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Application of Arc Thermal Spray Process in Corrosion Protection of Steels and Electromagnetic Pulse Shielding

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Abstract
In the present work, an overview has been discussed on the application of arc thermal spray technology. This process used in erosion, corrosion and electromagnetic pulse (EMP) shielding. The Al coating exhibits excellent corrosion properties in simulated weathering i.e., Society of Automotive Engineers (SAE) J2334 as well as 3.5 wt.% NaCl solution at long run of application. However, weathering condition possesses Cl^- and CO_3^{--} ions, which simultaneously influence in the deterioration of Al coating. Once the Zn is alloyed with Al in coating, it enhances the corrosion attributed to the formation of severe defects and galvanic coupling between Al and Zn. The stainless steel and Ti coatings have been used on the concrete surface to reduce the corrosion of waste water reservoir where Ti is exhibited more corrosion resistance due to dense and uniform morphology as well as on the surface of Ti coating during exposure in acidic solution, it forms rutile and anatase, which further provide corrosion protection. Moreover, the Zn has beneficial properties in regards of EMP shielding rather than iron and Cu plate. Zn with copper has excellent EMP shielding compared to pure Cu. As the thickness is increased, the EMP shielding properties are increased. From this review article, it is suggested to reduce the porosity of arc thermal sprayed coating using some chemical post treatment.

Keywords- Corrosion, Steel, Arc thermal spray, Coating, Electromagnetic pulse.

1. Introduction

The corrosion of steel structures causes huge economic loss to the country. Therefore, there are different techniques used to combat the corrosion of steel structures. Table 1 shows the technologies adopted to mitigate the corrosion using different techniques (Lee et al., 2015). Among them, the thermal spray technique is the most useful because it can be used at the construction site where other process is very difficult to be applied. The thermal spray technology used to improve or restores the surface of materials by depositing different metals, polymer and ceramic for various applications. It is used in many industrial sectors including aerospace, automobile, power, petrochemical and offshore. In this coating system either wire or powder are being used as feed stock materials where the molten or semi-molten particles hit and adhere to the substrate (Tucker, 2013) and form a coating. In this coating process, the thermal and kinetics energy causes the molten particles to flatten or splat to make a cohesive coating. The powder or wire (feed stock) heated above the melting point of materials to be used for coating and sprayed on the substrate where the molten metal particles are solidifying on the substrate resulting deposition of thin or thick coating depending upon the application as well as feed rate. It is used to provide wear, erosion, corrosion or heat resistance. There are different thermal spray coating processes as shown in Figure 1 (Muhamad et al., 2013). The arc thermal spray, plasma thermal spray and high velocity oxy-fuel (HVOF) are frequently used to deposit the different metallic coatings. These coating systems used to depend upon the application.

HVOF coating exhibits excellent properties where the porosity is minimum, with high mechanical bonding with the substrate. The HVOF process is shown in Figure 2 where the powder as feed stock is used and injected into the stream and get heated with the carrier gas (oxygen). The molten particles with accelerated speed impact on the substrate, therefore, form a homogenous coating (Fauchais et al., 2014). However, this coating system is very expensive and cannot use to deposit on the big structure where corrosion is dominant. Alternatively, it requires closed condition to deposit the coating.

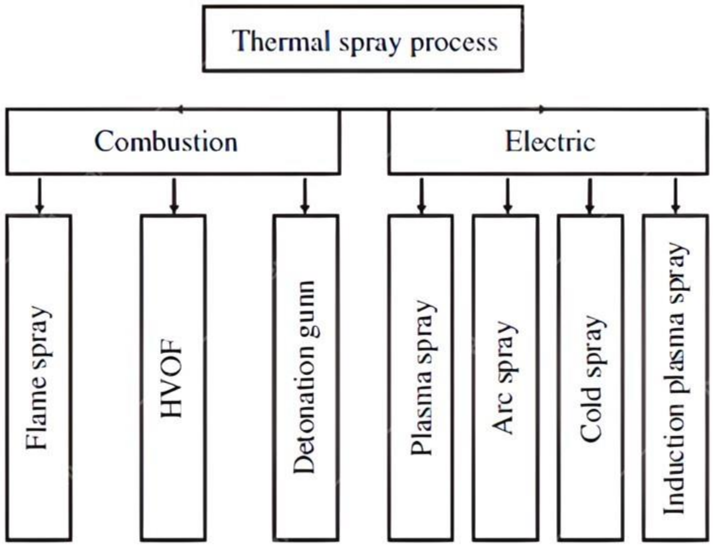

Figure 1. Schematic for types of thermal spray process(Muhamad et al., 2013).

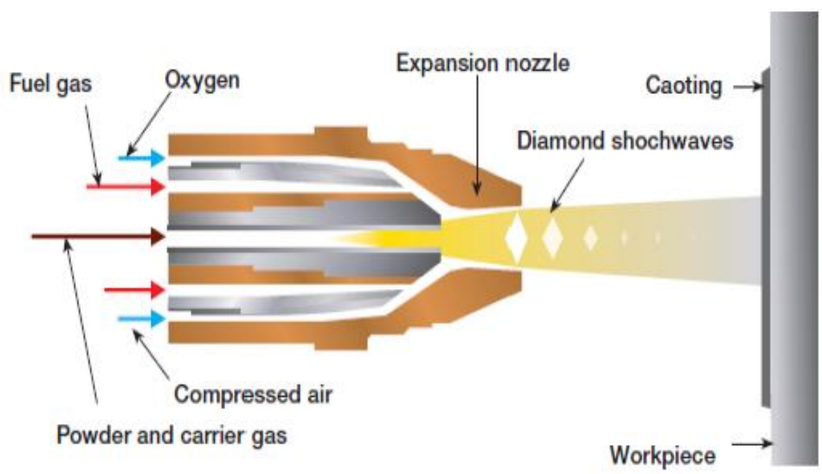

Figure 2. Schematic of HVOF spraying process (metco, 2016).

