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Application of Thermal Spray Coatings for Corrosion Control in Oil and Gas Refineries

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Abstract

In today's context, Thermal Spray Coating (TSC) has emerged as a highly durable and reliable alternative to traditional Hot-Dip Galvanizing (HDG). It is increasingly being adopted for both new and existing industrial structures due to its long-lasting protection—often exceeding 25 years—while requiring little to no maintenance. Unlike HDG, which cannot be welded on-site and often poses challenges with repair methods such as liquid coating or cold spray, TSC offers greater flexibility. It can be safely applied, repaired, and maintained directly at the site, making it a more practical solution. Many industry standards and customer specifications now recognize TSC as a viable replacement for HDG. TSC provides robust anti-corrosion protection for onshore and offshore structures, pipelines, and equipment. It is the only coating system endorsed by international codes and standards to deliver a service life of more than 25 years before its first maintenance cycle, even in harsh environments such as offshore platforms where corrosion risk is extremely high. This paper compares Thermal Spray Metallic Coating with conventional HDG and highlights its superior benefits. TSC can be applied using multiple processes, including Arc Spray, Flame Spray, High Velocity Oxygen Fuel (HVOF), High Velocity Air Fuel (HVAF), Atmospheric Plasma Spray, Vacuum Plasma Spray, and Cold Spray, among others. These methods allow cost optimization across diverse industries such as oil and gas, petrochemicals, marine, shipping, and power generation—including nuclear facilities. The coating can be formulated with different filler materials—ranging from pure metals and alloys to ceramics and composites—in wire or powder form. Furthermore, TSC can be applied to both metallic and non-metallic substrates, with minimal surface preparation depending on the required coating thickness.

Keywords: TSA, Arc spray, flame spray, corrosion, electrochemical, adhesion, SEM, XRD, coating thickness.

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INTRODUCTION

Based on recent trends in oil and gas refineries for enhancing life of coating thermal spray coating is the most prestigious alternative metallizing coating in present scenario. Thermal Spray Coating is a recognized and reliable alternative to traditional Hot Dipped Galvanizing for both new and existing industrial structures. Depending on coating thickness, it provides long-lasting, maintenance-free protection in highly corrosive environments. Unlike Hot Dip Galvanizing, Thermal Spray Coating can be safely applied on-site, is easier to apply, and is widely accepted in customer specifications as a qualified substitute. Research shows its durability matches that of hot-dip coatings in most corrosive conditions. Offering robust anti-corrosion protection, it ensures extended service life for onshore and offshore structures, equipment, and piping. Periodic coating health assessment is desirable as per asset management philosophy for long durability of coating as recommended by international standards. Thermal Spray Coating acts as a sacrificial coating and protects the structures. This coating has excellent corrosion resistance as well as thermal resistance and is most popular in Oil and Gas Industries as Corrosion Under Insulation (CUI) Coating which gives more than 25 years costing design life. This study investigates the performance of thermal spray metallic coatings through laboratory testing, including electrochemical corrosion analysis, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS), to assess their effectiveness as an alternative to hot-dip galvanizing. The research specifically examines the corrosion behavior of thermal spray aluminum (TSA) applied to steel in a 3.5 wt.% NaCl solution using open circuit potential (OCP), electrochemical impedance spectroscopy (EIS), polarization resistance (Rp), and potentiodynamic polarization (PDP). Furthermore, SEM was employed to observe microstructural and morphological changes. The goal of this work is to contribute to a deeper understanding of the corrosion characteristics of TSA-coated steel.

