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The Effect of Corrosion on Slurry Abrasion of Wear Resistant Steels

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ABSTRACT: Pipeline maintenance and replacement for slurry transportation constitutes a significant fraction of cost in many mining operations, particularly in the oil sand industry. It is thus important to better understand wear attack mechanisms and major factors affecting wear in such applications. In this study, the effect of corrosion on slurry abrasion response of pipe steels and abrasion resistant steels has been investigated using the Miller tester in silica slurries (water- or salt solution-based). A concept of relative synergy is introduced to illustrate the importance of corrosion-enhanced wear for a given material, which is defined as the percentage difference in wear rates between sliding in salt slurry and in de-ionized (DI) water slurry with respect to wear rate in DI water slurry. Steel hardness is found to have significant effect on the corrosion-abrasion behavior. Hard steels tend to show higher relative synergy. Extensive pitting corrosion is observed for hard steels after testing in salt solution slurry. For low hardness steels, general corrosion (with micro-pitting) is the dominant corrosion mechanism. Based on semi-empirical analysis, a wear map is constructed to illustrate the transitions of abrasion-corrosion regimes under different materials and working/testing conditions. The importance of mechanical interaction frequency and severity on corrosion-abrasion synergy is highlighted. The effect of material's corrosion resistance on relative corrosion-abrasion synergy is currently not well understood and is not explicitly shown in the wear map. However, qualitatively, corrosion resistant materials generally show lower synergy under similar working/testing conditions. Hard and corrosion resistant materials should

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be employed when the working conditions fall within the abrasion-corrosion regime.

KEYWORDS: corrosion, slurry abrasion, steels, wear

Introduction

Slurry handling is involved in many industrial processes, particularly in the oil sands, mining and mineral processing sectors. Costs due to wear of components in slurry handling systems such as pumps and pipes and the related production shutdown can be an important factor affecting production efficiency. There is thus a constant demand to improve wear performance of components for these applications. Wear in such slurry handling systems is a fairly complex process. To facilitate technology development as well as materials selection in such applications, cost effective laboratory tests are necessary. Among the available testing methods, the Miller slurry abrasion test is easy to perform and yields useful results in wear situations where low stress abrasion dominates [1]. This method was originally designed for evaluating the abrasivity of slurries composed of different minerals by running sliding abrasion test in a slurry bath using a standard material (centrifugally cast 27Cr white chromium cast iron). It has now been established also to simulate and rank wear performance of materials in given slurry conditions [2].

Various types of materials are used for slurry handling applications, including cast irons, steels, ceramics, cermets, polymers, and elastomers. Among these, steels offer the advantages of low cost, easy fabrication, and good mechanical properties (high strength, high toughness, and ductility), and are thus widely used. In this study, the slurry abrasion response of a series of pipe steels and abrasion resistant steels has been evaluated using the Miller tester under various testing conditions. The effect of corrosion and corrosion-abrasion interactions, i.e., the synergistic effect, is examined to seek some insights into the tribo-corrosion phenomenon during slurry abrasion process.

Experimental Details

Materials

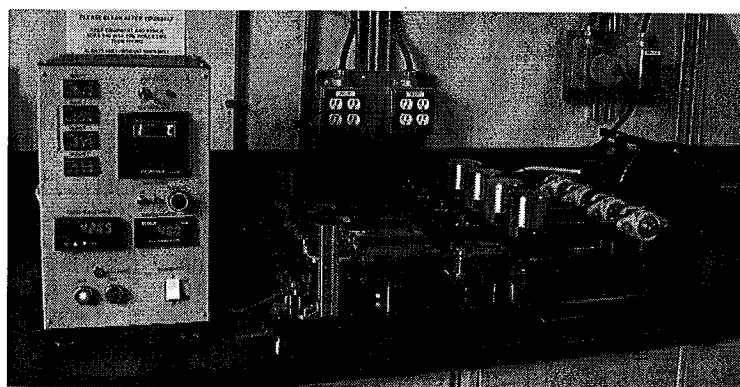
Materials to be discussed in this paper are listed in Table 1. They include pipe steels, abrasion resistant (AR) steels, and several reference materials (AISI D2 tool steel, Stellite 6, CA6NM cast stainless steel, and AISI 316 stainless steel).

Testing Conditions

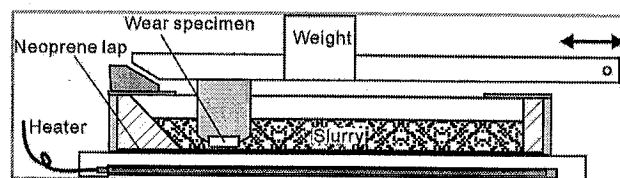
A Miller tester (Fig. 1) constructed in conformity to the ASTM G75 standard [2] has been used to evaluate the slurry abrasion response of the selected materials.

TABLE 1—Testing materials and their hardness.

Sample ID	Material	Comments/Conditions	Hardness	Eqv. HV
✓ OFH ⁴	Fedur 90 (roll bonded)	Bimetallic-high C pipe steel	62.0 HRC	746.0
✓ OEO	Fedur 40 (roll bonded)	Bimetallic-high Cr pipe steel	59.0 HRC	674.0
✓ NUH	NASPIPE	Internal induction hardened—medium C pipe steel	59.1 HRC	676.0
✓ OAG-24	IPSCO IT 80 Well Casing	Low alloy pipe steel	231 HB	243.0
✓ BPO	Kawasaki B 0.36 C	Medium C pipe steel	237 HB	248.0
✓ NUD	SRT 600	Medium C pipe steel	57.5 HRC	643.0
✓ OUD 4?	AR 360 <i>if it is uniform structure</i>	Bisplate 360 + 6 plate?	390 HB	412.0
✓ OIG 4	AR 400-425	Algotuf 400 F	41.3 HRC	405.0
✓ NUG 1/4	AR 450	En30 B Steel	47.0 HRC	471.0
✓ OFL	AR 600	Hardox 600	55.6 HRC	605.0
QBV	Q & T 100 steel		28.7 HRC	283.0
QBW	D2 tool steel (Ref)		60.3 HRC	704.0
316 SS	Stainless steel		200.8HV	200.8
OOV-2	Stellite 6 clad	TIG Stellite 6 clad on 316 SS substrate	544.6HV	544.6
CBQ-2	Alloy CA6NM S.S.	Cast	306 HB	322.0



(a)



(b)

FIG. 1—The Miller tester.

The testing conditions are as follows:

– Sand: AFS 50/70 silica sand

– Slurry:

- Slurry concentrations: (a) 50 wt. % (150 g sand + 150 mL liquid); (b) 10 wt. % (20 g sand + 180 mL liquid).
- Liquid used in making the slurry: (a) de-ionized (DI) water; (b) 3.5 % NaCl (salt) solution.

– Sliding speed: (a) 48 rpm (0.325 m/s, standard speed); (b) 32 rpm (0.217 m/s); (c) 16 rpm (0.108 m/s).

– Normal load: 22.25 N (5 lb).

