Chapter

Corrosion Resistance, Evaluation Methods, and Surface Treatments of Stainless Steels

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Abstract

Stainless steels are widely recognized and find applications in many engineering industries and companies due to their excellent properties including high resistance to corrosion as a result of their minimum 10.5% chromium content, exceptional strength and durability, temperature resistance, high recyclability, and easy formability. In the present book chapter, the basic concepts of stainless steel including its applications, classifications, and corrosion properties will first be discussed. Thereafter, their corrosion behaviour will then be explained. The various methods by which the corrosion resistance behaviour can be significantly improved including surface treatments such as coatings/electrodepositions, alloying, mechanical treatment, and others will be discussed in detail.

Keywords: stainless steels, surface treatment, corrosion, passivation, chromium content, electrodeposition

1. Introduction

Stainless steels (iron-based alloys) are widely recognized due to their high machinability, hardness, mechanical strength, good heat resistance and excellent corrosion resistance [1–3]. Compared to other steels, the superior corrosion resistance exhibited by many stainless steels can be attributed to the chromium content (about 10.5 wt.%) which initiated the formation of a stable layer of chromium oxide on the steel surface [2, 3] thereby preventing chemical reactions with the bulk material hence reducing corrosion attack to the minimum. Chromium is one of the major elements that play a vital role in the corrosion resistance of stainless steels. However, when exposed to water for a long period, their corrosion resistances reduce at elevated temperatures, hence the need to come up with more robust techniques for protecting the sample surface.

Even though they exhibit good corrosion resistance, efforts have continually been made to further improve the corrosion resistance behaviour of stainless steels. Heat treatment such as annealing due to the oxidation of steel surface [4–6], surface mechanical treatment [7–12], coatings/electrodepositions [13–16], alloying, machining/molding [17] and many more are presently in use to further improve the corrosion resistance behaviour of stainless steels. Other protection methods include epoxy coating, cathodic protection, and thicker concrete cover. For instance, surface modifications, as well as heat treatments of the modified sample surface by low temperature annealing, were used to enhance the corrosion resistance of 301, 17-4PH, 304 steels, 316, and mild steels [4–5, 9, 12]. To sum it up, stability, compaction, chemical composition, thickness, and many more are the main factors influencing the corrosion resistance of stainless steels [18–20].

In the present study, the general overview of stainless steels including their properties and application is presented. The corrosion resistance of stainless steel and evaluation methods are evaluated. The surface treatment methods aimed at enhancing the overall corrosion and mechanical properties are then presented.

2. Corrosion resistance of stainless steel and evaluation methods

Due to the nature and change in the environment, many metallic materials are expected to possess a good corrosion resistance against corrosion attacks over time. However, the corrosion resistance ability of materials differs from each other, and corrosion does set in when the corrosion-resistant limit of a material is exceeded [21–23]. Hence, the major reason why many material scientists and corrosion experts always pay much attention on how to continuously protect the material surface from degradation and corrosion via surface treatment method, coatings, and other related techniques. For clarity's sake, the corrosion behaviour can be studied when the material is exposed to an aggressive corrosive environment alone (polarization) [9, 16] or under the action of both tensile stress and corrosion reaction (stress corrosion cracking—SCC) [18].

The conventional polarization tests are normally carried out using an electrochemical workstation consisting of the traditional three-electrode system; (1) reference electrode (RE), whose material can be made of saturated calomel electrode (SCE) or silver/silver chloride (Ag/AgCl), (2) counter electrode (CE), which can be Platinum (Pt), graphite, gold or carbon rod, and (3) working electrode (the testing material).

Generally, the corrosion resistance of metallic materials can be evaluated through electrochemical tests which can be done in the following ways (**Figure 1(a–f)**); (1) open circuit potential (OCP) study, (2) potentiodynamic polarization study, (3) potentiostatic polarization study including the current-time transient (CTT) study and double-log plot, (4) electrochemical impedance spectroscopy (EIS) analysis including the Nyquist plot, Bode impedance, and phase angle plots, and (5) Mott-Schottky analysis which is normally carried out to determine the semiconducting characteristics of the passive film.

To a large extent, the OCP test determines the stability of samples in the electrolyte before performing polarization and EIS tests. Here, it is believed that the higher the corrosion potential, the more stable the sample, and probably the better the corrosion resistance [5, 11], i.e., the sample "A" in **Figure 1(a)** possessed higher corrosion potential and is therefore expected to be more stable than sample "B". The potentiodynamic polarization shows the corrosion behaviour in terms of corrosion current density (i_{corr}) and corrosion potential (E_{corr}) which can be determined from the corrosion graph using the Tafel extrapolation method. It is generally believed that the lower the i_{corr} and higher the E_{corr}, the more the formation of the passive film, hence the better the corrosion resistance [7–9].