REVIEW OF PREVIOUS RESEARCH

In the present world scenario for all industrial sectors today, the catch phrase “faster, cheaper, better, ease of application” is very common and valid demand considering ever-increasing demands for corrosion protection. Highly aggressive services often lead to the premature failure of coating. To overcome this Thermal Spray coating application was introduced since early 1900 as coating to prevent corrosion and can be applied on-site very easily to overcome the coating failure or disbandment issues to resolved to the certain extent [1]. In the year 1984, Conoco Hutton TLP apply thermal spray aluminum at 200 microns coating thickness with sealer coating on the risers for offshore platform at North SeaWhen inspected after eighty years of application, the coating was found to be in good condition. This is the beginning of a thermal spray coating application in the world at large scale as one of the accepted coating processes to prevent corrosion for marine offshore platforms. Steel is widely used in manufacturing onshore and offshore engineering structures with various preventive and protective measures to enhance service life of structures in most corrosive environments [2]. Thermal spray coating is more popular due to its ability to withstand corrosion, high process temperature, erosion and competitive cost solution to the industries for high durability. Various industries like transport, chemical, petrochemical, marine undergo severe corrosion if not protected by means of coating [3], [4]. At the same time steel is very much prone to environmental damage due to corrosion, specifically in offshore humid chloride locations having variation in temperature and exposure of structures due to high and low tide scenario in sea environment [5]. The corrosion of these structures leads to environmental and economic losses but may involve loss of life due to catastrophic failures. Any such incident may lead to disturbing the sea creatures. The corrosion can be mitigated with proper material selection, coating or cathodic protection [6]. The coating for corrosion protection is evaluated by applying various methods like hot dipping [7], thermal spraying [2], [8], [9], [10], physical vapor deposition, chemical vapor deposition [11], chemical conversion coating [3], electroplating [4], pack cementation [12], laser cladding [13], sol-gel [14], etc. Thermal Spray coating is comparatively economical and can be applied onsite with water getting to create proper surface profile for coating adhesion [6]. Thermal Spray Coating is the only coating system acknowledged by international codes and standards that can provide a service life of nearly 20 years before its first maintenance, even in highly corrosive environments such as marine offshore structures, industrial equipment, and rural infrastructure.

Based on studies, corrosion can occur due to formation of anode, cathode, electrolyte, metallic pathway to complete the circuit between anode and cathode to form an electro chemical cell. Corrosion is a prestigious issue as well as safety risk and needs immediate replacement of corroded structure or component to meet the industry’s demand. Thermal spray process can act as coating and serve cathodic protection requirements with aluminum as coating material in the most corrosive environment. Nowadays thermal coating is a cost competitive solution in production and maintenance activities as one of the acceptable coating technologies with the help of metal wire and powder use based on corrosive services categories.

Based on a recent study thermal spray coating is having highest design life as compared to other liquid coatings for insulation application. Corrosion Under Insulation (CUI) resistance for Thermal Spray coating is more than 25 years. Therma coating has dual properties as it acts as thermal and corrosion resistance barrier between structure and environment. In general, thermal costing is used for hot and cold thermal insulation for heat conservation or heat gain purpose based on process requirements. CUI is the issue, and many articles and papers have been published since 1983. In research there are many ways and means to protect the equipment and piping by use of metallizing where Al and Zn play a vital role considering thermal and corrosion resistance due to sacrificial action considering galvanic potential being more active as compared to structure to be protected under insulation. The study of thermal degradation properties is essential for high-temperature application of coating commonly used for CUI, especially in view of their possible use as reinforcement for protective atmospheric coating[15]. The inclusion of aluminum as mesh reinforcement significantly enhances adhesion, cohesion, structural integrity, and resistance to environmental degradation, emphasizing the importance of engineered barrier layers for extending service life in harsh operating conditions[16]. Surface engineering approaches to combine strong interfacial bonding with barrier protection are essential to extend component durability under aggressive mechanical and chemical environments can cause the corrosion and degradation of structure items[17]. The thermal degradation behavior, crystallinity, and surface morphology of coating materials critically determine the durability under aggressive environments, highlighting the need for engineered protective layers in demanding industrial applications towards corrosion protection[18]. The application of hybrid composites proved suitable for wear and corrosion protection applications in real conditions, including the possibility of water absorption, which does not lead to a substantial decrease in mechanical strength due to coating[19].

