# Experimental Study On Corrosion Behavior Of Different Ceramic Plasma Coatings In Sulfuric Acidic Solution

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**Abstract** — Ceramic coatings materials are considered to be optimal in their applications as compared with metallic or organic coating materials, which are used under different environmental conditions. In this study, the corrosion behavior of austenitic steel substrates with different types of ceramic coating materials was investigated. The corrosion tests was carried out using Gamry PCI300/4 analyzer in a 0.5M $H_2SO_4$ solution as a corrosive environment. The corrosion behavior of ceramics coatings using plasma spray process was employed on a substrate with multilayers deposition of $Al_2O_3$, WC–12% Co and WC-12% Co/$Al_2O_3$ using atmospheric plasma spray (APS) equipment by using different parameters and deposition techniques. The microstructure of the coatings and corroded coatings were characterized by SEM. It was concluded that the corrosion resistance depends strongly on the type of coating material. Specimen which was coated by WC-12% Co/$Al_2O_3$ exhibited lower corrosion rate (8.8 mm/year) as compared with other types of coating materials. The corrosion potential of coated specimen was shifted toward the noble direction compared to uncoated specimen.

**KEYWORDS:** Ceramic coatings; $Al_2O_3$; WC-12% Co; Coatings; Plasma spray; Corrosion protection.

## 1. INTRODUCTION

Coating is the most commonly used process for, reducing, preventing or controlling corrosion due to an available and possible variation of coating materials and coating processes for different conditions and applications [1]. Plasma spraying is an operational surface engineering technology that has been commonly useful in various industrial fields [2-4]. Plasma spray coating is selected because of low cost, easiness and high deposition rate. However, coating of ceramic using plasma spray technique leads to higher inherent porosity which helps the electrolyte to attack on substrate which in turn leads to corrosion. Different ceramics coating materials help in avoiding the corrosion, as $Al_2O_3$, $ZrO_2$, WC-12% Co and $TiO_2$ [5]. Alumina offers electric insulation and low thermal conductivity; low friction coefficient and good corrosion resistance in both saline and acid environment. Alumina coating is generally useful in these applications involving sliding wear together with exposure to corrosive environment. WC-Co coatings are composed of WC particles disseminated in a metallic Co matrix [8]. This type of coating reveals the high temperature and abrasion resistance of ceramics and the ductility of metallic materials. Owing to these properties, WC-Co coatings are extensively used for applications where high mechanical performance and corrosion resistance are required, such as for airplane landing gear, and rollers in paper industries [9]. Many factors influence the corrosion characteristics of coatings, including their quality and structure. The porosity is usually used as a parameter of the structure of plasma sprayed coating [10]. Therefore, reduction of porosity of the sprayed coatings plays a key role in improving the corrosion resistance of the coatings. To overcome these issue bilayered coatings of $Al_2O_3$ and WC-12%Co has been used in present paper. The aim of this study is to evaluate the corrosion resistance of austenitic stainless steel, coated with $Al_2O_3$, WC-12%Co and WC-12% Co/$Al_2O_3$.



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## 2. EXPERIMENTAL PROCEDURE

The substrates used in this study were austenitic steel with the dimensions 25x20x2 mm. The specimens was coated with $Al_2O_3$, WC-12%Co and WC-12% Co/$Al_2O_3$. The characterizations of different coating materials are given in

Table 1. Coating materials characterizations.

| Coating materials | Density (g/cm³) | Melting Temperature ºC | Grain Size (μm) | Coating Hardness HV0.1 |
|---|---|---|---|---|
| Aluminum oxide Powder | 4.05 | 1788-2000 ºC | 15-40 | HV 1000 |
| Tungsten Carbide (WC) - Cobalt (Co) (WC-12%Co) | 13.75 | 1459 $^oC$ for Co<br>2777 $^oC$ for WC | 25-45 | HV 2000 |

Table (1). The ceramic coatings were carried out via atmospheric plasma spray (APS) equipment with a F4-MB torch. Surface coatings were produced using a plasma spray parameters as presented in Table (2). Electrochemical tests were conducted in 0.5 M $H_2SO_4$ solution prepared prior to each test using distilled water. All electrochemical experiments were conducted with a Gamry PCI300/4 Potentiostat/Galvanostat/Zra analyzer, connected to a PC. The Echem Analyst Software (version 5.21) was used for all electrochemical data analysis. A three electrode cell was used in these experiments. Tafel polarization tests were carried out using a scan rate of 0.5 mV/min at 25 °C. Specimens with exposed surface area of 1.5 $cm^2$, were used as a working electrode. Prior to electrochemical tests, the specimens were cathodically cleaned for 15 min at -1500 mV (SCE) to remove the air-formed oxide film. The applied routine automatically selects the data that lies within the Tafel region (±250 mV with respect to the corrosion potential). The microstructure of tested specimen after corrosion was examined using scan electron microscope.

