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Modification of Aluminide Coating with Yttrium for Improved Resistance to Corrosive Erosion

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Aluminide coatings on a mild steel substrate were modified by using an oxygen-active element, yttrium, for improved resistance to corrosive erosion. The performance of the yttrium-containing coating during the following three erosion conditions was evaluated: dry sand erosion at different temperatures, erosion in a dilute NaCl slurry containing 30% silica sand, and erosion in a dilute H_2SO_4 slurry containing 30% silica sand. Results of the study demonstrated that yttrium significantly improved the resistance of the aluminide coating to both corrosive erosion and dry sand erosion.

Keywords corrosion, corrosive erosion, erosion, yttrium-modified aluminide coating

1. Introduction

Surface modification and coating are economical and effective approaches to the protection of mechanical components from surface damage caused by wear and corrosion. Various coating techniques have been used in industry for wear applications. However, many coatings are ineffective when wear takes place in corrosive environments or at elevated temperatures because of the synergistic action of wear and corrosion. Efforts have continuously been made to develop protective coatings that are able to resist corrosive wear encountered in various industries such as mining, chemical processing, and food processing industries.

Aluminum-diffusion coatings or aluminide coatings are known as a widely used protective coating against oxidation and high-temperature corrosion (Ref 1-3). An aluminide coating formed on low carbon steel usually consists of an outwardly grown FeAl layer, an intermediate layer with Fe_3Al and FeAl intermetallic compounds as major phases (Ref 4), and an inner layer of α-solid solution of aluminum in iron (Ref 5). This type of coating has recently been used to reduce erosion at elevated temperatures, for instance, to protect sinter machine cooler grates from erosion caused by high-temperature burden as well as the oxidation from excess air and corrosion from combustion products (Ref 6). The aluminide coating has demonstrated its efficiency in preventing erosion or low-stress wear at elevated temperatures.

It is no doubt that the performance of aluminide coatings could be improved, and its application could be extended through material modification and process optimization. This article reports the authors' recent study on modification of aluminide coating on 1030 steel with an oxygen-active element, yttrium, for improved resistance to corrosive erosion. Yttrium has been proven effective as an alloying element in improving oxidation resistance of high-temperature alloys with enhanced oxide adherence (Ref 7-13). Yttrium plays a similar role in resisting oxidation when used as an addition in surface coatings, such as for physical vapor deposition coatings (Ref 14), low-pressure plasma spraying overlay coatings and CO_2 laser processed coatings (Ref 15), ion implantation (Ref 16-20), and yttrium-modified aluminide coatings (Ref 21-24). Recent work on the corrosive wear of yttrium-containing stainless steel by Zhang and Li (Ref 25) demonstrates that, in addition to resisting oxidation and corrosion, yttrium is also beneficial to the wear resistance of stainless steel in aggressive environments. Interest has also increased recently in the tribological performance of yttrium-containing coatings. For instance, Li et al. (Ref 26) investigated the friction behavior of plasma deposited MCrAlY coatings sliding against a low-pressure plasma sprayed NiCoCrAlYTa coating under fretting conditions. Zhang et al. (Ref 27) studied corrosion, wear, and oxidation resistance of H13 steel implanted with yttrium, chromium, yttrium and carbon, and ytrrium and chromium ions. Their results showed that the resistance of such implanted steel to wear, corrosion, and oxidation resistance were improved. However, the knowledge about yttrium effects on wear is far from being sufficient for effective industrial applications.

Research was conducted by the authors to investigate erosion behavior of aluminide coatings on 1030 steel in dilute NaCl and H_2SO_4 slurries, respectively, containing 30% silica sand particles with the emphasis on effects of yttrium on the performance of a yttrium-containing aluminide coating. In this study, a pack diffusion process, as described in Ref 14, was used to make aluminide coating on 1030 steel substrate. The aluminide coating was modified with a small amount of yttrium. The performance of the modified coating during corrosion, dry sand erosion, and corrosive erosion processes was evaluated and compared to the yttrium-free aluminide coating as well as the 1030 steel substrate. Promising results were obtained, which demonstrate that yttrium is greatly beneficial to the aluminide coating with improved resistance to corrosive erosion and dry sand erosion as well.