The corrosion protective coatings are evaluated with laboratory test using 3.5 wt% NaCl solution [20]. Wang et al evaluated corrosion behavior of low carbon steel in 3.5% NaCl environment. [21] The study reported formation of loose and porous corrosion product layer of γ-iron hydroxide on short exposure while with increased exposure corrosion product was dense lump and block-like made of β- and α- iron hydroxide. It was claimed that γ-iron hydroxide promotes while β- and α- iron hydroxide inhibit corrosion. Paul studied corrosion of damaged coating of thermal sprayed aluminum (TSA) in prepared sea water. [2] It was reported that damaged TSA coating polarized steel to a large extent. Though the damage initially affected corrosion rate but could not affect the corrosion performance. Grinon-Echaniz et al evaluated corrosion behavior of Al and Zn thermal spray coating on steel substrate in laboratory and real sea environment. [8] The study reported good correlation of collected electrochemical data with change of environment. While aluminum coating showed better corrosion protection in full immersion conditions, the zinc coating demonstrated better corrosion behavior in atmospheric and splashing conditions. Ge et al compared corrosion behavior of convectional and super hydrophobic aluminum coating on steel. [5] The study reported poor wettability, lower corrosion current density and better charge transfer resistance for super hydrophobic coating. Chen et al studied corrosion behavior of single and double layer metallic aluminum coating prepared with sol gel on steel substrate in 3.5 wt% NaCl environment. [14] The result obtained demonstrated better corrosion resistance for double layer coating because of the shielding effect. Luo et al studied the effect of Cr addition to laser coated Fe-Al coating on steel substrate on corrosion. The best results were reported with 5% Cr addition while increased Cr formed Al_8Cr_5 in grain boundaries and decreased corrosion resistance. [13]

AIMS OF CURRENT PROJECT

This paper investigates the corrosion behavior of Thermal Spray Aluminum (TSA) coatings on steel in a 3.5 wt% NaCl solution, employing open circuit potential (OCP), electrochemical impedance spectroscopy (EIS), polarization resistance (Rp), and potentiodynamic polarization (PDP) techniques. Additionally, to evaluate morphological changes in coating characterization was evaluated with respect to the microstructure examination with the help of SEM. The paper aims to improve the existing knowledge pool of thermal spray coating corrosion characterization of carbon steel in chloride environment considering sea water offshore platform application.

PREPARATION OF TEST SPECIMENS

As the received plate was 10 cm, long and to perform any characterization, this size was not ideal. So Coating plate was cut into the desired sample size with the help of an Abrasive Cutting machine, for microstructural analysis, and or characterization. Cutting operation was obtained by using an abrasive cutting machine The long pieces of the sample were mounted on the vice attachment on the ACO-50 Banbros Abrasive Cut-off Machine. The abrasive cutter uses a 2HP motor with a cutting wheel speed of 2800 RPM and vice movement of 100 mm and 120 mm in the X and Y-axis respectively. A lever arm was provided on the side of the machine, the downward movement of which helps in cutting off the workpiece. The tool uses an emulsion mixture of water and oil as a coolant to avoid heating the workpiece. The material was sectioned along the longitudinal direction, and samples measuring approximately 20 mm × 15 mm were prepared for microstructural analysis and corrosion testing.

The base metal plate samples were then polished using the polishing disk machine because they were rusted. The grinding of the mounted samples was performed on P220, P400, P600, P800, P100, and P1200 grit papers until all the scratches were aligned in the same direction for 5 minutes each. The samples are continuously being rinsed with water to avoid any heat for generations. The samples were cloth polished using a one-micron alumina micro-suspension to achieve a scratch-free surface. Polished samples were Ultrasonically cleaned in DI water to remove any dirt, grease, or oxides that may interfere with coating adhesion. That may affect the characterization and other testing values during corrosion may lead to a change in corrosion behavior

EXPERIMENTAL METHODOLOGY

The corrosion measurement of the Thermal Spray Aluminum coated steel sample was studied using electrochemical corrosion techniques. The corrosion study was performed on ‘Gamry Reference600+’ electrochemical workstation in 3.5 wt.% NaCl electrolyte media. The measurement was performed using three electrode cell setups where saturated calomel electrode (SCE) used as a reference electrode, 6 mm diameter graphite rod was taken as a counter electrode, and test specimen was considered as a working electrode. In this study potential values were represented with respect to the potential of SCE.