Table 2. Spray parameters for plasma burner PT F4-HB/ F4-MB.

| Spray parameters | Unit | Aluminum Oxide Powder ($Al_2O_3$) | Tungsten Carbide-Cobalt (WC-12%Co ) |
|---|---|---|---|
| Plasma gases | - | Ar/ $H_2$ | Ar/ He |
| Amperage | A | 500 | 820 |
| Voltage | V | 70- 72 | 57-60 |
| Plasma gas flow | SLPM | 47/ Ar and 12/ $H_2$ | 74/Ar and 122/ He |
| Powder flow | g/min | 30 | 30 |
| Carrier gas flow | SLPM | 2.5 | 2.6 |
| Anode diameter | mm | normal | 6 ( inside ) |
| Spray distance | mm | 100 | 125 - 130 |
| Powder injector | mm | 1.8 | 2 |
| Cooling | | air | Air or $CO_2$ |

## 3. RESULTS AND DISCUSSION

### 3.1. Corrosion behavior

Fig. 1 displays polarization curves of coating specimens and uncoated specimen in 0.5 M $H_2SO_4$ solution. In this figure, it is obvious that the best corrosion protection was found for specimen coated by WC-12% Co/$Al_2O_3$. Moreover, a significant shift of the anodic curves towards higher current values was observed for polarization curves of uncoated specimen. The results illustrated in Fig.2 and Fig.3 show that the ceramic coating type greatly influenced the coating performance. As shown in Fig.2, uncoated specimen had the highest corrosion rate (75.6 mm/year).

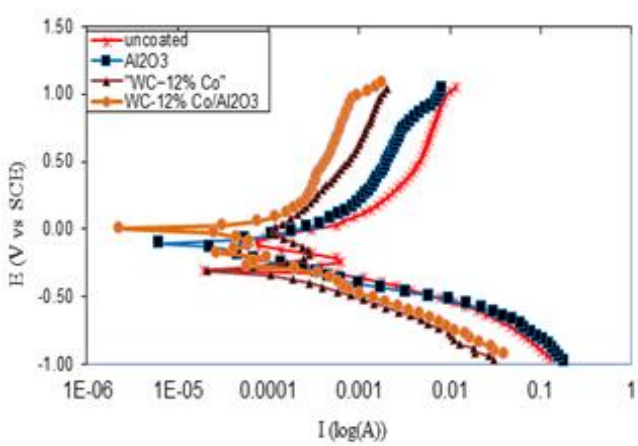


Fig. 1: Polarization curves of coating specimens and uncoated specimen in 0.5 M $H_2SO_4$ solution.

Specimen which was coated by WC-12% Co/$Al_2O_3$ has a lower corrosion rate (8.8 mm/year) as compared with other type of coating. According to Fig.3 the corrosion potential of coated specimen was shifted toward the noble direction compared with uncoated specimen. The corrosion potential

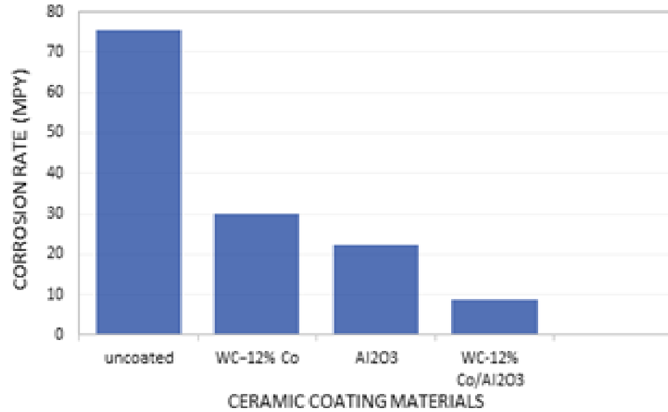


Fig.2: Corrosion rates of coated samples with different ceramic coatings.

of uncoated specimen recorded -299 mV. While the corrosion potential of coated specimen with Al2O3 was -113 mV. The results confirm that WC-12% Co/Al2O3 coating exhibited a significantly better corrosion-resistance than the other coatings by virtue of more noble corrosion potential.