2. Experimental Procedure

The substrate material used in this study was a commercial grade of 1030 steel. Rod-shaped specimens, 25 mm long and 6

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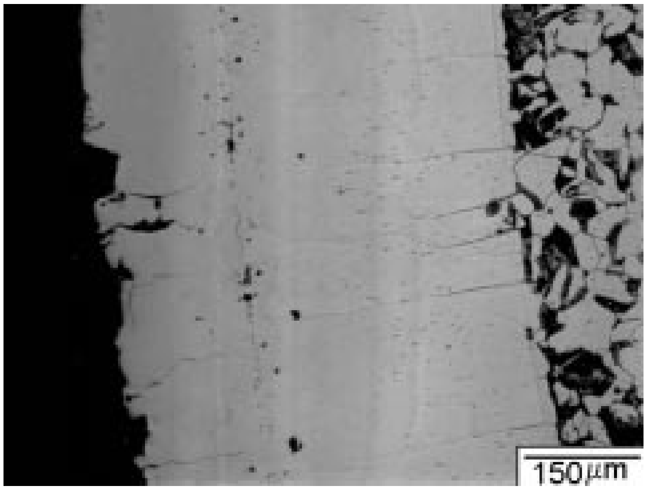
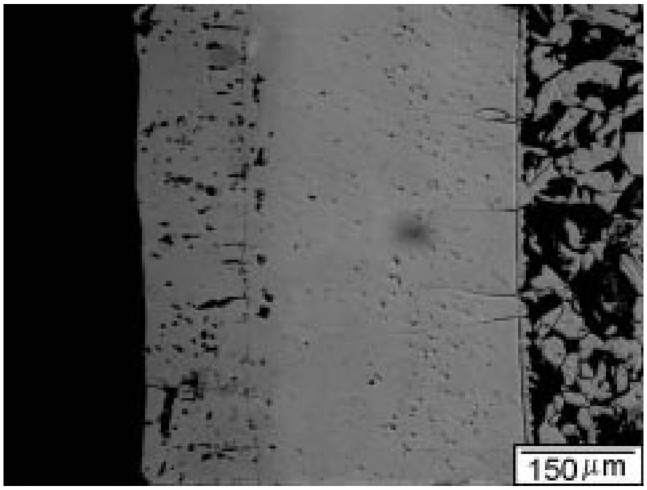
mm in diameter, were machined from a commercial 1030 steel rod. All specimens were mechanically polished with 600 grit paper and cleaned in acetone. The 1030 steel specimens were then coated by the pack-aluminizing process. An FeAl (50%Fe-50%Al) alloy powder was used as the aluminum resource, NH_4Cl powder was used as an activator, and Al_2O_3 powder was used as a filler material. A small amount of commercial yttrium powder (–40 mesh) was mixed with the FeAl powder to produce the yttrium-containing aluminide coating. Table 1 lists compositions and diffusion conditions for the pack cementation.

Table 1 Conditions for pack cementation

Pack composition	Diffusion temperature	Diffusion time
49%FeAl + 49%Al_2O_3 + 2%NH_4Cl	950 °C	10 h
47%FeAl + 47%Al_2O_3 + 3%yttrium + 3%NH_4Cl	950 °C	10 h



(a)



(b)

Fig. 1 Cross-section micrographs of (a) Y-free aluminide coating and (b) Y-containing alumiide coating

The coating microstructure was examined using optical microscopy and transmission electron microscopy (TEM). The composition of coatings was analyzed by energy dispersive x-ray spectroscopy (EDS). Microhardness of coatings was determined using a Shimadzu microhardness tester type M (Shimadzu Corp., Kyoto, Japan), under a load of 100 g for 25 s.

In order to better understand the protective function of aluminide coating, corrosion rates of coated and uncoated steel specimens were measured using an immersion method, that is, measuring the material loss of a sample after being immersed in a corrosive solution for a certain period. A 3.5% NaCl solution and a 0.1 M/L H_2SO_4 solution were used as the aggressive media. The corrosion test was conducted at room temperature for 168 h. The corrosion rate of a sample was then calculated using the following formula:

$$V_{\text{Corr}} = \frac{w_2 - w_1}{S \cdot t} \cdot \frac{1}{\rho} \qquad \text{(Eq a)}$$

where V_{Corr} is the corrosion rate, that is, the volume loss per unit area and per unit time (mm^3/m^2h); W_2 and W_1 are the weight, in grams, of the sample before and after corrosion, respectively; S is the surface area, m^2, of the sample exposed to the aggressive medium; t is the immersion time, in hours; and ρ is the density of the tested material, g/mm^3.