Before conducting the electrochemical measurement, the sample were sectioned from the larger thermal spray Al coated steel workpiece using high speed abrasive cutter. Then the sample were cleaned in an ultrasonic bath with ethanol media for 15 minutes to remove the dirt and grease from the sample surface. The back surface was also polished using 220 grit SiC emery paper to remove the oxide layer to ensure better electrical connection. The sample was then mounted in a vertical corrosion cell, and all the electrodes related to electrochemical workstation using cell cable. During measurement, 1 cm^2 area of working electrode was exposed to the electrolyte; all the current values were considered as current density (Figure 1).

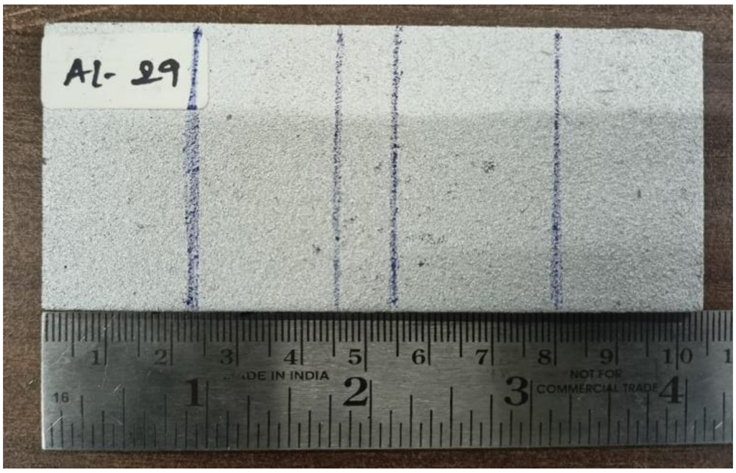

Figure 1. Thermal spray coated plate (Sample Image).

In this study, three electrochemical methods were employed to characterize the corrosion behavior of the Al-coated steel sample. The material was sectioned along the longitudinal direction, and samples measuring approximately 20 mm × 15 mm were prepared for microstructural analysis and corrosion testing.

Before starting the measurement, a 1-hour open circuit potential (OCP) was measured to ensure the stabilization of the sample in the electrolyte media. The EIS measurement was conducted by perturbing the equilibrium system using a sinusoidal a.c. signal voltage of 7 mVrms. During the measurement, frequency of a.c. signal varies from 105 Hz to 0.1 Hz and the response is measured. The potential varies from -20 mV (vs OCP) to 20 mV (vs OCP) at a scan speed of 0.167 mV. s-1 to conduct the Rp test. While the PDP measurement was carried out by polarizing the working electrode with an initial potential of -0.5 V (vs OCP) to a final potential of 0.8 V (vs OCP) with a scan rate of 0.5 mV. s-1.

The obtained results were analyzed in 'EchemAnalyst' software provided by the 'Gamry Instruments', and results were plotted using 'Origin' plotting software.

After conducting the electrochemical measurements, the sample was ultrasonicated in deionized water bath for 5 minutes followed by rinsing with ethanol to remove the extra salt present over the sample surface to avoid further corrosion reaction. The sample was then allowed to dry in atmospheric condition. The morphological change as a result of corrosion was also identified using SEM technique performed on 'JEOL JSM7900F' equipped with 'Oxford' EDS detector.