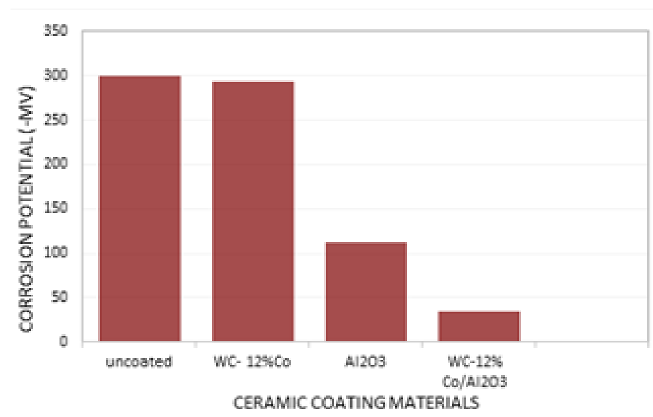


Fig.3: Corrosion potential of coated sample with different ceramic

As shown in Fig.4, the Nyquist plots for uncoated and coated specimens also supports the findings in Fig.2. The plasma coated sample exhibits higher corrosion resistance in tested solution H2SO4, while uncoated specimen suffered from severe corrosion. Ceramic coating of WC-12% Co/Al2O3 appears to afford significantly higher protection compared with the other coating specimens. Dosta et.al. [8] concluded that the WC-12Co coating was effective in corrosion resistance for the duration of 400 h of immersion in 3.5% NaCl solution. At extensive immersion times, dissolution of the Co phase and the loss of WC particles led to the creation of interconnected porosity, letting access of the solution and corrosion of the substrate. The low thickness, higher porosity, and possibly a larger quantity of defects were accountable for frailer performance of this coating. Celik et al. [11] studied the effect of grit blasting of substrate on the corrosion behavior of plasma sprayed Al2O3 coatings and they

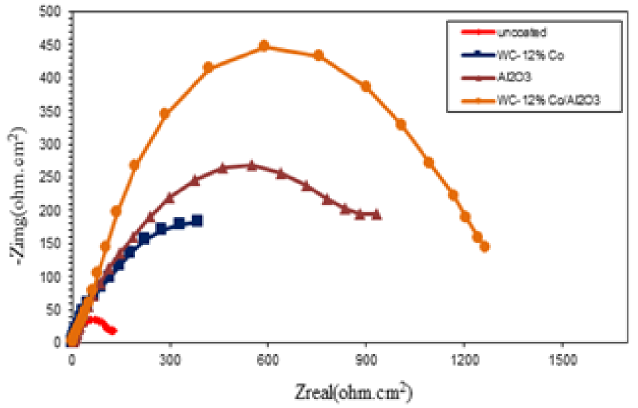


Fig.4: Nyquist plots of samples with different coatings in 0.5M H2SO4

identified that the corrosion resistance of the alumina coatings increased with decreasing porosity and coating thickness. Dianran et al. [12] investigated the corrosion behavior of $Al_2O_3$ based ceramic composite coatings in dilute HCl solution and they reported that the connected porosity in the $Al_2O_3$ based ceramic composite coatings rises with the open porosity and is independent of the density of the coating. The as-sprayed alumina coatings ($Al_2O_3$-APS) revealed a poor corrosion performance in the test solution due to their high degree of interconnected pores simplifying the penetration of aggressive species towards the bulk material [13]. Indermeet et.al. [5] noticed that in $Al_2O_3$ surface coating, $Al_2O_3$ was seen as major phase while $Fe_2O_3$ was noticed as minor phase by XRD, SEM/EDS analysis. The formation of $Fe_2O_3$ might be due to diffusion of Fe from the base alloy through the porosities in the alumina coating. However, they were noticed that the $ZrO_2$ and $Al_2O_3$ ceramic coating supported to improve corrosion resistance of these coatings. Carbajal et.al. [14] reported that the surface coating of stainless steel by $SiO_2$-$Al_2O_3$ ceramic coating exhibited good indication of corrosion resistance in 1 M HCl solution and in1 M $H_2SO_4$ solution. In addition, the more positive $E_{corr}$ was obtained by coated specimens. Furthermore, the resulted corrosion rate values were smaller than the resulted corrosion rate from uncoated material.
It is clear from previous studies that the source of the deterioration of the coatings was clearly revealed by the presence of porosities and microcracks that acts as connecting pathways for the corrosive environments. In addition, the use of one type of coating material as $Al_2O_3$ or WC+ 12%Co alone may be contained more porosity than the use of two types of ceramic materials as WC-12% Co/$Al_2O_3$ as a surface coating material.