Calculation of Wear Rate

Wear rate is expressed using the slurry abrasion response (SAR) number as defined in the ASTM G75 standard [2], i.e.,

$$\text{SAR} = 18.18 \left(\frac{dM}{dt} \right)_{t=2h} \left(\frac{7.58}{\rho_{\text{sample}}} \right) \quad (1)$$

where:

ρ_{sample} = density of the material under investigation and

M (in mg) = cumulative mass loss at different sliding time, t (in h).

The definition for SAR number in Eq 1 is for sliding at the standard speed of 48 rpm. The cumulative mass loss, M , is obtained by measuring sample mass changes at three equally spaced 2 h testing intervals, i.e., at a total/accumulated sliding time, t , of 2, 4, and 6 h respectively. A curve fitting is conducted for a relationship between the cumulative mass loss, M , and sliding time, t , from which the mass loss rate, $dM/dt|_{t=2h}$, at 2 h sliding is obtained and is used for obtaining the SAR number according to Eq 1.

In the current study, different sliding speeds have been used to investigate the relative contributions of mechanical wear and corrosion on material loss/damage. To compare the results under the different sliding speeds at similar abrasive degradation conditions, equivalent SAR numbers are obtained as described below. The slurry abrasion test was conducted for three equally spaced time intervals such that the total sliding cycles in each time interval is the same as that in sliding for 2 h at the sliding speed of 48 rpm, i.e., 5760 cycles. For example, at 16 rpm, each time interval runs for 6 h. Thus, in calculating SAR numbers at the different sliding speeds, the sliding time interval is equivalent to 2 h sliding at 48 rpm. Using the equivalent sliding time, the same equations are used for calculating the SAR number at all the sliding speeds.

Experimental Results

The Synergistic Effect of Corrosion and Abrasion

The SAR numbers obtained for the selected materials under various testing conditions are summarized in Table 2. The data in Table 2 has been listed according to steel hardness in the decreasing order. For most of the materials investigated, there is an apparent increase in wear rate (SAR) when the testing was conducted in the salt solution slurry as compared with that in DI water slurry. This increase was considerably higher at the lower sliding speeds (32 or 16 rpm) than at the sliding speed of 48 rpm. Numerous tribo-corrosion studies under different wear conditions in the literature have shown that the total material loss during wear in a corrosive environment is different from, usually greater than, the simple sum of material loss due to corrosion only without the action of wear and that due to wear only without the action of corrosion. This additional increased or decreased material loss is commonly known as the corrosion-wear synergy and is generally defined as [3]:

$$\text{Synergy} = \text{Wear (in corrosive environment)} - [\text{Wear (without corrosion)} + \text{Corrosion (without wear)}] \quad (2)$$

TABLE 2—Summary of SAR numbers for the tested materials under the various testing conditions.

Sample ID	50 % slurry				10 % slurry		
	DI Water, 48 rpm	3.5 % NaCl, 48 rpm	3.5 % NaCl, 32 rpm	3.5 % NaCl, 16 rpm	DI Water, 48 rpm	3.5 % NaCl, 48 rpm	3.5 % NaCl, 16 rpm
OFH	119.5	128.8	174.9	223.2	72.4	103.4	187.4
QBW	128.3	126.9		154.3			
NUH	192.3	215.6	259.6	304.6	92.8	144.6	236.4
OEO	205.4	226.5	256.6	278.5	126.6	159.0	172.7
NUD	174.7	195.1	217.2	245.7	81.5	119.2	192.5
OFL	190.4	205.0	224.5				
OOV-2	397.9	353.0		372.1	161.9	185.8	178.0
NUG	424.2	436.0	446.2				
ODU	642.6			721.9			
OIG	529.4	590.0	624.2	495.2			
CBQ-2	638.4	755.4		651.7	273.1	335.4	402.3
QBV	919.0			1080.1			
BPO	772.4	783.1		813.1	330.8	406.3	374.2
OAG-2	879.9	967.6		981.7	479.6	541.3	606.9
316 SS	1137.0	1185.0	1044.3				

The synergy can be further divided into the components of corrosion-enhanced wear and wear-enhanced corrosion [3]. Wear-enhanced corrosion is generally believed to be a result of removal of passivating films to expose fresh metal surfaces for active dissolution and creation of high energy metal surface layer due to mechanical deformation. However, mechanisms for corrosion-enhanced wear are much more complicated and are still not well understood at the moment. They may also vary depending on particular tribo-systems.

Due to the complexity of the Miller testing system, it was difficult to measure the material loss under pure wear conditions without corrosion and it was thus difficult to obtain the quantitative synergy as defined in Eq 2. To evaluate the abrasion-corrosion behaviour of the various materials under different testing conditions, in this paper, the wear rate (SAR) in DI water slurry is taken as a reference for "non-corrosion" condition and a parameter "relative synergy", RS, is introduced. This is calculated according to the following equation:

$$\text{RS}(\%) = \frac{\text{SAR} - \text{SAR (in DI water slurry)}}{\text{SAR (in DI water slurry)}} \times 100 \quad (3)$$

Obviously, this definition of "relative synergy" also includes the contribution of material loss from pure corrosion and is not strictly the same as the commonly recognized definition of synergy as defined in Eq 2. It reflects the overall effect of corrosion on the total material loss. However, before more elaborate testing capabilities are available, it is justifiable to use the parameter RS to indicate the severity and sensitivity of a given material to corrosion-abrasion interactions.

Based on the definition in Eq 3, the relative synergy for the tested materials under the various testing conditions are calculated and shown in Table 3.

It can be noticed from Table 3 that the relative synergy generally increases with decrease in sliding speed and is much higher in the 10 wt. % slurry than in the 50 wt. % slurry. In addition, harder steels tend to show higher relative synergies. To more clearly demonstrate this trend and the effect of testing conditions (slurry concentration and sliding speed), some of the relative synergy data in Table 3 are re-plotted in Fig. 2. The wear- and corrosion-resistant Stellite 6 shows the least relative synergy while the hard steels OFG and NUH show the most sensitivity to corrosion-abrasion damages.

Effect of Material Hardness on the Corrosion-Abrasion Synergy

Plotted in Fig. 3 is the variation of relative synergy as a function of material hardness under different testing conditions. Although a few scatters/exceptions can be noticed, a clear overall trend can be seen that the relative synergy increases with increase in material hardness. The two corrosion-resistant hard

TABLE 3—Relative synergy (calculated according to Eq 3) of the tested materials under various testing conditions.