Electrochemical polarization behaviors of coated and uncoated specimens, respectively, in 3.5% NaCl solution and in 0.1 M/L H_2SO_4 solution were determined at room temperature. A saturated calomel electrode (SCE) was used as the reference electrode with a platinum net counter electrode. The scan rate was 20 mV/min.

Erosion tests were performed in a slurry erosion pot tester. The slurry pot was made of 304 stainless steel with four vertical baffles used to break up the rotational flow of slurry. The test temperature can be changed from room temperature to 200 °C. The speed of specimen can be controlled from 0 to 375 m/min. For the present study, the speed of specimen was selected to be 315 m/min. Silica sand (AFS 50/70 mesh test sand) particles were mixed with 3.5% NaCl solution and 0.1 M/L H_2SO_4 solution, respectively, to make corrosive slurries for the corrosive erosion test.

3. Results and Discussion

3.1 Microstructure of Aluminide Coatings

Pack aluminizing of 1030 steel with and without yttrium at 950 °C for 10 h resulted in the formation of aluminide coatings about 500 µm thick, as shown in Fig. 1. The aluminide coatings on 1030 steel consist of three layers. The outer-growth layer was an amorphous layer about 150 µm thick, followed by an intermediate layer about 150 µm thick that mainly contained Fe_3Al and FeAl intermetallic compounds. Beneath the intermediate layer was an extended aluminum-containing solid solution zone. Transmission electron microscopy and EDS analysis showed that there was about 1 at.% yttrium in the outer-growth layer (Fig. 2a), 0.4 at.% yttrium in the intermediate layer (Fig. 2b), and about 0.2 at.% yttrium was observed at the grain boundaries in the inner layer, as shown in Fig. 2(c). The three-layer structure of aluminide coating is similar to those on low-carbon steels observed respectively by El-Azim et al. (Ref 4) and Soliman and El-Azim. (Ref 5).

