Vacuum 86 (2012) 1886–1894

Contents lists available at SciVerse ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Determination of the best behavior among AISI D3 steel, 304 stainless steel and CrN/AlN coatings under erosive-corrosive effect

J.C. Caicedo [a,b,*], G. Cabrera [a], W. Aperador [c], H.H. Caicedo [d,e,**], A. Mejia [f]

[a] Thin Films Group, Universidad del Valle, Colombia
[b] Advanced Materials for Micro and NanoTechnology Research Group, Universidad Autónoma de Occidente, Cali, Colombia
[c] Ingeniería Mecatrónica, Universidad Militar Nueva Granada, Bogotá, Colombia
[d] Department of Bioengineering, University of Illinois at Chicago, IL 60612, USA
[e] Department of Anatomy and Cell Biology, University of Illinois at Chicago, IL 60612, USA
[f] Escuela Colombiana de Ingeniería Julio Garavito, Bogotá, Colombia

ARTICLE INFO

Article history:
Received 30 January 2012
Received in revised form
7 May 2012
Accepted 7 May 2012

Keywords:
Impact angle
Erosion-corrosion
Multilayer coating
Electrochemical tests
Surface analysis

ABSTRACT

The erosive-corrosive effect of aqueous NaCl slurries on metals and metals coated with a multilayer system was analyzed. The erosion-corrosion experiments were performed in a test machine in which the impingement velocity, impact angle, concentration of solids and pH of the solution were controlled. Polarization curves were simultaneously obtained to correlate the electrochemical effects to the erosive wear mechanisms. The slurry used consists of silica particles suspended in a mixture of acid solution and 3.5% NaCl, with a pH value of 5.6. Electrochemical results showed the best corrosion resistance for steel coated with CrN/AlN system deposited with 50 bilayer. Additionally, the surface analysis by SEM micrograph revealed formation of cracks in CrN/AlN multilayers coating and plastic deformation in both steel substrates (AISI D3 steel and 304 stainless steel), especially when the mean impact angle is a critical value of 90°. Measurements of critical and passive current densities showed that the behavior of coated materials differed depending on the substrate that is used. Nonetheless, in a general way, by increasing the impact angle and by changing its incidence from normal to grazing, it led to an improved resistance to erosion-corrosion processes.

1. Introduction

The mechanical, tribological and resistance to corrosion properties of materials, as well as the synergy between them, play a critical role in a myriad of scientific and industrial applications. Strikingly, corrosion–erosion processes are vastly investigated due to the devastating effects that are observed in materials such as metals, ceramics or polymers. In the case of metals, corrosion–erosion processes affect engineered structures such as pipes, diaphragms, offshore to energy conversion, food processing systems and many others for chemical, petrochemical and marine applications [1]. The AISI D3 steel with high carbon-high chromium steel was developed for applications requiring high resistance to wear and for improved resistance to heavy pressure rather than to sudden shock. Because of these qualities and its non-deforming properties, steel D3 is unsurpassed for die work on long production runs. It is primarily an oil-hardening steel, and it hardens to a great depth, but this steel does not have high corrosion resistance due to its low content of nickel, which is below the carbon content [2]. Additionally, there are a variety of chemical compositions for stainless steel, which yield desired particular qualities, For instance, the degree of medical implant, to facilitating manufacture of surgical instruments. On the other hands, among the different steels used in the medical industry, AISI 304 steel is commonly a choice. It may be subjected to a heat treatment to modify its physical properties; because of its low carbon content with respect to the alloy 302, it gives better corrosion resistance in welded structures [3]. Even in highly aggressive environments the AISI D3 steel and 304 stainless steel usually present electrochemical changes that affect their performance. When corrosion and erosion act together the degradation mechanisms are complex and generally the measured mass losses are higher than the sum of separated material losses due to both corrosion and erosion [1,4]. Impact velocity and impact angle have been recognized as two parameters that noticeably influence the wear rates and surface degradation in

* Corresponding author. Thin Films Group, Universidad del Valle, Colombia. Tel.: +57 2 339 46 10x42; fax: +57 2 339 46, +1 312 9960402.
** Corresponding author. Department of Bioengineering, University of Illinois at Chicago, IL 60612, USA.
E-mail addresses: jcaicedoangulo1@gmail.com, Jcesarca@calima.univalle.edu.co (J.C. Caicedo), caicedo.hugo@gmail.com (H.H. Caicedo).

0042-207X/$ – see front matter
doi:10.1016/j.vacuum.2012.05.007

tribosystems that suffer erosion and corrosion–erosion. Burstein and Sasaki [5] studied the effect of the impact angle on corrosion–erosion of AISI 304L stainless steel and found that the maximum values of both erosion and corrosion–erosion rates in chloride solution occurred at oblique angles between 40° and 50°, and that the synergism was positive in all conditions and greater for lower angles [5]. Other authors have also reported positive corrosion–erosion synergism in slurry wear tests of stainless steels [6–8]. Positive synergism arises from the notion that when the metal is submitted to hard particle impact, each erosive event causes rupture or removal of the protective oxide film from the surface, leaving the metallic substrate exposed to the solution. Moreover, in microstructures where hard and disperse second phases such as chromium carbides are present, uniform corrosion of metallic matrix can accelerate the hard particle release from the surface and increase the total mass loss. Usually, in the stainless steels case, the control of little changes in microstructure or in the environmental conditions is crucial, since the synergistic effects are sensitive to microscopic features such as second phase precipitates, grain boundaries and surface texture of the components [8–12]. On the other hand, development of hard corrosion resistant coatings has always been a limited solution to minimize the erosive and corrosive combined attack. In that sense, physical vapor deposition (PVD) technology has progressed in recent years resulting in multilayer coatings of various combinations of metals, their oxides and nitrides possessing high tribological properties and corrosion resistance [13,14], e.g. steel substrates coated with multilayer system have showed an increase of corrosive protection as function the bilayer period (Λ) CrN/AlN [9]. The last one system has shown good results related specifically to the improvement of mechanical properties and oxidation resistance as compared to the single layer CrN, AlN and CrAlN coatings [15,16]. The enhancement of these properties in the multilayer system is attributed to different mechanisms of layer formation with nanometric thickness such as the Hall–Petch effect, and the interface numbers that act as obstacles for the inward and outward diffusions of atomic species between layers in the case of oxidation resistance or dissipation of crack energy in the case of toughness [17,18].