Sample ID	Hardness (HV)	50 wt. % slurry			10 wt. % slurry	
		48 rpm	32 rpm	16 rpm	48 rpm	16 rpm
OFH	746	7.8	46.4	86.8	42.7	158.9
QBW	704	-1.1		20.3		
NUH	676	12.1	35.0	58.4	55.9	154.7
OEO	674	10.3	24.9	35.6	25.6	36.4
NUD	643	11.7	24.3	40.6	46.2	136.1
OFL	605	7.7	17.9	57.1		
OOV-2	544.6	2.0		-6.5	14.7	10.0
NUG	471	2.8	5.2	16.7		
ODU	412			12.3		
OIG	405	11.4	17.9	36.4		
CBQ-2	322	18.3		2.1	22.8	47.3
QBV	283			17.5		
BPO	248	1.4		5.3	22.8	13.1
OAG-2	243	10.0		11.6	12.9	26.6
316 SS	200.8	4.2	-8.2	-5.0		

materials, Stellite 6 (OOV-2, 544.6HV) and Fedur 40 (OEO, 674HV), exhibited significantly lower relative synergy than the other steels at the comparable hardness levels (Fig. 3). This indicates that both hardness and corrosion-resistance are important factors in affecting the corrosion-wear interaction during slurry abrasion process. Based on the chemical compositions, the CA6NM stainless steel should have also shown lower synergistic effect than the other

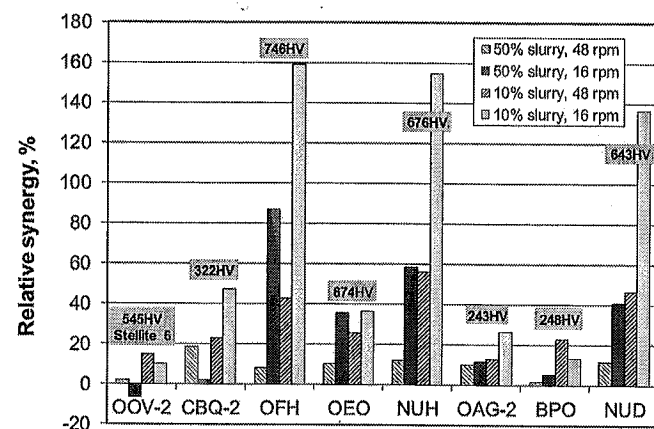


FIG. 2—Relative synergy of the tested pipe steels under various testing conditions.

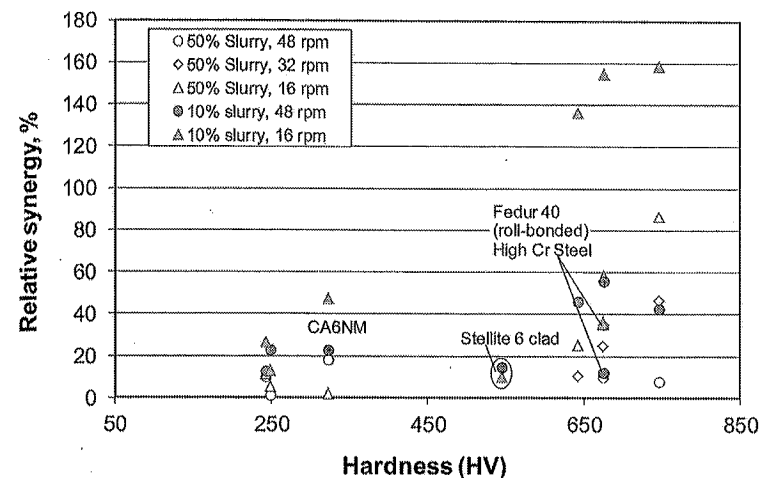


FIG. 3—The effect of hardness on relative abrasion-corrosion synergy of steels under various testing conditions.

steels at the comparable hardness. However, this was not observed. It behaved very similarly to the other less corrosion-resistant steels in terms of the relative synergy at the given hardness level. This was presumably due to the fact that the sample had a cast microstructure which is non-uniform and therefore showed low corrosion resistance behaviour.

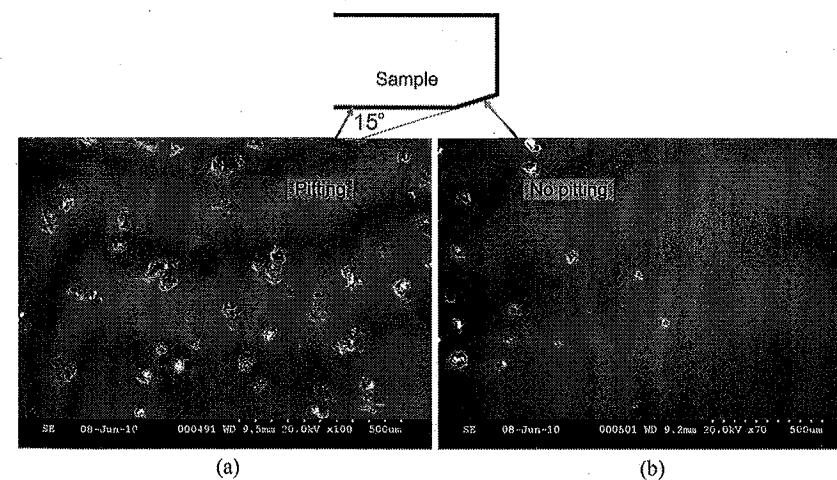


FIG. 4—Typical wear surface for hard steels after sliding in salt solution slurry (NUH sample, HV676, 16 rpm, 50 wt. % salt solution slurry, 18 h). (a) Pitting on the wear surface; (b) no pitting towards the chamfer region of the specimen.

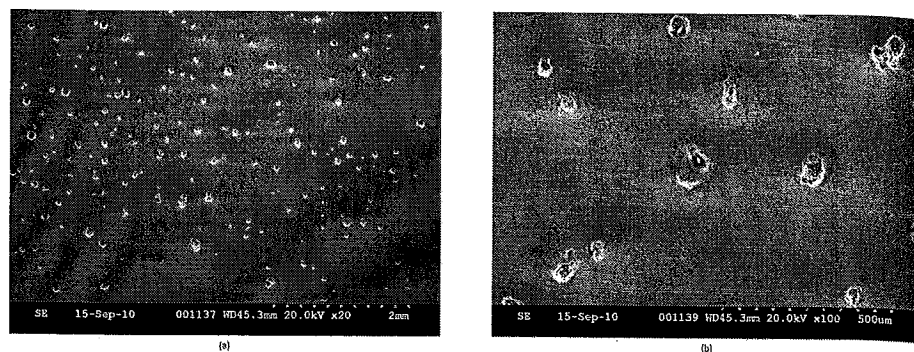


FIG. 5—SEM photos showing the effect of corrosion-enhanced wear due to the creation of corrosion pits (OFL sample, 3.5 % NaCl slurry, 50 % solids, 16 rpm, 18 h). (a) Striations along the sliding direction observed at low magnification; (b) increased wear surrounding corrosion pits.