In addition, the anodic polarization process can be categorized into four regions, as illustrated in **Figure 1(b)**; (1) activation zone, where the i_{corr} gradually increases with E_{corr}, (2) activation-passivation transition zone, where the i_{corr} decreases gradually and started forming passivation film, (3) passivation zone, which involves further decrease in i_{corr}, signifying the formation of more passivation film, and (4) transpassive zone, signifying the degradation of the passive film with

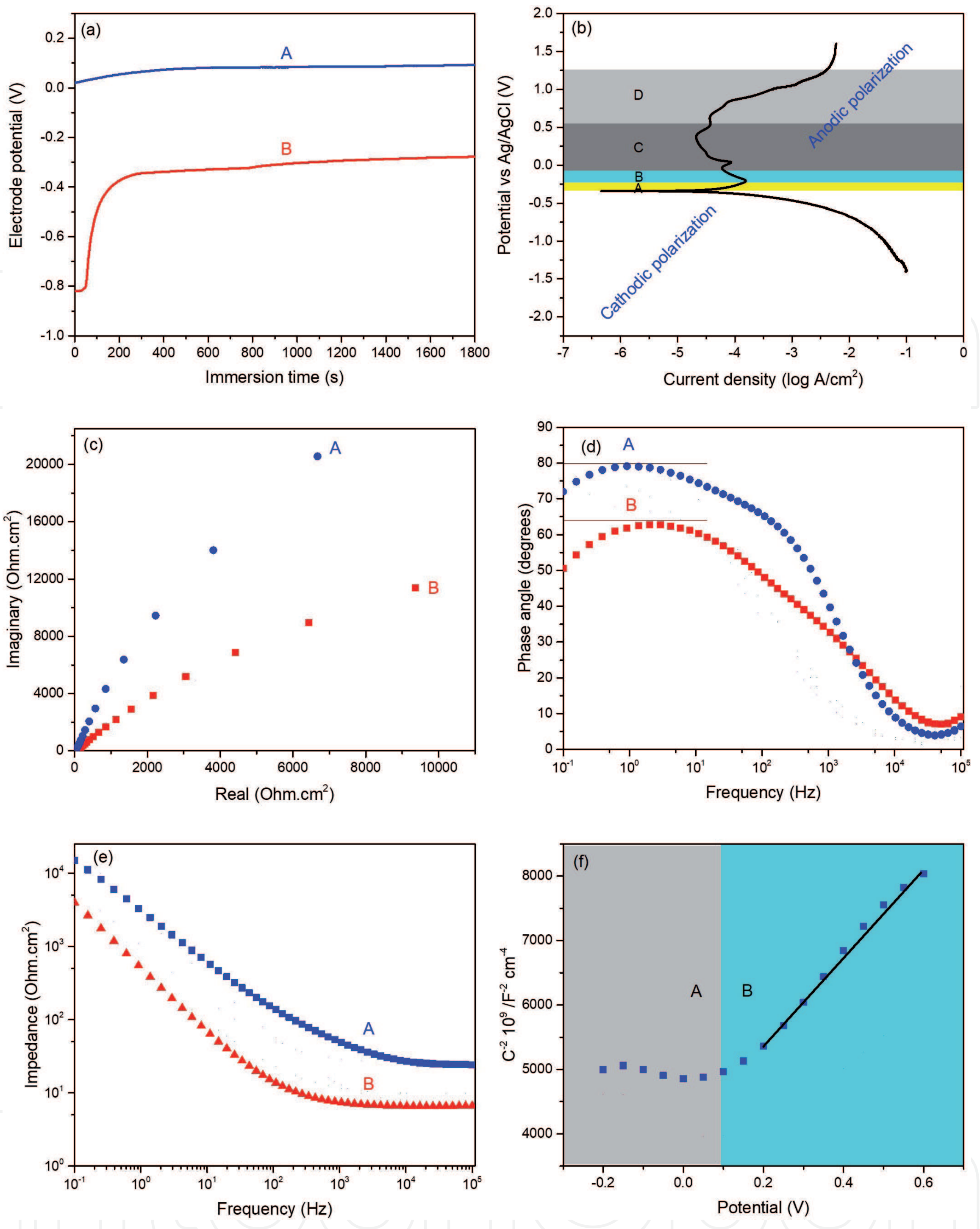

Figure 1.
Illustration of the corrosion properties of metallic materials; (a) open circuit potential (OCP), (b) potentiodynamic polarization, (c) Nyquist plot, (d) Bode phase angle plot, (e) Bode impedance plot, and (f) Mott-Schottky plot.

a rapid increase in i_{corr}. In EIS analysis, the samples with better charge-transfer resistance, higher impedance, and phase angle are believed to have a stabilized and more protecting passive film, hence possessing better corrosion resistance [10, 12]. For instance, sample "A" in **Figure 1(c–e)** is better than sample "B" in terms of corrosion resistance since it has a larger diameter of the semi-circle, higher phase angle, and impedance.