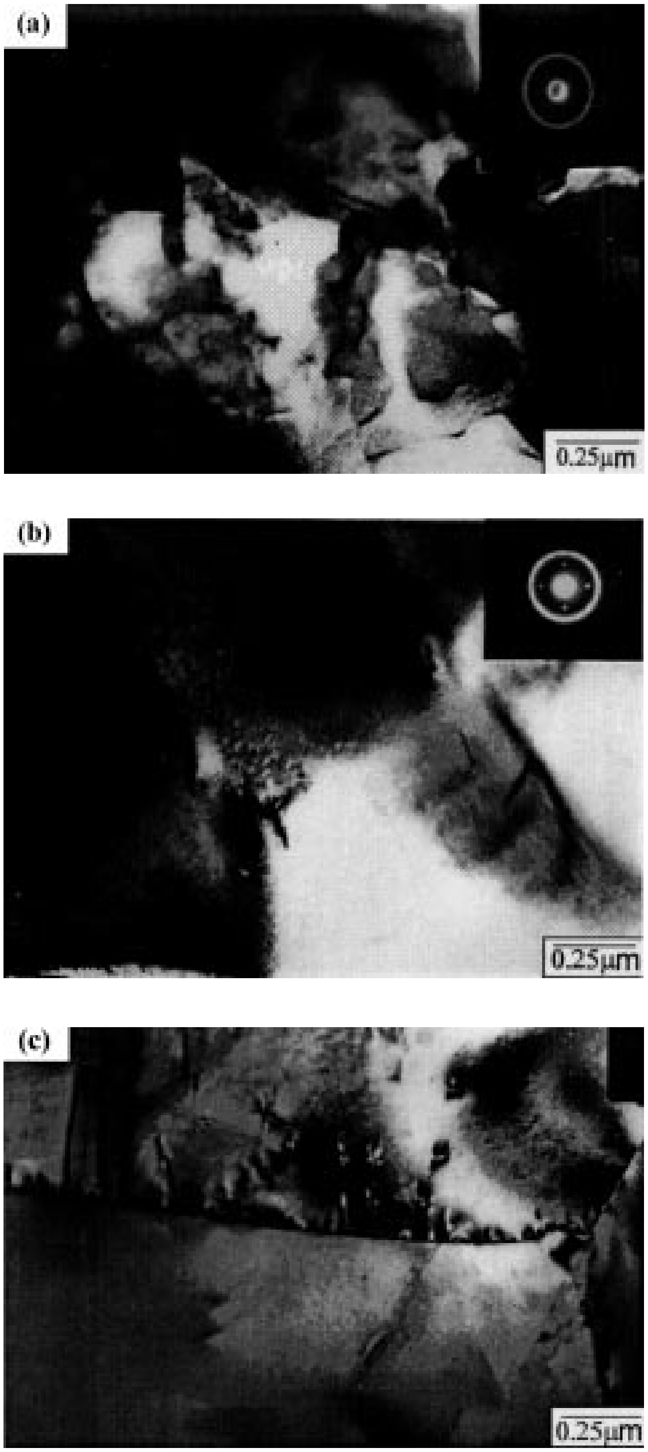


Fig. 2 TEM images of the cross-section of a Y-containing aluminide coating. (a) The outer growth amorphous layer containing 1 at.% Y (detected by EDS). (b) The intermediate layer containing about 0.4 at.% Y. (c) The inner layer in which 0.2 at.% Y was detected at grain boundaries.

3.2 Corrosion Behavior

In order to understand the performance of aluminide coating under the synergistic attack made by corrosion and erosion, corrosion rates of 1030 steel substrate, the aluminide coating, and the yttrium-containing aluminide coating were determined, respectively. Figure 3(a) and (b) illustrates steady corrosion rates of uncoated and coated specimens in dilute NaCl and H_2SO_4 solutions, respectively. In Fig. 3(a), the corrosion rate of 1030 steel in a 3.5% NaCl solution is about 2.5 times higher than that of the aluminide coating and 6.1 times higher than that of the yttrium-containing aluminide coating. This indicates that the aluminide coatings exhibit higher corrosion resistance than the steel substrate in the dilute NaCl solution. In particular, the yttrium addition rendered the aluminide coating considerably superior. The situation was similar when coated and uncoated specimens were corroded in a 0.1 *M*/L H_2SO_4 solution, as shown in Fig. 3(b). It can be seen that the corrosion resistance of aluminide coating was remarkably higher than that of 1030 steel, and the coating was greatly improved when yttrium addition was added. The corrosion rate of 1030 steel in 0.1 *M*/L H_2SO_4 solution is 1.5 times higher than that of the yttrium-free aluminide coating and 2.9 times higher than that of the yttrium-containing aluminide coating.

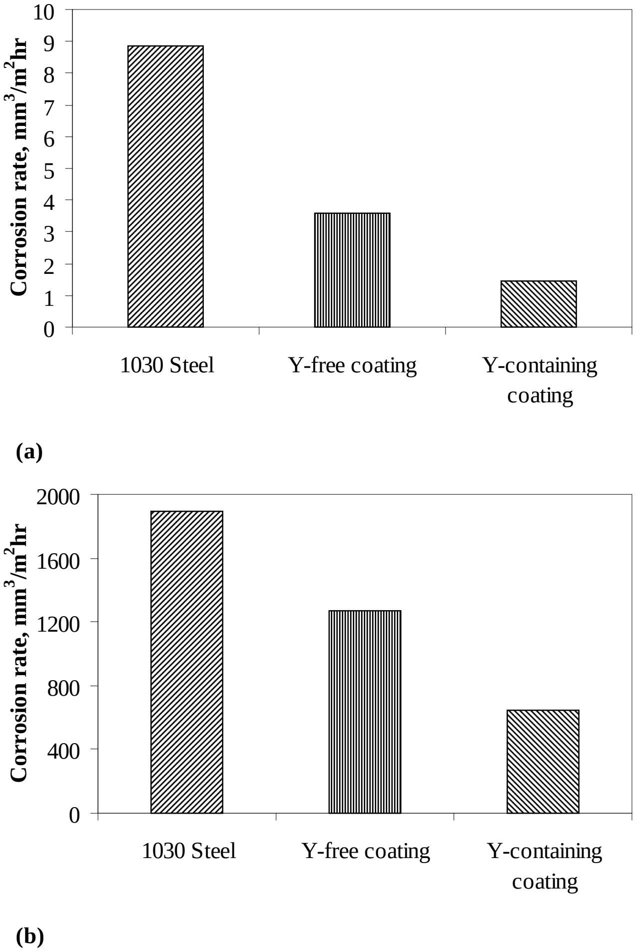


Fig. 3 Corrosion rates of aluminide coatings and the substrate steel in (a) 3.5% NaCl solution and in (b) 0.1 *M*/L H_2SO_4 solution. The measurement error is about ±3 to 5%.