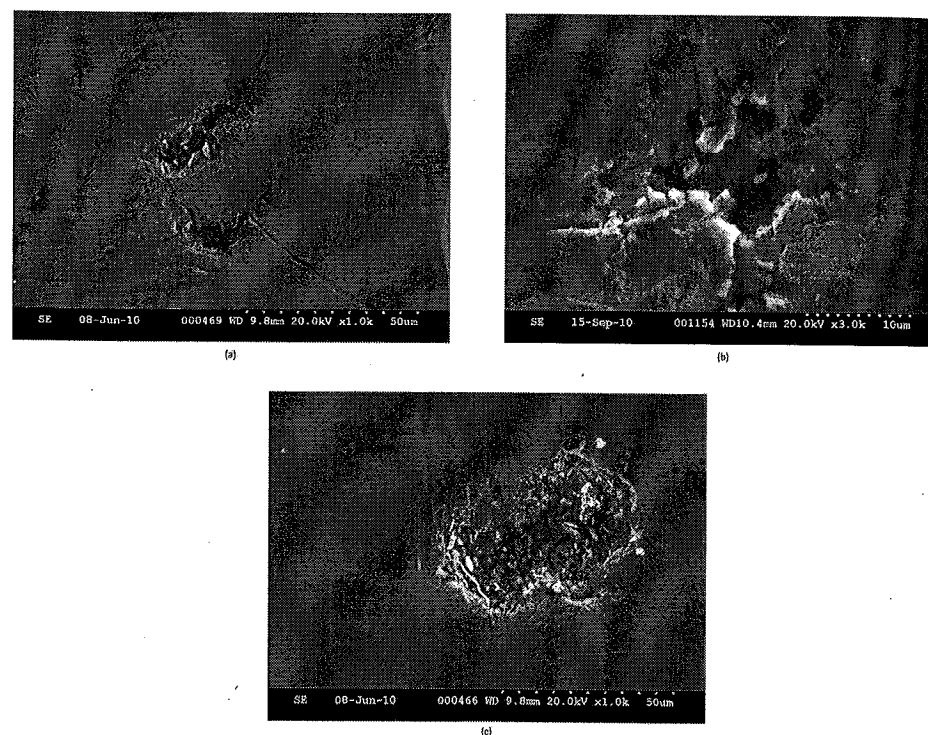


FIG. 6—The development of pitting in hard steels during slurry sliding abrasion in salt solution slurry. (a) Pitting at the early stage; (b) early stage growth of pitting through deepening and spreading along pit bottom; (c) developed pitting with mud-like bottom.

Characterization of Wear Surfaces

Wear surfaces formed after sliding in the corrosive slat slurries showed distinctively different characteristics for steels with different hardness levels as well as with different corrosion resistance.

Hard Steels—Extensive pitting corrosion occurred on the wear surface of hard steels when tested in salt solution slurry, particularly at the low sliding speed (16 rpm) or at the 10 wt. % solid concentration [Fig. 4(a)]. However, pitting was not observed in the chamfered end portion of the wear specimen [Fig. 4(b)]. This clearly indicates that pitting corrosion is induced by the combined actions of abrasion and corrosion. It is well known from corrosion studies that localized pitting corrosion preferentially nucleate/form along scratches or plastically deformed regions for iron [4,5].

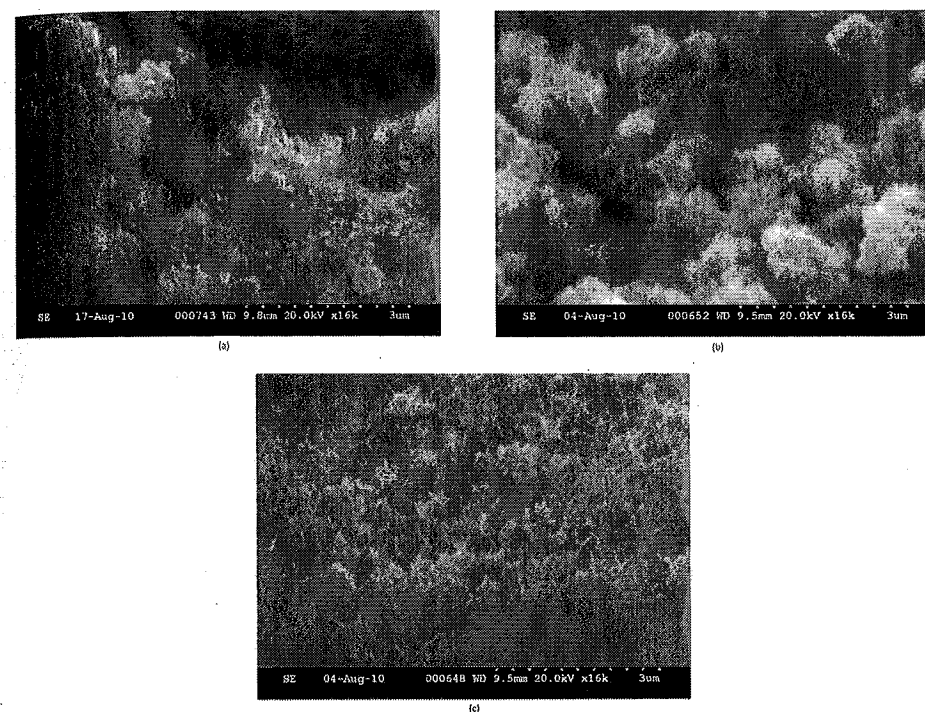


FIG. 7—Detailed features of corrosion pits formed during slurry abrasion testing in salt solution slurry. (a) Corrosion products on bottom of corrosion pits (NUD, 3.5 %NaCl slurry, 10 wt. % solids, 16 rpm, 18 h); (b) Globular corrosion products covered with crystallites formed on bottom of corrosion pits (NUH, 3.5 %NaCl slurry, 10 wt. % solids, 48 rpm, 6 h); (c) Crystalline-like structures formed near the pit mouth/opening (NUH, 3.5 %NaCl slurry, 10 wt. % solids, 48 rpm, 6 h).

On some of the wear surfaces, striations can be noticed along the sliding direction when observed at low magnifications [Fig. 5(a)] and the surface is worn off more deeply, forming basins, surrounding the corrosion pits [Fig. 5(b)]. This suggests that corrosion (pitting) has enhanced wear due to the creation of sharp edges around the pits, where abrasive penetration and cutting become easier.

In the early stages of pit formation, the pits have irregular shapes [Fig. 6(a)]. However, the fully developed pits are more rounded and often show mud-like features on the pit bottom [Fig. 6(c)]. Corrosion seems to spread around the bottom of the pit in the early stages [Fig. 6(b)].

At and near the bottom of corrosion pits, small crystallites are formed, as shown in Figs. 7(a) and 7(b). These are probably corrosion products. Near the opening/mouth of corrosion pits, some crystalline-like structures are observed [Fig. 7(c)]. This suggests that corrosion proceeds along certain preferential crystal planes. Similar features have also been observed in a pitting corrosion study of iron in chloride, sulfite salt and hyper-chloride salt solutions [6]. It was noticed that these early stage pits are polygonal in shape and are bounded by crystalline planes. Similar small polygonal-shaped pits are also observed in the early stage pitting of Cr steels [4], Cr-Ni steels [7], and Al alloys [8,9].