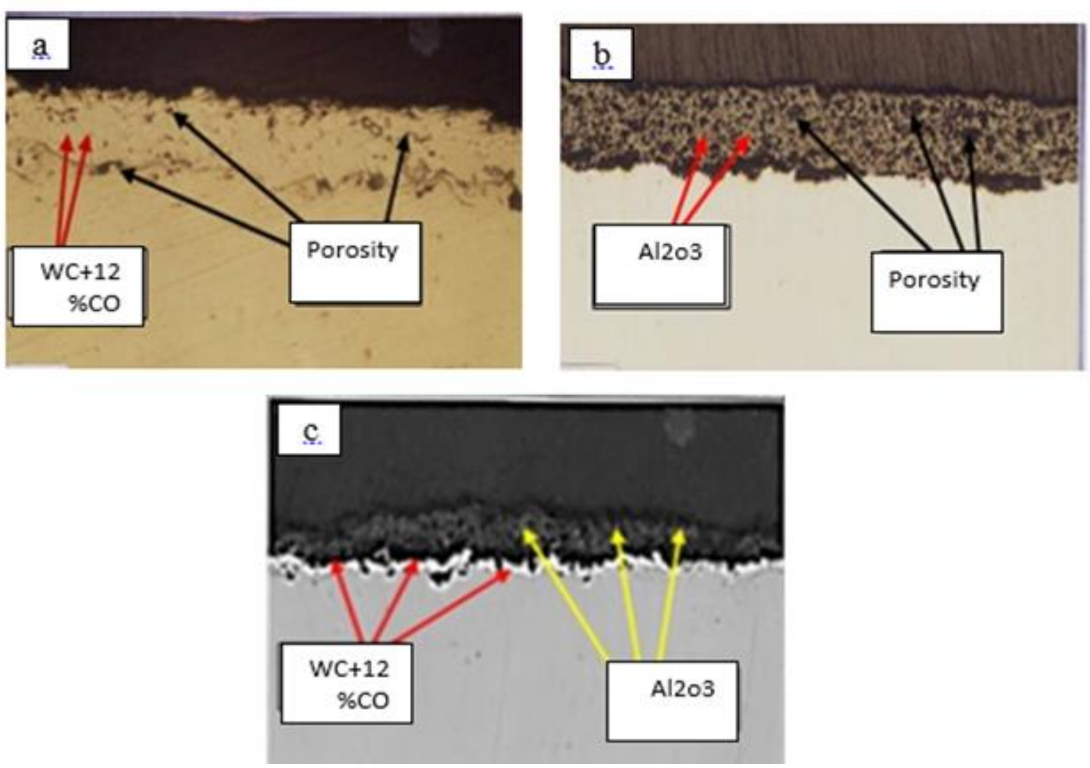


Fig.5: The micrographs of substrates with; (a) WC–12%Co coating, (b) $Al_2O_3$ coating, and (c) WC-12% Co/$Al_2O_3$.

**3.2. Microstructure**

The micrographs of the surface morphology of coated specimens with different types of coating materials is given in Fig.5. The plasma spray coating usually exhibit porosity, oxides, un-melted particles and inclusions. From Fig.5, it is clear that WC–12% Co coating exhibits higher porosity with large pore sizes and relatively wide distribution than $Al_2O_3$ coating. The presence of pores could degrade corrosion resistance [15]. Fig. 6 shows the SEM microstructure of the corroded surfaces with different coating materials. Apparently, the uncoated specimen suffered severe corrosion as shown in Fig.6a. On the other hand, Fig.6 (b-d) shows that the coating of the specimens with different ceramic coatings improves corrosion resistant of the substrates. In addition, the specimen coated with WC-12% Co/$Al_2O_3$ ceramic coating exhibited a very good corrosion resistant, which is attributed to the high dense coating surface with a minimum number of pores as indicated in Fig.5-c and Fig. 6-d.