Corrosion fatigue is a common phenomenon that frequently occurs when materials are often exposed to simultaneous actions of corrosive environment and repeated stress, which leads to a markedly decrease in fatigue strength. In addition, unlike stress corrosion cracking which causes intergranular cracking and mostly occurs in harmful environments, corrosion fatigue which causes transgranular cracking, can occur at any time and cannot be avoided in some cases [4–5, 12].

Furthermore, Mott-Schottky analysis determines the electronic properties of the passive film by measuring the capacitance as a function of potential, which ultimately determines the semiconducting characteristics of the passive film. It is generally believed that a negative slope represents a p-type semiconductor while a positive slope signifies an n-type semiconductor. When a positive slope is obtained, it means there is no change in the semiconducting characteristics of the passive film, hence an enhancement in the stability of the passive film which can eventually increase the corrosion resistance. As illustrated in **Figure 1(f)**, the section denoted by "A" represents the flat band potential zone while the portion denoted by "B" represents the n-type semiconductivity zone.

3. Surface treatments: enhancing the overall corrosion and mechanical properties

The overall corrosion and mechanical properties of stainless steels can be enhanced by subjecting them to different types of surface treatments including anodization, electrodeposition, dip-coating, micro-arc oxidation (MAO), and surface mechanical treatments. Anodization is a surface modification technique involving the passage of constant current and voltage through the cathode and anode resulting in the deposition of the natural oxide layers on the material surface [24] with an improved thickness and properties thereby turning the metal surface into an excellent finish which is anodic oxide in nature, corrosion-resistant, durable, and wear/abrasion-resistant.

As a form of surface treatments (anticorrosion processing methods), electrodeposition is a conventional phenomenon, and the combination of reduction and oxidation reactions whereby dissolved metals and alloys cations are cathodically reduced by the passage of electric current in electrolytes leading to the formation of a thin layer coating on electrodes [25]. By this, thin layers of functional materials including alloys and metals can be electrolytically deposited on the surface of Mg alloys (acting as the cathode in the electrolytic cell) to improve the corrosion properties and the overall mechanical behaviour.

The dip-coating process can be highlighted in five ways depending on the immersion time and speed as well as the withdrawal speed, (a) dipping the substrate into the desired solution, (b) removal of the dipped substrate from the solution, (c) deposition of the film on the substrate after removal, (d) removal of excess liquid from the material surface, and (e) dispersal of the solvent from the liquid film. Meanwhile, micro-arc oxidation is the electrochemical oxidation process through which hard, dense, and protective ceramic oxide coatings are formed on metal surfaces for corrosion protection under the influence of various processing conditions and parameters [26–28].

4. Conclusion

Despite their good corrosion resistance, stainless steels still experience failure, especially when exposed to an aggressive environment for a prolonged period of time. This can be corrected by adopting the right surface treatment methods including alloying, heat treatment, coating/electrodeposition, and surface mechanical treatment. The corrosion resistance of stainless steels often depends on the stability, compaction, chemical composition, thickness of the passive film generated on the material surface.

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References

[1] Dias D, Nakamatsu S, Rovere CAD, Otubo J, Mariano NA. Characterization and corrosion resistance behavior of shape memory stainless steel developed by alternate routes. Metals. 2020;**10**:13

[2] Nishimura T. Crevice corrosion resistance and structure of passive film on Fe–Mn–Si–Cr–Ni steel. ISIJ International. 2016;**56**:654-660

[3] Rovere CAD, Alano JH, Silva R, Nascente PAP, Otubo J, Kuri SE. Influence of alloying elements on the corrosion properties of shape memory stainless steels. Materials Chemistry and Physics. 2012;**133**:668-673

[4] Olugbade TO, Lu J. Characterization of the corrosion of nanostructured 17-4 PH stainless steel by surface mechanical attrition treatment (SMAT). Analytical Letters. 2019;**52**:2454-2471

[5] Olugbade T, Liu C, Lu J. Enhanced passivation layer by Cr diffusion of 301 stainless steel facilitated by SMAT. Advanced Engineering Materials. 2019;**21**:1900125

[6] Abioye TE, Omotehinse IS, Oladele IO, Olugbade TO, Ogedengbe TI. Effects of post-weld heat treatments on the microstructure, mechanical and corrosion properties of gas metal arc welded 304 stainless steel. World Journal of Engineering. 2020;**17**:87-96

[7] Olugbade T, Lu J. Effects of materials modification on the mechanical and corrosion properties of AISI 316 stainless steel. In: Twelfth International Conference on Fatigue Damage of Structural Materials. Hyannis, USA: Cape Cod; 2018

