion synergism S : is the rate of material loss due to the interaction of the mechanical wear and corrosion process, given by the T minus the sum of W_0 and C_0 . The S' component is the increase in the mechanical wear rate due to corrosion, and S'' is the increase in the rate of electrochemical corrosion due to mechanical wear.

The relation can be summarized by the equations:

$$T = W_0 + C_0 + S \quad (2)$$

Eq. 1 implies that corrosion can affect mechanical wear and mechanical wear can affect corrosion. Under conditions of corrosive wear, C_w can be measured by electrochemical means. C_w is generally greater than C_0 due to the interaction of mechanical wear. Eq. 1 can be rewritten [21]:

$$T = W_0 + C_w + S' \quad (3)$$

In which, S' is the increase in the rate of mechanical wear due to corrosion. Increases in the rate of corrosion due to mechanical wear are included in the C_w .

From Eq. 2 and 3 it can be shown that the change in the electrochemical corrosion rate due to mechanical wear ($C_w - C_0$) is equal to the difference between S and S' . This difference is indicated by S'' as Gant, Gee and May [21]:

$$S'' = S - S' = C_w - C_0 \quad (4)$$

Thus, total synergism is the sum of increased mechanical wear due to corrosion (S') and increased corrosion due to mechanical wear (S'') [21]:

$$S = S' + S'' \quad (5)$$

The synergy, total wear, wear due to abrasive action only and wear due to corrosion only, are plotted in Fig. 14a, Fig. 14b, Fig. 15a and Fig. 15b for sulfuric acid (pH 1.1) in terms of HV30 (a) and binding content (b) [21].

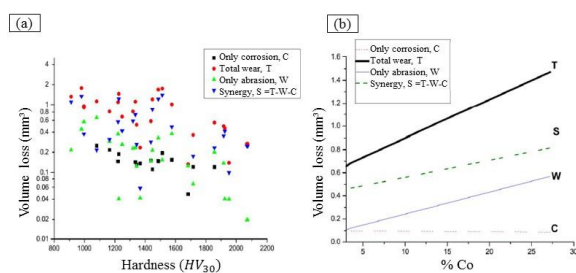


Figure 14. (a) The plot of the components of loss of volume vs. HV₃₀; pH 2.6 sulfuric acid. (b) The linear arrangement of the components of loss of volume vs. binder content; pH 2.6 sulfuric acid [21].

One of the most conventional and widely used measures of hard metal wear is with regard to hardness. Fig. 16 and Fig. 17 shows the loss of volume with respect to the hardness measured on the Vickers scale with a load of 30 kg for each of the conditions. Fig. 17 was included as a summary of all crude data produced. It clearly illustrates that there is a tendency for the loss of material (together with silica sand), which increases with the lowering of the pH of the medium. In order to increase the volume loss calcium hydroxide solution (pH 13), deionized water (pH 6.3), sulfuric acid (pH 2.6) and sulfuric acid (pH 1.1) were used. The results obtained without the addition of silica sand also show a trend towards greater volume loss with the decrease of pH [21].

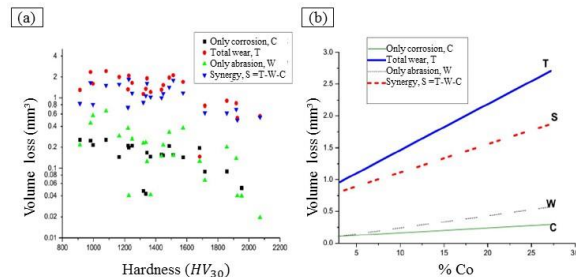


Figure 15. (a) The plot of the components of loss of volume vs. HV₃₀; pH 1.1 sulfuric acid. (b) The linear arrangement of the components of loss of volume vs. binder content; pH 1.1 sulfuric acid [21].

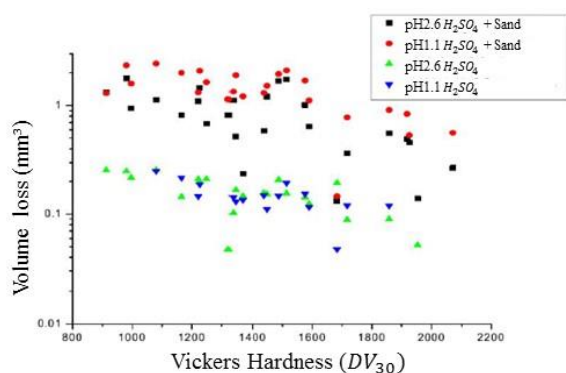


Figure 16. Loss of volume vs. DV₃₀ for sulfuric acid alone and with 50/70 silica sand [21].