RESULTS AND DISCUSSION

OCP Analysis

The change in OCP with respect to time was plotted in Figure 2. It was observed that there was no such fluctuation in the potential during OCP. The potential varies gradually with time, and a final potential of -797.7 mV SCE was attained after 1 hour of OCP. The OCP graph indicates that the potential of the working electrode decreases with time due to electrochemical reaction happening at interface of sample and electrolyte. Other researchers [22] have reported similar results of decreasing OCP after one hour.

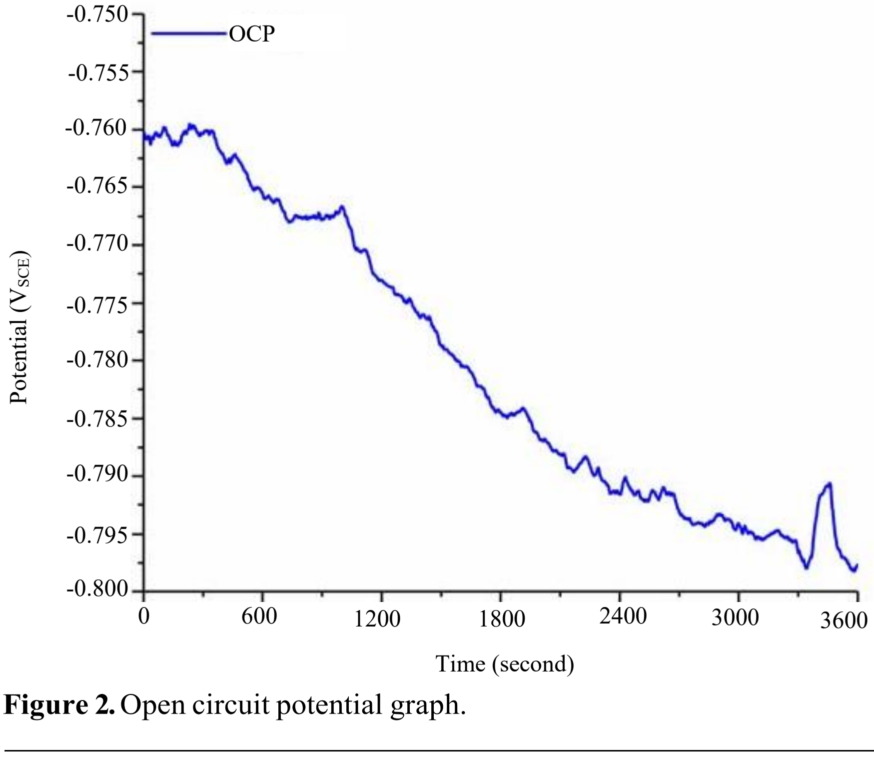

Figure 2. Open circuit potential graph.

EIS Analysis

The EIS analysis was performed by fitting the Nyquist curve (Figure 3) using a suitable electrical equivalent circuit (Figure 4). The analysis indicates that specimen was under charge transfer control at higher frequency range whereas diffusion control reactions were happening at lower frequency range. The fitting data confirms the presence of Warburg component which governs the diffusion control at lower frequency (Figure 4). The solution resistance (Rs) offered by the electrolyte was measured to be 17.24 Ω, while the charge transfer resistance (R1) was found to be 598.8 Ω. The value of double layer capacitance (CPE1) and Warburg impedance (Wd) is computed as 220.4×10^{-6} S.sa and 1.028×10^{-3} S.s0.5 respectively, which signifies that sample was offering good charge transfer control, but it has a lower diffusion control in electrochemical reaction (Table 1). Similar trend was reported in literature [9], [23]

PDP and Rp Analysis

The polarization resistance test was carried out to measure the polarizability of the working electrode under the small amount of over-potential.

The Rp plot (Figure 5) was plotted between potential and current, and the tangent on the plot provides the value of polarization resistance (Rp). Higher polarization resistance indicates the better resistance against the corrosion [24]. In this study, the Rp value is obtained as 4.522 kΩ, which indicates that the deposited Al is providing better corrosion resistance to the steel.