[8] Olugbade T, Lu J. Improving the passivity and corrosion behaviour of mechanically surface-treated 301 stainless steel. International Conference on Nanostructured Materials (NANO 2020), Australia. 2020;**117**

[9] Olugbade TO. Electrochemical characterization of the corrosion of mild steel in saline following mechanical deformation. Analytical Letters. 2021;**54**:1055-1067

[10] Olugbade TO, Lu J. Literature review on the mechanical properties of materials after surface mechanical attrition treatment (SMAT). NanoMaterials Science. 2020;**2**:3-31

[11] Olugbade T. Datasets on the corrosion behaviour of nanostructured AISI 316 stainless steel treated by SMAT. Data-in-brief. 2019;**25**:104033

[12] Olugbade TO, Lu J. Enhanced corrosion properties of nanostructured 316 stainless steel in 0.6 M NaCl solution. Journal of Bio- and Tribo-Corrosion. 2019;**5**:38

[13] Dang C, Yao Y, Olugbade TO, Li J, Wang L. Effect of multi-interfacial structure on fracture resistance of composite TiSiN/Ag/TiSiN multilayer coating. Thin Solid Films. 2018;**653**: 107-112

[14] Abioye TE, Olugbade TO, Ogedengbe TI. Welding of dissimilar metals using gas metal arc and laser welding techniques: A review. Journal of Emerging Trends in Engineering and Applied Sciences. 2017;**8**:225-228

[15] Dang C, Olugbade TO, Fan S, Zhang H, Gao LL, Li J, et al. Direct quantification of mechanical responses of TiSiN/Ag multilayer coatings through uniaxial compression of micropillars. Vacuum. 2018;**156**:310-316

[16] Olugbade TO, Abioye TE, Farayibi PK, Olaiya NG, Omiyale BO, Ogedengbe TI. Electrochemical properties of MgZnCa-based thin film metallic glasses fabricated via magnetron sputtering deposition coated on a stainless steel substrate. Analytical Letters. 2021;**54**:1588-1602

[17] Zu H, Chau K, Olugbade TO, Pan L, Chow DH, Huang L, et al. Comparison of modified injection molding and conventional machining in biodegradable behavior of perforated cannulated magnesium hip stents. Journal of Materials Science and Technology. 2021;**63**:145-160

[18] Olugbade TO. Stress corrosion cracking and precipitation strengthening mechanism in TWIP steels: Progress and prospects. Corrosion Reviews. 2020;**38**:473-488

[19] Mohammed T, Olugbade TO, Nwankwo I. Determination of the effect of oil exploration on galvanized steel in Niger Delta, Nigeria. Journal of Scientific Research and Reports. 2016;**10**:1-9

[20] Olugbade TO, Ojo OT, Omiyale BO, Olutomilola EO, Olorunfemi BJ. A review on the corrosion fatigue strength of surface-modified stainless steels. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2021;**43**:421

[21] Olugbade TO, Olutomilola EO, Olorunfemi BJ. Review of passivity and electrochemical properties of nanostructured stainless steels obtained by SMAT: trend and progress. Corrosion Reviews. 2021

[22] Olugbade TO, Omiyale BO, Ojo OT. Corrosion, corrosion fatigue and protection of magnesium alloys: mechanisms, measurements, and mitigation. Journal of Materials Engineering and Performance. 2021. DOI: 10.1007/s11665-021-06355-2

[23] Olugbade TO, Omoniyi OO, Omiyale BO. Electrochemical Properties of Heat-Treated Al Alloy A6061-T6 in 0.5 M H_2SO_4 Solution. Journal of The Institution of Engineers (India): Series D. 2022. DOI: 10.1007/s40033-021-00313-x

[24] Kuromoto N, Simao R, Soares G. Titanium oxide films produced on commercially pure titanium by anodic oxidation with different voltages. Materials Characterization. 2007;**58**:114-121

[25] Zhang Y, Lin T. Influence of duty cycle on properties of the superhydrophobic coating on an anodized magnesium alloy fabricated by pulse electrodeposition. Colloids and Surfaces, A: Physicochemical and Engineering Aspects. 2019;**568**:43-50

[26] Zhang L, Zhang J, Chen C, Gu Y. Advances in microarc oxidation coated AZ31 Mg alloys for biomedical applications. Corrosion Science. 2015;**91**:7-28

[27] Dziaduszewska M, Shimabukuro M, Seramak T, Zielinski A, Hanawa T. Effects of micro-arc oxidation process parameters on characteristics of calcium-phosphate containing oxide layers on the selective laser melted Ti13Zr13Nb alloy. Coatings. 2020;**10**:745

[28] Mu W, Han Y. Characterization and properties of the MgF_2/ZrO_2 composite coatings on magnesium prepared by micro-arc oxidation. Surface and Coating Technology. 2008;**202**:4278-4284