Polarization tests were conducted for further information on corrosion resistance of the coated and uncoated specimens. Figure 4(a) illustrates anodic polarization curves of 1030 steel substrate and aluminide coatings with and without yttrium in the 3.5% NaCl solution. Both the coated and uncoated steel specimens did not passivate in the dilute NaCl solution; that is, they anodically dissolved in the solution. However, the corrosion potential of aluminide coating shifted to higher potential level in contrast to that of the steel substrate, and therefore, the aluminide coating exhibited a higher corrosion resistance. In particular, it can be noticed that the yttrium-containing aluminide coating had the highest corrosion potential. Of these three types of specimens, the yttrium-containing coating clearly showed the highest resistance to corrosion, which is in agreement with the immersion test.

Figure 4(b) illustrates polarization curves of 1030 steel and aluminide coatings in 0.1 *M*/L H_2SO_4 solution. The differences in corrosion potential between the substrate steel, the yttrium-free coating, and the yttrium-containing coating in the dilute H_2SO_4 solution are very small. However, their passive current densities or critical current densities for passivation are quite different. The aluminide coating and the yttrium-containing coating significantly reduced the passive current density of 1030 steel by factors of 22 and 94, respectively. The aluminide coating effectively protected the steel from corrosion in the dilute H_2SO_4 solution, and its protection role was further enhanced by yttrium to a significant degree.

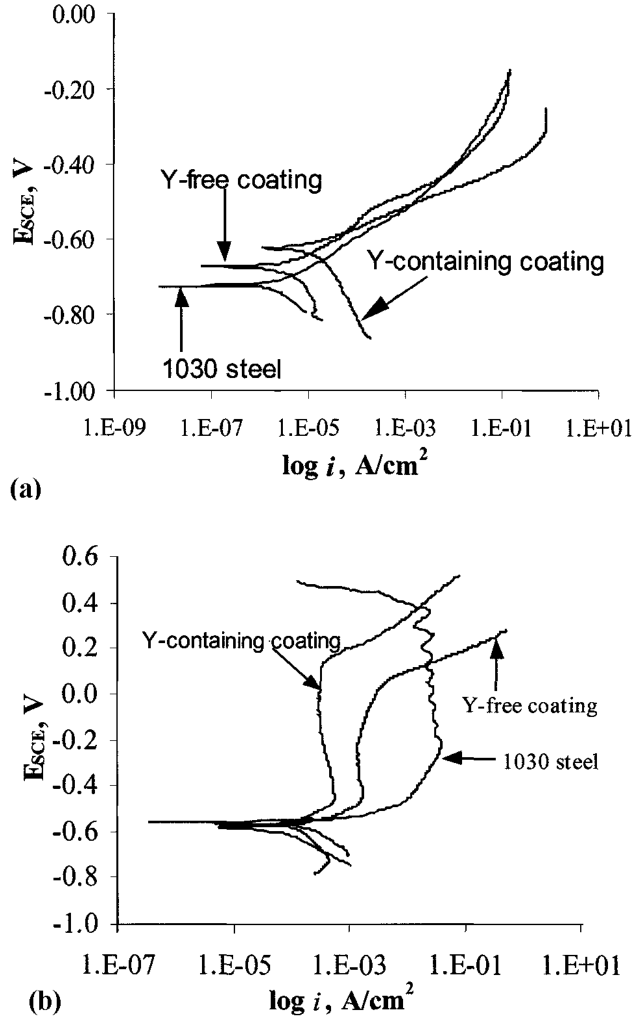


Fig. 4 Polarization curves of aluminide coatings and the substrate steel in (a) 3.5% NaCl solution and in (b) 0.1 *M*/L H_2SO_4 solution