Low Hardness Steels—For low hardness steels, no pitting occurs under most of the testing conditions except for the OAG-2 (243HV) specimen at

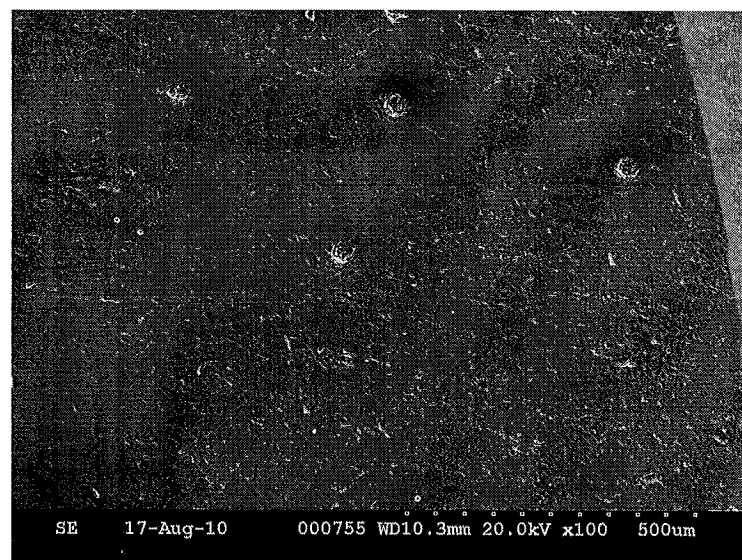


FIG. 8—Certain extent of pitting corrosion was observed in the low hardness steel, OAG-2 (243HV), under the low wear intensity conditions (salt slurry, 10 wt. % solids, 16 rpm, 18 h).

the low sliding speed of 16 rpm and low concentration (10 wt. % solids) salt solution slurry, where a small number of pits were observed after prolonged testing, Fig. 8. The dominant wear scar characteristics for low hardness steels are ploughing/cutting scratches [Figs. 9(a) and 9(b)] with general corrosion after sliding in salt solution slurry [Figs. 9(a)–9(c)]. General corrosion is also known as uniform corrosion. This is defined as a type of corrosion attack (deterioration) that is more or less uniformly distributed over the entire exposed surface of a metal. It also refers to the corrosion that proceeds at approximately the same rate over the exposed metal surface. In our case, considerable general corrosion is evidenced by the uniformly distributed small (micro-scale) corrosion pits on the wear surface (Fig. 9). Obviously, abrasion constantly creates fresh non-passivated metal surfaces and leads to continuous corrosion at high (active) corrosion rate. The corrosion rate is also significantly increased by the severe mechanical deformation in the wear surface layer due to the abrasion actions (micro-ploughing or micro-cutting). It is well known that corrosion rate

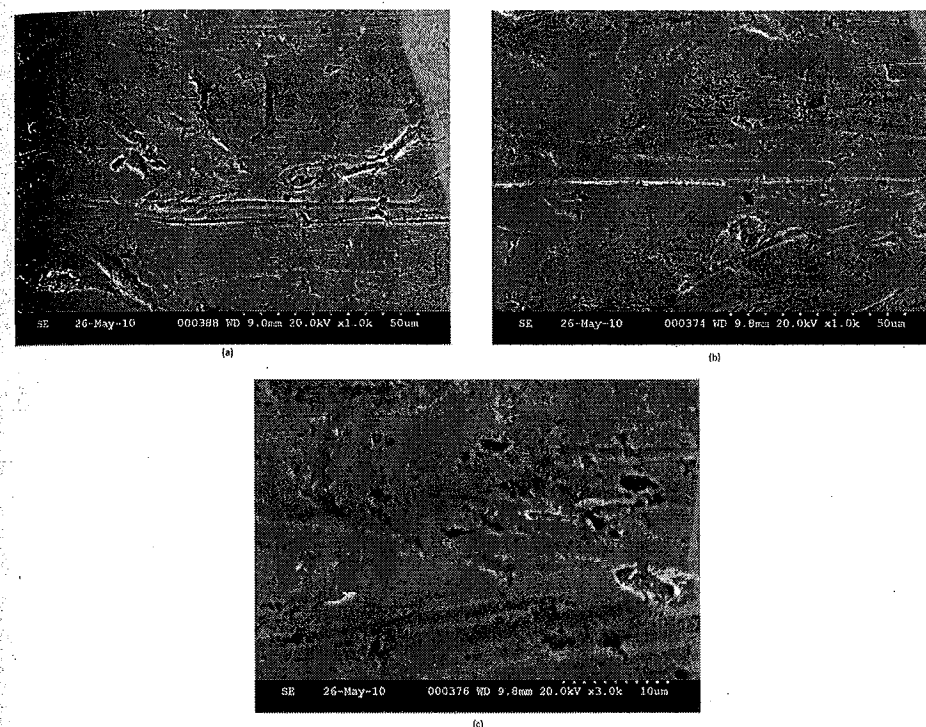


FIG. 9—Typical wear surfaces on low hardness steels after slurry abrasion test in corrosive (salt) slurry. (a) OAG-2 (HV243), 3.5NaCl slurry, 50 wt. % solids, 48 rpm, 6 h; (b) BPO (HV248), 3.5NaCl slurry, 50 wt. % solids, 48 rpm, 6 h; (c) general corrosion of wear surface as typified by the small corrosion pits at higher magnification.

of deformed metals is usually much higher than in their non-deformed states. The micro-pits on the wear surface (Fig. 9) are most probably initiated at high energy locations such as scratches. However, due to the high rate of wear for these low hardness steels, the pits do not have time to grow into large scale localized pitting as observed for the hard steels. These are the two major mechanisms by which the commonly observed wear-enhanced corrosion occurs, i.e., total corrosion loss in the presence of wear is usually higher (thus enhanced) than corrosion under otherwise the same conditions without wear.

Corrosion Resistant Materials—For the corrosion resistant materials investigated, pitting was not observed no matter whether the hardness is high or low, as shown in Fig. 10. For example, the sample OEO (high chromium steel) has a hardness of HRC59.0 (674HV). However, the wear surface is covered only by uniform cutting/ploughing scratches with few signs of corrosion [Fig. 10(a) and 10(b)]. Cutting/ploughing grooves are denser after testing in the higher