Table 1. Fitting parameters of EIS measurement.

Rs (Ω)	CPE1 (S.sa)	n	Wd (S.s0.5)	R1 (Ω)
17.24	220.4×10-6	0.756	1.028×10-3	598.8

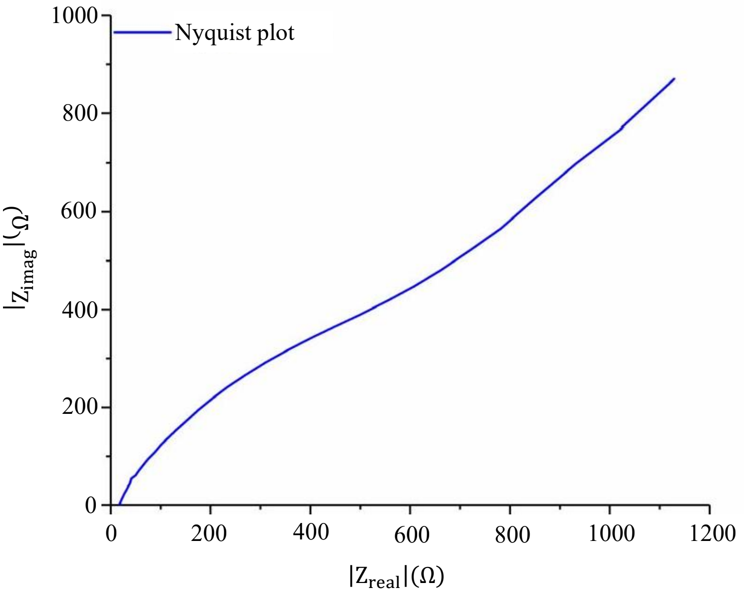

Figure 3. Nyquist plot obtained in EIS measurement.

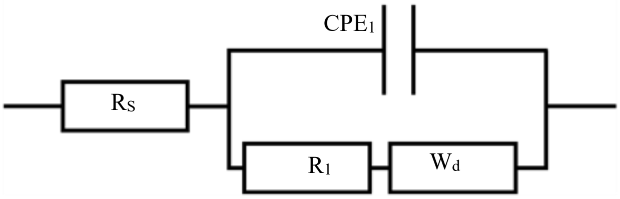

Figure 4. Electrical equivalent circuit used for EIS fitting.

The PDP analysis was used to compute the corrosion current density (i_{corr}) and corrosion potential (E_{corr}) using Tafel extrapolation method. In this study, both anodic and cathodic curves were extrapolated in Tafel plot (Figure 6) to get the value of i_{corr} and E_{corr}. The results obtained were tabulated (Table 2) which indicates the i_{corr} values were obtained of 105 order.

The higher current density indicates a higher corrosion rate. The higher current density can be due to the higher roughness over the sample surface (Figure 7a and 7b), which was formed after the thermal spray deposition. The higher surface area leads to more anodic current, which was the obvious reason for obtaining higher current density. Ge claimed lower current density with lower corrosion [5].

Table 2. Results obtained in TAFEL analysis.

Ecorr (mVSCE)	icorr (A.cm-2)	βa (V/decade)	Bc (V/decade)
-972	1.25×10-5	0.7958	0.2962