3.3 Dry Sand Erosion Behavior

In this study, dry sand erosion tests were conducted in a slurry pot at different temperatures from room temperature to 190 °C. Erosion behavior of uncoated and coated steel specimens was evaluated. The erosion test at each temperature was performed for 5 h in dry silica sand. Figure 5 illustrates erosion rates of the coatings and the 1030 steel substrate with respect to temperature. The erosion rates of all specimens were almost linearly proportional to the test temperatures. The aluminizing greatly diminished the erosion of the 1030 steel, and in particular, the yttrium addition further improved the aluminide coating to a considerable degree. In addition, slopes of the erosion rate versus temperature curves of the aluminide coatings are lower than that of the 1030 steel. The slope of erosion rate versus temperature curve of 1030 steel substrate changed from 3.28 mm^3/m^2h °C to 2.36 mm^3/m^2h °C when it was coated by aluminizing and further down to 1.41 mm^3/m^2h °C when the coating contained yttrium. This decrease in the slope of erosion rate versus temperature curve implies that the protection function of the aluminide coatings is effective not only at room temperature but also at elevated temperatures.

In general, wear loss is inversely proportional to material hardness. The improvement in the erosion resistance could be attributed to the higher hardness of the aluminide coatings. The microhardness measurement demonstrated that the aluminide coating was about two times as hard as the substrate steel (see Fig. 6). Yttrium slightly strengthened the aluminide coating with an increase in its hardness. In the case of erosion at elevated temperatures, oxidation might be more or less involved though it could not be severe in the tested temperature range. The aluminide coating can reduce oxidation, and this can improve its erosion resistance at elevated temperatures. Yttrium is a well-known oxygen-active element, and its existence can enhance the oxidation resistance, thus further diminishing the

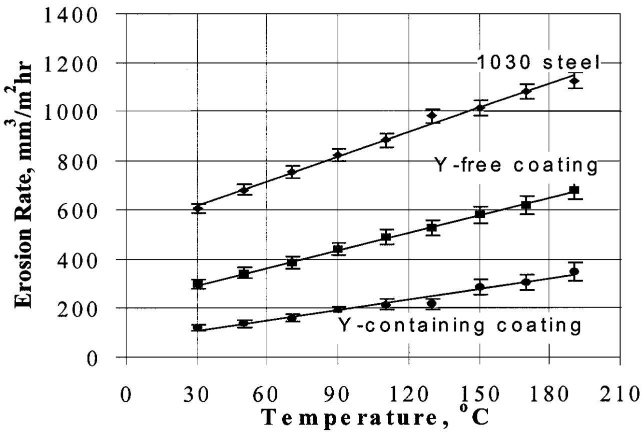


Fig. 5 Erosion rates of aluminide coatings and the substrate steel in dry sand

erosion loss at elevated temperatures. Similar function of yttrium was also observed in 304 stainless steel during sliding wear; in that case, the wear resistance of the stainless steel was significantly improved by alloying with yttrium, especially under high loads accompanied by large release of friction heat (Ref 25).

3.4 Corrosive Erosion Behavior

The main objective of this research is to evaluate yttrium effects on the protection efficiency of aluminide coating against corrosive erosion in salty and acidic slurries. Corrosive erosion rates of the steel substrate, the yttrium-free aluminide coating, and the yttrium-containing coating were determined, respectively, in a 3.5% NaCl slurry containing 30% silica sand particles as well as in a 0.1 *M*/L H_2SO_4 slurry containing 30% silica sand particles. The obtained results demonstrated that the aluminide coating had significantly higher resistance to corrosive erosion than the mild steel substrate in both the salty and acidic slurries (see Fig. 7a and b).

The protection role of the aluminide coating was further enhanced by yttrium addition. In particular, yttrium considerably improved the aluminide coating eroded in the NaCl slurry. This is clearly illustrated in Fig. 7(a). However, the beneficial effect of yttrium on the aluminide coating eroded in the slurry containing H_2SO_4 solution and sand particles was not as remarkable as that in the case of erosion in the NaCl slurry.