## 4. CONCLUSIONS

The experimental results in this present research indicated that the corrosion behavior is affected by the types of surface coating materials. Uncoated specimen revealed the highest corrosion rate (75.6 mm/year). The surface coating process improved the corrosion resistance of the base metal. The defects in $Al_2O_3$ coating layer were relatively few compared to WC−12%Co coating, and hence, the corrosion resistance of the substrates with $Al_2O_3$ coating was higher than that of the substrates with WC−12%Co coating. The best corrosion resistance was achieved in case of using WC−12%Co /$Al_2O_3$ coating. In addition, the corrosion potential of coated specimen was shifted toward the noble direction as compared with uncoated specimen.

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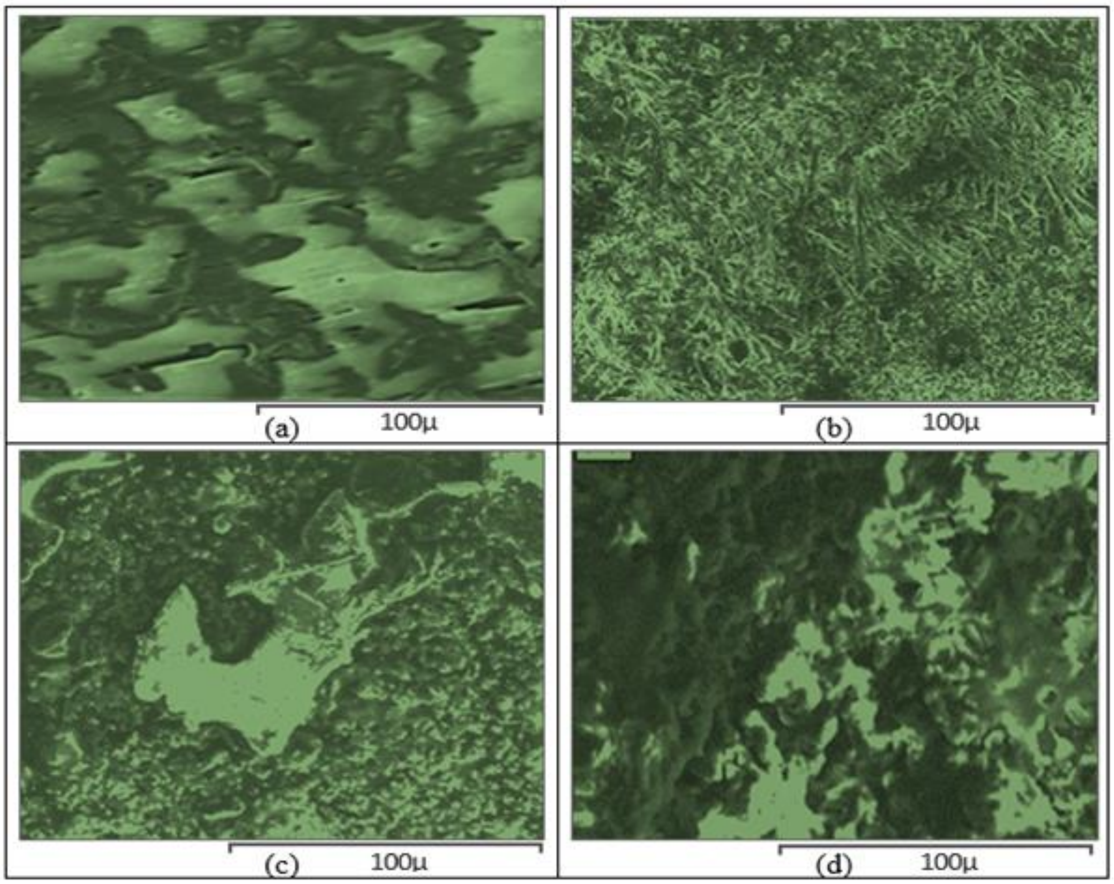


Fig.6: SEM micrographs of corroded surface; (a) without coating, (b) with $Al_2O_3$ coating, (c) with WC+12%Co coating, and (d) with WC+12%Co/$Al_2O_3$ coating.

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