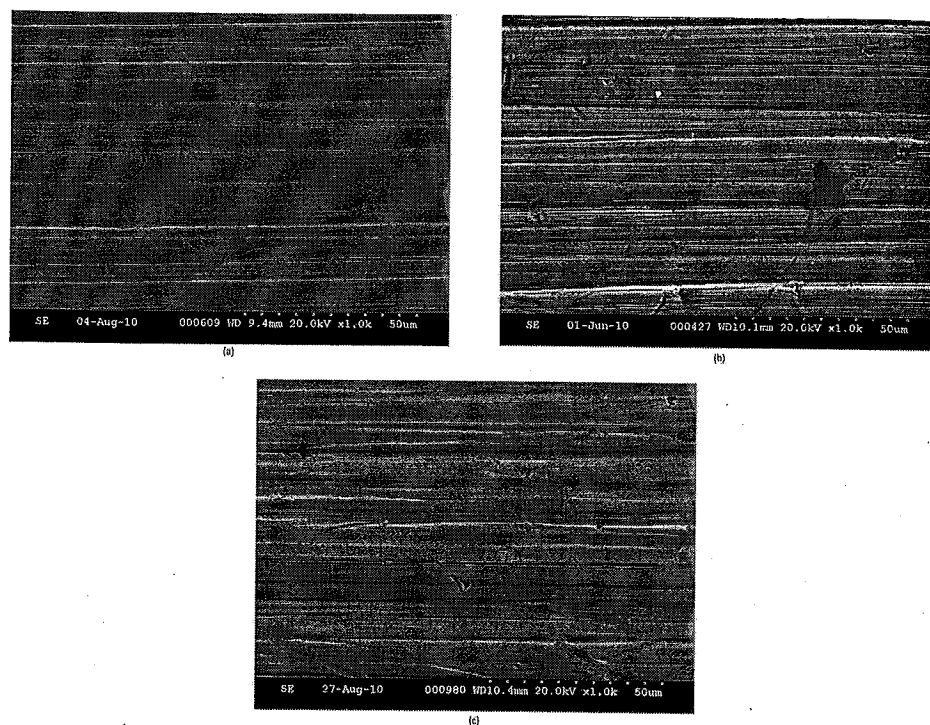


FIG. 10—Typical wear surfaces after slurry abrasion testing for the corrosion-resistant steels (OEO – high chromium steel, HV670). (a) OEO, salt solution slurry, 10 wt. % solids, 48 rpm, 6 h; (b) OEO, salt solution slurry, 50 wt. % solids, 16 rpm, 18 h; (c) AISI 316 steel (HV200.8), salt solution slurry, 50 wt. % solids, 48 rpm, 6 h.

concentration slurry [50 wt. % solids, Fig. 10(b)] than in the lower concentration slurry [10 wt. % solids, Fig. 10(a)].

The cast CA6NM stainless steel (CBQ-2) has a relatively low hardness (322HV). Its wear surface after sliding in salt slurry showed similar features to those observed on other low hardness steel specimen surfaces, i.e., short ploughing/cutting grooves with many small general corrosion pits (Fig. 11). As has been presented earlier, the wear behaviour of this steel also falls on the same trend as that of the low hardness steels (Table 2, Fig. 3), presumably due to the non heat-treated casting microstructure of the material.

The Stellite 6 cladding (OOV-2, 544.6HV) showed very low sensitivity to corrosion in the slurry abrasion testing under all the testing conditions (Tables 2, and 3, and Figs. 2 and 3). After sliding in salt slurry at the low speed and in low slurry concentration, the microstructure was revealed by corrosion/etching [Fig. 12(a)]. However, there were few signs of localised corrosion attacks. The main wear mechanism seems to be cutting.

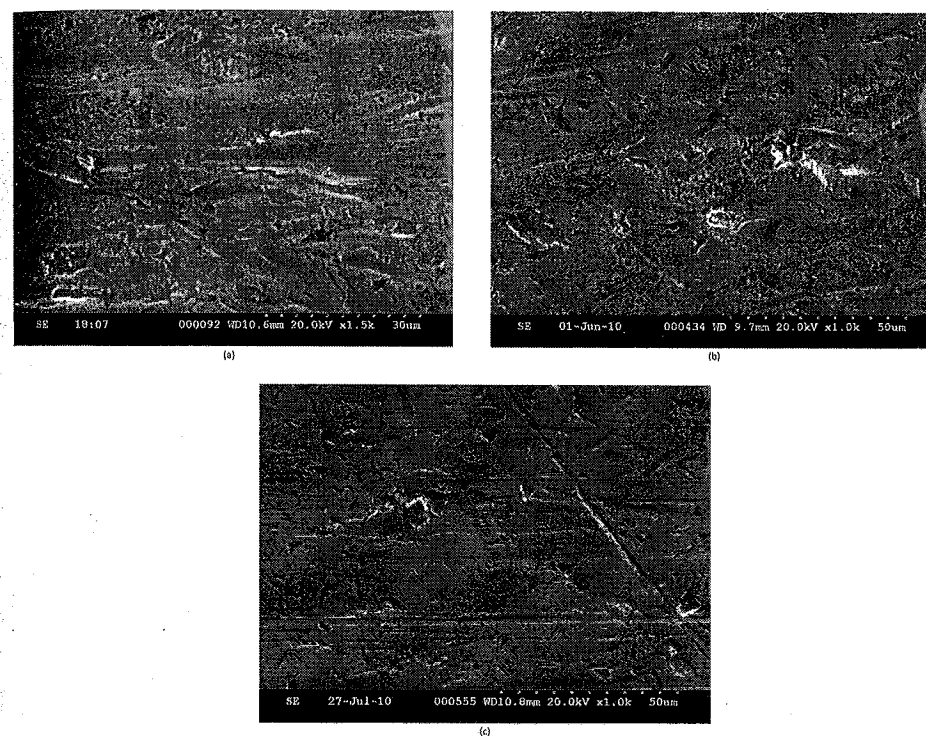


FIG. 11—Typical wear surfaces formed on the cast CA6NM stainless steel specimen (CBQ-2) after sliding in salt slurry. (a) 50 wt. % slurry, 48 rpm, 6 h; (b) 50 wt. % slurry, 16 rpm, 18 h; (c) 10 wt. % slurry, 48 rpm, 6 h.

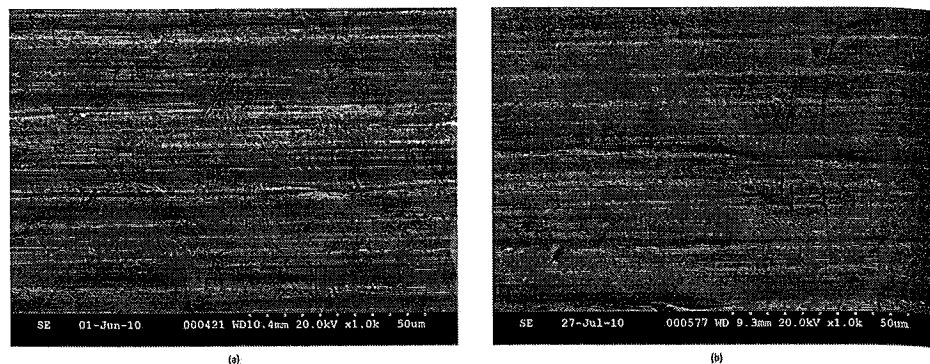


FIG. 12—Wear surface of Stellite 6 cladding (OOV-2) after sliding in salt slurry: (a) 50 wt. % solids, 16 rpm, 18 h; (b) 10 wt.% solids, 48 rpm, 6 h.

Discussion

Modelling the Synergistic Effect

From the experimental observations presented in the last chapter, the synergistic abrasion-corrosion is affected by the following factors: slurry concentration, sliding speed, materials' hardness, and corrosion resistance. This is in line with a model developed for analyzing synergistic effect in sliding wear of metals in corrosive environment [10].

According to the model presented in Ref [10], the mechanism for wear debris generation in most wear processes can be regarded as a micro-crack initiation and propagation process. This is essentially a micro-fatigue process. Thus, under heavy loading conditions, wear debris generation is analogous to a low cycle fatigue process, while under lightly loaded conditions, the wear debris generation is similar to a high cycle fatigue process. In corrosive environment, wear is enhanced mainly through accelerated crack propagation because bonds at the micro-crack tip are activated by certain corrosive/reactive species. Corrosion initiated surface defects such as pits may also lead to increased micro-crack initiation and wear. For wear-enhanced corrosion, the main mechanism is assumed to be repeated creation and re-passivation of fresh/active wear surface by the wear actions. A wear map constructed based on the model showed good qualitative agreement with experimental results published in the literature [10].