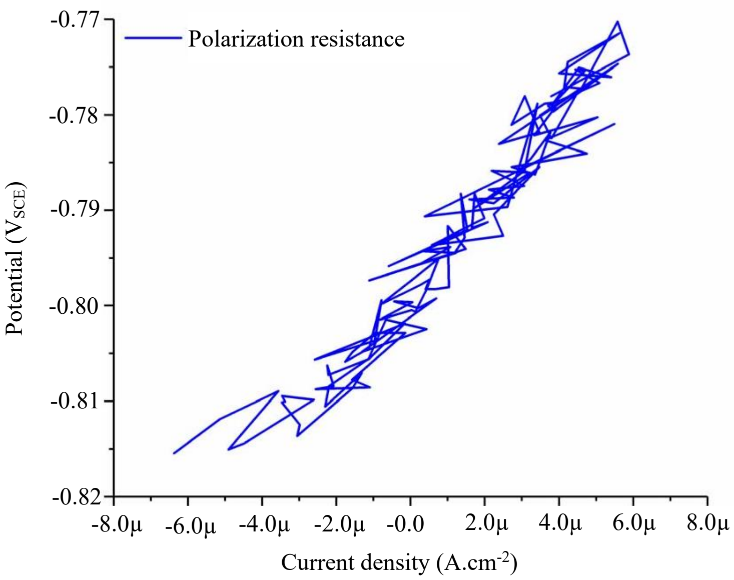

Figure 5: Polarization resistance plot.

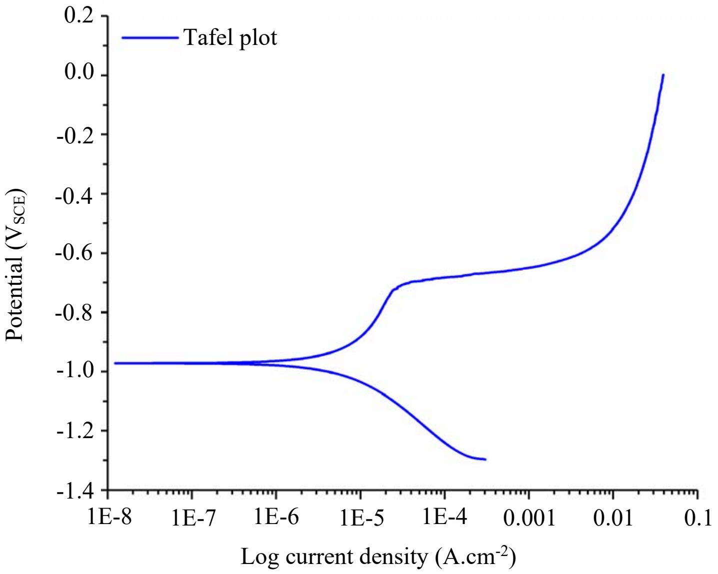

Figure 6. Tafel plot obtained in PDP test.