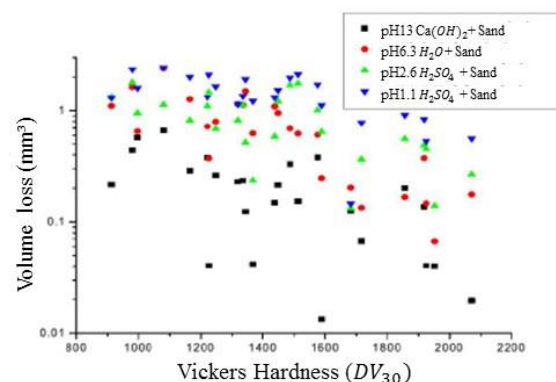


Figure 17. Loss of volume vs. DV₃₀ for various media + 50/70 silica sand [21].

Ball-on-disk type test

A disk-type test apparatus was used in the study of García, Drees and Celis [12], with a load on the disk, which is at the top of the sphere. This arrangement allows a better escape of the fragments that are detached from the contact area, thus limiting interactions of a third body. The ball is secured within a nozzle whereby a constant replacement of electrolyte in contact with the sliding disc is achieved. A three-electrode cell arrangement was used having a working electrode disk, a Pt wire as a counter electrode, and a saturated calomel electrode (ECS) as the reference electrode. The potentiostatic control during the abrasion-corrosion sliding tests and current measurement was done with an EGG 273A potentiostat. The material of the disk investigated was the stainless steel AISI 316, with 60 mm in diameter, and the sphere used as corundum counter body, with 10 mm of diameter. The electrolytic solution used in the abrasive-corrosive test of 0.5 M H₂SO₄ composition prepared with deionized water. The diameter of the wear mark was 20 mm. The rotation frequencies ω of the disk were between 0.83 and 2.5 Hz, and in normal loads, FN applied between 1 and 20 N. The corresponding maximum pressure on the flat surface of the stainless steel varied between 800 and 1270 MPa. The dimensions of the test apparatus were selected so as to best simulate the characteristic size of the wear marks obtained on the stainless steel discs after the tests of disco-ball realized with a normal load of 20 N and a distance of 130 m.

Results of the ball-type test on the disk

The mean anodic current recorded during the abrasion-corrosion tests (Fig. 18a) increased linearly with frequency. This indicates that the current is proportional to the number of corrosion activation events per unit time [12]. An activation event is when the metal area is deposited by an abrasion event [10].

When plotting the data again from Fig. 18a vs. the applied load (Fig. 18b), a parabolic relationship

between current and applied load clearly appears for loads up to 20 N [12].

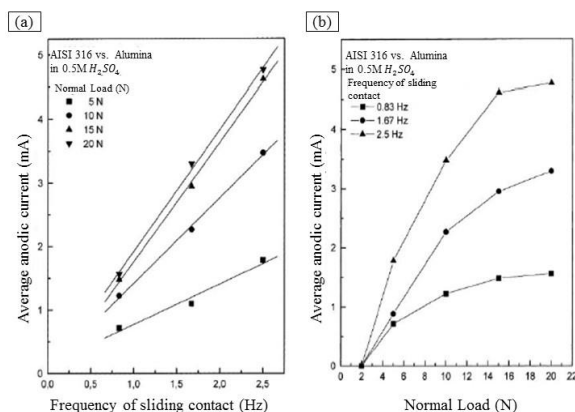


Figure 18. Variation of the mean anodic current during the abrasion-corrosion tests performed in 0.5 M H₂SO₄ in 0.3 V vs. ECS, with (a) frequency of contact; and (b) applied load [12].

CONCLUSIONS

Abrasion may contribute to the increased speed of the corrosion process as it helps in removing the protective layer of oxide on the metal surface, thus leaving areas more vulnerable to corrosive attack. The increase in the load on the work found in the literature, that is, increase of the contact force during the slippage, also showed a higher abrasive wear and an increase in corrosive wear was observed.

The abrasive wear occurring in conjunction with the corrosive wear generates a more severe effect on the total mass loss of a material. This effect, however, contrary to what can be deduced, is not basically a sum of the wear generated by abrasion and corrosion, but rather a synergetic effect, which is greater than the sum. Thus, it can be said that the synergy of the abrasion-corrosion process considerably decreases the useful life of a material as compared to only abrasive or only corrosive wear.

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