Although the model presented in reference [10] was developed for sliding wear, the basic concepts used in developing the model can also be generalized to analyze the synergistic effect in abrasion. For example, by re-analyzing the experimental data reported by Kato and co-workers [11–13], who systematically studied material removal mechanisms in heat treated steels using a

single particle scratching test method, Jiang and Arnell [14] concluded that low cycle fatigue is most probably the underlying mechanism controlling the generation of wear debris in the single particle scratching. Such single particle scratching test closely simulates material removal during abrasive wear. Depending on the depth of particle penetration, the dominant material removal mechanism can be ploughing or cutting for non-brittle materials such as steels. In the light of low cycle fatigue failure, a wear debris particle is generated when the fatigue life is reached under a given plastic strain amplitude. Cutting can essentially be regarded as an extreme situation of the low cycle fatigue model where material in front of the abrasive particle reaches its fatigue life in one cycle of contact.

By simplifying the model in Ref [10] and applying it to the current slurry abrasion-corrosion system, the critical conditions (boundary) that separate wear-induced corrosion dominated regime from corrosion-induced wear dominated regime can be described by the following relationship:

$$\frac{W}{H} \propto \phi(f, \tau_0) \quad (4)$$

where:

W = load,

H = material hardness,

f = the contact frequency on a certain point of the rubbing surface by an abrasive particle that can potentially lead to wear, and

τ_0 = a characteristic time for the corrosion passivation reaction of the metal. The lower the value of τ_0 , the faster the metal passivates in the given environment.

It should be pointed out that the parameter, τ_0 , in Eq 4 is relevant for non-abrasive sliding wear conditions as shown in [10] where the dominant corrosion mechanism is general (or uniform) corrosion. However, it may not be appropriate for describing the abrasion-corrosion situation such as that encountered in the current study. As is shown in Figs. 4 and 5, extensive pitting corrosion occurred on wear surface of the high hardness steels when sliding in salt slurry, although pitting did not occur outside the wear surface. On the other hand, of the tested low hardness steels, only one showed pitting corrosion (OAG-2 low alloy pipe steel) which occurred only under the conditions of combined low sliding speed and low concentration slurry (Fig. 8). For corrosion-resistant materials and the low hardness steels, general corrosion was the main corrosion mechanism (Figs. 9–12). At this stage, the mechanisms and conditions for the different types of corrosion under the slurry abrasion conditions are still unknown. It is thus unclear how materials' corrosion resistance will affect the abrasion-corrosion synergy. More efforts are obviously

needed to understand and model the contribution of corrosion in the abrasion-corrosion process. For now, the parameter, τ_o , included in expression 4 should simply be regarded as some characteristic indicator for the corrosion resistance of the material being investigated. In the following analysis, this effect is taken as a constant for all the materials/situations, i.e., the difference in materials' corrosion resistance is neglected.

In the Miller slurry abrasion testing system the contact frequency of the wear surface by abrasive particles, f , is related to sliding frequency, F , and slurry concentration, C . However, it is not apparent how these parameters are interrelated. In order to gain some insight about possible forms of such relationships, a series of experiments were conducted on the variation of wear rate, SAR, as a function of slurry concentration, C , for four steels of various characteristics including high and low hardness steels, a tool steel and a stainless steel. The slurry used was composed of AFS 50/70 silica sand and DI water. The results are shown in Fig. 13(a). Regression analysis of the data shows that all the steels follow a logarithmic relationship between SAR number and the slurry concentration, C . This agrees very well with the results for chromium white cast iron by Miller and Miller [15], as shown in Fig. 13(b). It is also obvious that f should be proportional to the sliding frequency, F . Thus, based on experimental observation, as a first approximation, the following empirical relationship can be assumed for the frequency of abrasion events, f :

$$f \propto (F \ln C) \quad (5)$$

Substituting Eqs 5 into 4, the boundary condition separating wear-dominated regime and corrosion-enhanced wear dominated regime can thus be expressed by

$$\frac{W}{H} \propto (F \ln C)$$

or

$$\alpha \frac{W}{H} = (F \ln C) \quad (6)$$

where:

α = arbitrary proportional constant that is related to the definition of what ratio of the corrosion-enhanced wear to wear-enhanced corrosion is taken as the boundary separating the two regimes.

A Slurry Abrasion-Corrosion Wear Map

Based on the above analysis, an abrasion-corrosion map can be constructed (Fig. 14) by plotting $25*(W/H)$ against the combined parameter, $F \ln(C)$, for

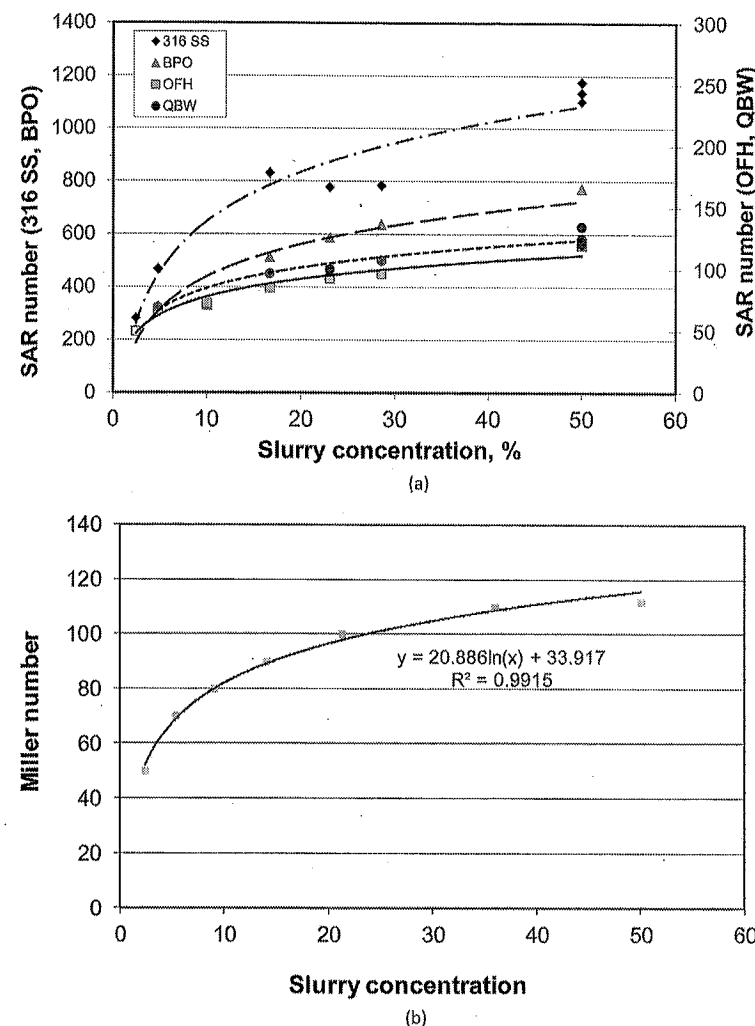


FIG. 13—The variation of SAR numbers of several steels as a function of slurry concentration. (a) Results for AISI 316 stainless steel, high hardness Fedur 90 pipe steel (OFH), low hardness medium carbon pipe steel (BPO), and AISI D2 tool steel (QBW). Slurry: AFS 50/70 sand + DI water, 50 wt. % solid. (b) Results extracted from Ref [1] for white chromium cast iron.