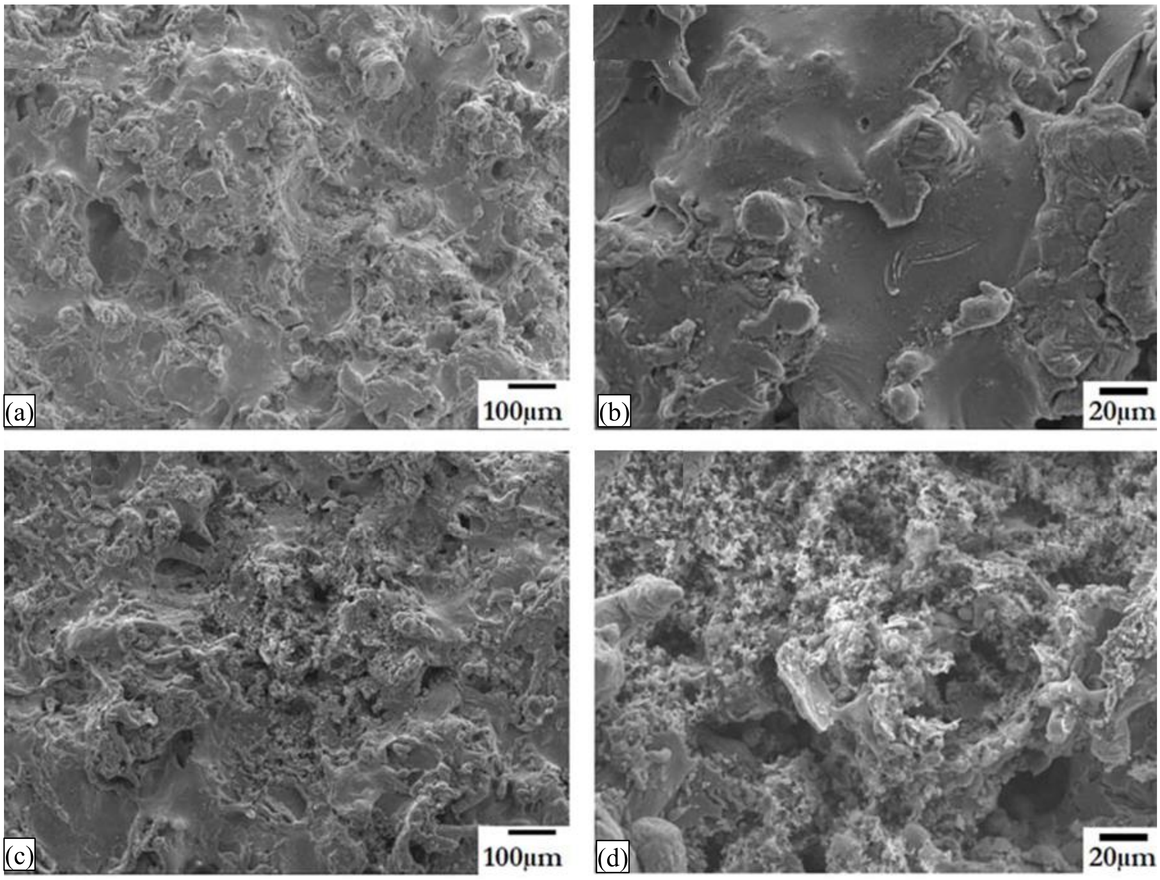

Figure 7. SEM micrographs of (a) and (b) before corrosion, and (c) and (d) after corrosion.

SEM Analysis

The SEM micrographs (Figure 7) were also captured before and after electrochemical corrosion study to compare the effect of corrosion on morphological changes. The morphological studies suggest that there was no significant pitting (Figure 7 (c) and (d)) occurred in the corrosion measurement. Therefore, the study concludes that even though a high anodic current was generated due to anodic dissolution which causes the uniform dissolution of the Al, but there was a significant reduction in pitting achieved by thermal spray coating. Lee et al [24] claimed better pitting resistance with coating.

CONCLUSION

Based on Thermal Spray Process for protection against the chloride corrosive environment. The EIS analysis confirms the presence of charge transfer and diffusion-controlled reaction during electrochemical measurement, where charge transfer controlled protection is contributing more toward corrosion protection. Considering aluminum as more active in galvanic series as compared to Carbon Steel it will protect the base material by sacrificial action and provide better corrosion protection in 3.5% NaCl solution which is typical sea water composition to simulate in the laboratory conditions.

Sacrificial action of aluminum can be further validated by potentiodynamic polarization (PDP) and polarization resistance (Rp) tests. The PDP and Rp test conclude the lower corrosion rate of deposited aluminum on steel in 3.5% NaCl solution proves that aluminum coating can be consider for offshore marine structures for corrosion protection against chloride environments.

The SEM micrographs reveal the improvement in the pitting resistance of thermal spray Al coated steel samples. SCM images have uniform pitting at superficial layer of the coating which is evidence of resistance against chloride pitting corrosion in marine environments.

Based on laboratory studies it can be proven that thermal spray coating with greater than 200 microns coating can resist chloride pitting corrosion and enhance the marine structure design life as compared to liquid coating.

Future Scope

1. Porosity of thermal spray coating can be study in detail with the help of SCM.
2. Oxidation as well as un-melted aluminum particle study can be performed.
3. Sealer coat over thermal spray coating can be verified for corrosive services requirements.
4. Blackening effect of thermal spray coating can be evaluated for sea transport equipment and piping.

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