It is generally expected that the total material loss caused by corrosive erosion can be diminished by either restraining the corrosion process or restraining the erosion process, depending on which one is predominant. It could be more efficient to reduce the material loss if both the processes can be suppressed simultaneously. This general guideline works well for yttrium-containing aluminide coating eroded in the slurry containing NaCl solution and silica particles. In this case, yttrium enhanced the aluminide coating with improved resistance to both the corrosion in dilute NaCl solution and the dry sand erosion, resulting in higher resistance to corrosive erosion in the NaCl slurry. However, the situation is different in the case of erosion in the slurry containing H_2SO_4 solution and silica particles. Although yttrium significantly increased the resistance of aluminide coating to both the corrosion in dilute H_2SO_4 solution and dry sand erosion, its effect on the performance of aluminide coating during the corrosive erosion in the sand-containing H_2SO_4 slurry was not significant. Because the synergistic action of corrosion and wear is complicated and not completely understood, further studies are needed to understand the mechanism responsible for the yttrium effect on corrosive erosion of aluminide coating in different slurries.

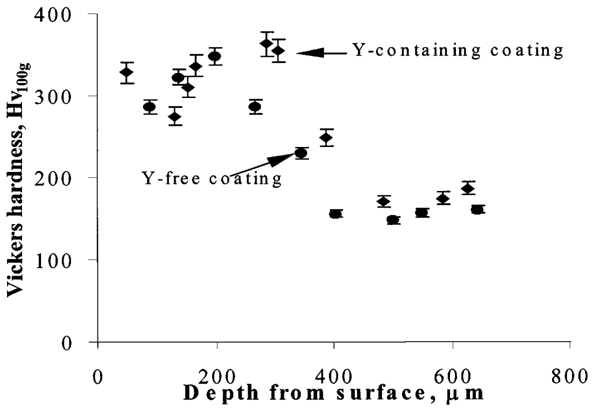


Fig. 6 Variation of Vickers hardness with respect to the coating depth from surface

4. Conclusions

Research was conducted to investigate the beneficial effect of the oxygen-active element, yttrium, on the resistance of an aluminide coating on corrosive erosion in salty and acidic slurries, respectively. Results of the research demonstrate that yttrium remarkably improved the resistance of aluminide coating to corrosion in both dilute salty and acidic solutions, as well as the resistance to dry sand erosion at different temperatures. In the case of corrosive erosion, yttrium significantly improved the performance of aluminide coating in a slurry containing dilute NaCl solution and silica particles; while the beneficial effect of yttrium was not as strong as that shown in the previously mentioned case, when the aluminide coating was eroded in a slurry containing dilute H_2SO_4 solution and silica particles.

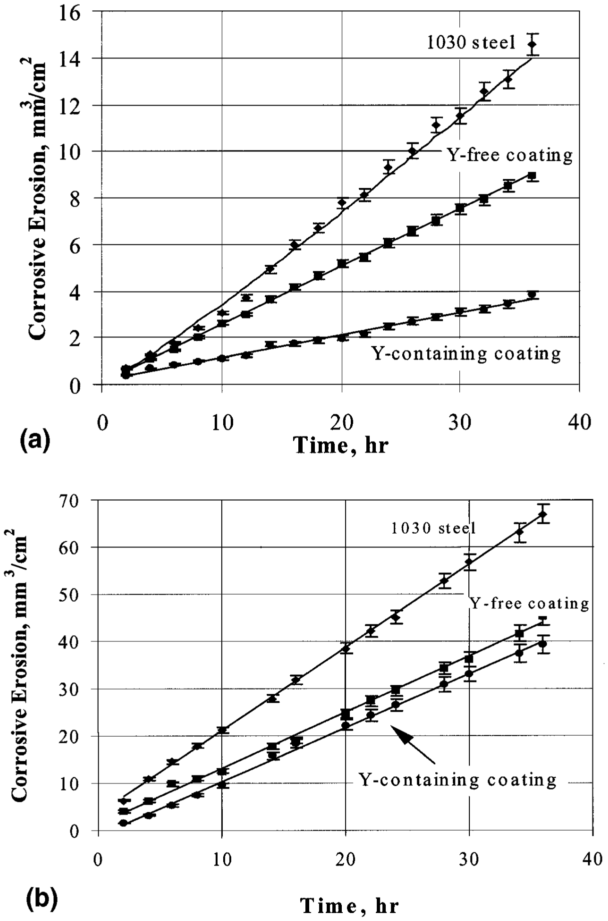


Fig. 7 Corrosive erosion of aluminide coatings and the substrate steel in a 30% silica sand slurry containing 3.5% NaCl (a) or 0.1 *M*/L H_2SO_4(b)

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