all the combinations of materials and testing conditions shown in Table 3. The corresponding relative synergy values are illustrated (in the textboxes) adjacent to the data point $[25*(W/H), F \ln(C)]$ for a given material/testing condition combination. The value of 25 for the arbitrary factor, α , in Eq 6 is taken simply to give a reasonable coordinate scale. It was shown in Ref [10] that this value covers fairly well the testing conditions of sliding wear reported in the

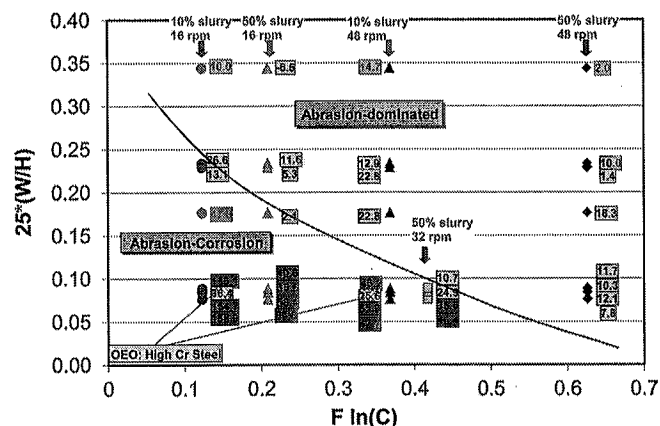


FIG. 14—A wear map showing the transitions of dominant material loss regimes between abrasion-corrosion and abrasion. Data in the textboxes show the relative synergy at the given conditions [W/H and $F \ln(C)$].

literature. Obviously, any other values can be taken for α without affecting the following discussions and conclusions.

Based on the data shown in Fig. 14 for relative synergy, a boundary can be drawn (the solid line) that divides the wear map into two regions. In the upper-right hand region, the relative synergy values are low, generally below about 20 %. Material loss due to the presence of corrosion environment is similar to or only slightly higher than sliding in DI water slurries. The dominant material loss mechanism is abrasion. Conditions in this region are: low material hardness or high load and high sliding speed and/or high slurry concentrations. On the other hand, in the lower-left hand region of the wear map (Fig. 14), high relative synergy values are observed, indicating considerably increased material loss when sliding in the corrosion environment. This is a region where corrosion-enhanced wear and probably also wear-enhanced corrosion (such as pitting) plays important roles in causing increased material loss. Conditions within this region are high material hardness, low load, low sliding speed, and low slurry concentrations.

Discussions on the Wear Map

In Fig. 14, the relative synergy values generally increases with decrease in the (W/H) ratio at the same $F \ln(C)$ value. In the meanwhile, the relative synergy increases as the $F \ln(C)$ value decreases at the same (W/H) ratio. For the OEO sample, which is a high chromium corrosion-resistant steel with high hardness, the relative synergy also decreases with increase in the $F \ln(C)$ value. However, under the same [W/H , $F \ln(C)$] conditions, the relative synergy for OEO

is considerably lower than that to be expected for carbon steels. Obviously, corrosion resistance plays a very important role in abrasion-corrosion synergy. Further study is required to understand the effect of corrosion-resistance on synergy in slurry abrasion-corrosion.

Variation of Material Loss Regimes as a Function of Wear Intensity, W/H —For a given material with a hardness, H , the depth of abrasive penetration to the material surface increases with increase in load, W . However, within the same given testing time (at the same sliding frequency, F , and slurry concentration, C), the total corrosion will remain similar at the different load levels (the surface is constantly activated by the high concentration abrasion actions). Thus, the ratio of material loss due to wear-enhanced corrosion to the total material loss will decrease with increase in load. That is, the mechanism of material loss will be dominated by abrasion at the high W/H ratios. Under such conditions, the main form of corrosion is general corrosion because any sites of pit initiation will have been removed rapidly by the severe abrasion actions before they can develop into full scale pitting, as has been shown earlier (Figs. 9 and 11).

Variation of Material Loss Regimes as a Function of the Corrosion Time Factor, $F \ln(C)$ —The parameter, $F \ln(C)$, essentially reflects the relative importance of corrosion in the overall material loss during abrasion corrosion. High values of this parameter (either high sliding frequency, F , or high slurry concentration, C , or combination of both) mean less corrosion attack time for the same number of abrasion events (cutting, ploughing). Thus, at a given W/H ratio, increasing the $F \ln(C)$ value will reduce the relative contribution of corrosion to the total material loss, decreasing the relative synergy (Fig. 14). Abrasion becomes the dominant material loss mechanism. This is similar to the conditions of high W/H ratios as discussed above. On the other hand, at low sliding speed and/or in low concentration slurries, corrosion will have more time to attack the material surface for the same number of abrasion events. The contribution of corrosion to overall material loss increases, leading to increased relative synergy, as is shown in Fig. 14. Under such conditions, the more severe form of corrosion, pitting, may also have sufficient time to develop, leading to much higher relative synergistic effect. The abrasion-corrosion regime becomes dominant under such conditions, as shown in the bottom-left region of Fig. 14. Under combined low sliding speed and low slurry concentration conditions, pitting can develop even on the low hardness steel (high W/H ratio), as mentioned earlier for the sample OAG-2 (Fig. 8).

From the above discussions, the following conditions will favour high relative synergy: low load, high hardness, low relative movement speed between abrasive and the wear surface, low slurry concentrations, low corrosion resistance, and low slurry abrasivity.

Conclusions

The effect of corrosion on slurry abrasion of pipe steels and abrasion resistant steels has been investigated using the Miller tester in slurries composed of AFS50/70 silica sand and de-ionized water or 3.5 %NaCl salt solution. Characteristics of wear surfaces formed under various testing conditions are examined using SEM. A wear map is constructed for slurry abrasion-corrosion regime transitions based on semi-empirical analysis of a model for sliding wear corrosion [10].

- (1) The relative slurry abrasion-corrosion synergy of steels is a function of hardness. Hard steels show considerably higher relative synergy than low hardness steels.
- (2) Extensive pitting corrosion has been observed after abrasion testing in salt solution slurry. For low hardness steels, general corrosion (with micro-pitting) is the dominant corrosion mechanism under the slurry abrasion-corrosion conditions.
- (3) The dominant material loss regimes are determined by the two parameters, W/H and $F \ln(C)$. Under conditions of low W/H and low $F \ln(C)$ values, corrosion significantly increases the total material loss and the dominant material loss regime is abrasion-corrosion. On the other hand, high W/H and high $F \ln(C)$ values favour the abrasion-dominated material loss regime.
- (4) It is important to use corrosion resistant materials under the abrasion-corrosion dominated regime [i.e., low W/H and/or low $F \ln(C)$].
- (5) Increased relative synergy is expected under the following conditions: low load, high hardness, low relative movement speed between abrasive and the wear surface, low slurry concentrations, low corrosion resistance, and low slurry abrasivity.

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