S Yang et al. [19] has previously reported the erosion effect in hard materials such as multilayer hard coatings based on CrN, but incorporating other metals. They are exploited in coated machining and forming cutting tools of a wide range of materials used in various environments. Also, K. Sung Min et al. [20] reported that the superior thermal stability of multilayer coating such as CrSiN/AlN could be attributed to the formation of the dense and stable oxidation barrier consisted of the Al_2O_3, Cr_2O_3, and amorphous SiO_2 phases near the surface region, which retard the diffusion of oxygen, Cl and another corrosive elements into the coating. In this sense Y.P. Purandare et al. [13] reported a study that includes multilayers grown by PVD, the coatings improved wear, corrosion and corrosion-erosion resistance owing to their high hardness and use of noble metals in relation to coatings grown monolithically and uncoated steel. Moreover the CrN/AlN multilayer system presents the structural coherence which offers high mechanical, tribological and electrochemical performance in relation to other systems as a monolithic single layer or non coherent multilayers [21].

From our previous study was determined that the multilayer period (Λ) or bilayer number (n) is an important characteristic for enhancements of structural, mechanical and tribological properties [21], thus, the electrochemical improve also is observed with the changes of multilayer period or increasing or bilayer number [9]. So, take in account the results presented in the literature, it was found that in CrN/AlN multilayer growth with a total thickness of 3.0 μm the bilayer number (50) showed the best mechanical tribological and electrochemical properties in relation to CrN/AlN multilayer with other bilayer values due to the coherent multilayer structural period.

In this way the literature present few researches focused on studying the nitride corrosive-erosive, therefore, this effect on steel coated with TiN/AlTiN has been study and reported by W. Aperador et al. [10]. In those studies, they found that coated substrates showed a better erosion resistance for impact velocity lower than 12 m/s. After that, the coating was removed from the substrate surface by perforation and spalling [10,11]. Take in account the above the synergy of tribological (erosive wear) and electrochemical (corrosion) effect on steel uncoated and steel coated with CrN/AlN has not yet been thoroughly studied, due to this synergy problems is highly observed in devices steel with industrial application (e.g. pumps for water supply).

The aim of this work is to study the effect of impact angle on the corrosion–erosion resistance of commercial AISI D3 steel uncoated, AISI 304 stainless steel uncoated and AISI D3 steel coated with CrN/AlN multilayer system deposited with 50 bilayers (with 3 μm of thickness) under corrosive slurry containing chloride ions (Cl^-) and hard erosive particles. Additionally, this work compared the corrosion–erosion behavior presented by the AISI 304 stainless steel AISI D3 steel coated with CrN/AlN multilayer system and AISI D3 steel uncoated.

2. Experimental details

2.1. Materials

AISI D3 steels and austenitic AISI 304 stainless steel cylinders with 10 mm in diameter and 7 mm in height were used. The chemical compositions of the steels are in relation to typical industrial steel AISI D3 (12% Cr, 2.10% C, 0.30% Mn, 0.30% Si), AISI 304 (18.40% Cr, 0.08% C, 8.20% Ni, 0.90% Mn, 0.66% Si). The AISI D3 samples were austenized at 1250 C for 1 h, oil-quenched and tempered at 970 °C for another hour.

2.2. Multilayers coating deposition

CrN/AlN multilayers were deposited with 50 bilayer onto silicon (100) and AISI D3 steel substrates by using a multi-target r.f. magnetron sputtering system, with an r.f. source (13.56 MHz) for the applied bias voltage (−50 V) on the substrate, and metallic Cr and Al targets with 99.9% purity. A 350 W magnetron power was applied to the Cr target, while a power of 400 W was applied to the Al target. The deposition chamber was initially pumped down to less than 5×10^{-6} mbar, using a gas mixture of Ar (92%) + N_2 (8%). The substrate temperature was around 250 °C and a substrate to target distance of 7 cm was maintained for all coatings. For multilayer depositions, the aluminum and chromium targets were covered periodically with a steel shutter. Before the depositions, the targets and substrates were sputter-cleaned over 20 min; during the depositions, the pressure of the chamber was kept at 2×10^{-3} mbar. The thickness ratios of CrN/AlN multilayers system were obtained by means of a *Dektak* 3030 profilometer. The crystal structure of the coating was determined by using a *D8 Advance Bruker* X-ray diffractometer with Cu-Kα ($\lambda = 1.5405$ Å) radiation. The structural assembly of the multilayers was analyzed by scanning electron microscopy (SEM) (*Philips XL30FEG*) equipped with a light optical magnification range: 525–24.000X.

2.3. Surface properties tests

For the analysis of the erosive–corrosive effect a system built for the evaluation of chemical attack in metallic materials was used.