The arc thermal spray technology was developed in 1960s for commercial use (Peabody and Bianchetti, 1967; Revie, 2011). It is considered by many industries owing to the process simplicity, economical and high efficiency (Brito et al., 2012). In this process, 1.6 mm diameter of twin wires are used as the feed stock and they are drove through the roller where oppositely charged power supply melt the wires at the intersection/arcing point. In the meantime, with the help of the compressed air, the molten metal particles blown and hit the substrate resulting deposition of the coatings and the details are shown in Figure 3 (Choe et al., 2014). The beauty of the arc thermal spray process is that the spray gun can be brought any place for the coating and coat the big structure while other coating systems need close room or a specific condition for the deposition. By considering aforementioned qualities of the arc thermal spray process, we will discuss about the corrosion resistance and electromagnetic pulse (EMP) shielding applications.

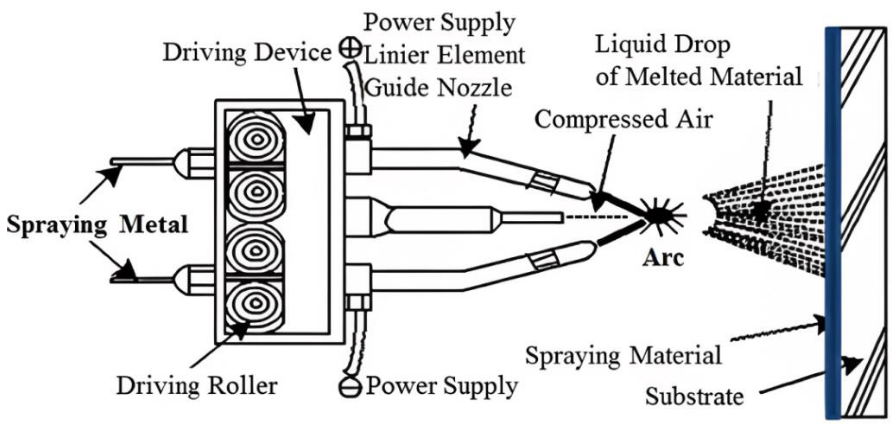

Figure 3. Schematic of arc thermal spay process (Choe et al., 2014).

2. Application in Corrosion Protection of Steels

Different metal or alloy such as Al, Zn, Al-Zn and Al-Mg coatings are being used to protect the steel structures from the corrosion. Figure 4 demonstrates the pit formation in Al and Al-Zn coating in humid condition by COMSOL multi physics 5.4 software (Chen et al., 2021). In arc thermal sprayed coating, generally defects or voids are formed, therefore, the electrolyte (solution) can stagnant and initiate the corrosion.

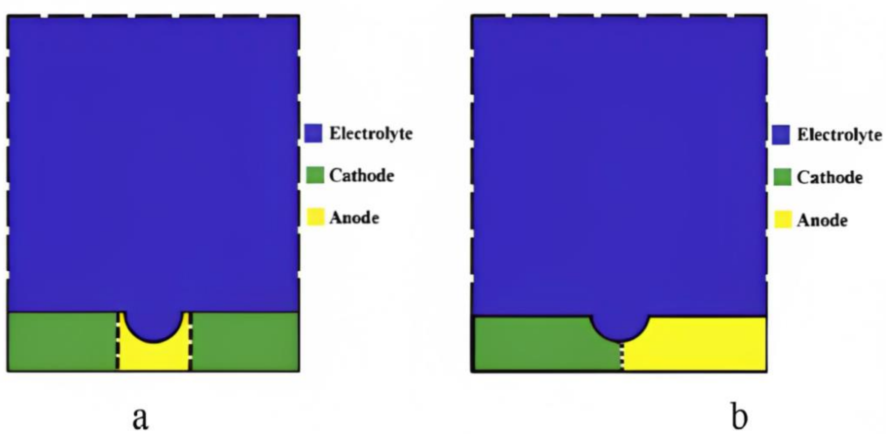

Figure 4. Pit formation in (a) Al, and (b) Al-Zn coating (Chen et al., 2021).

The Al coating possesses some defects where the oxygen content is high while there is no overlapping phenomenon is observed in coating as shown in Figure 5(a) and Figure 5(b). The Al coating is adhered to the substrate. In the case of Al-Zn coating, there is intero-ccluded in coating layer observed (Figure 6(a)), while the black color is disappeared as observed in the case of Al coating attributed to the Al and Zn, which exhibits different melting points and density. The black color in coating might be due to the oxide film while white and gray owing to the Al and Zn, respectively (Li et al., 2017). This could be confirmed by elemental analysis at different spots marked in Figure 5 and 6 and the results are shown in Table 1 (Chen et al., 2021).

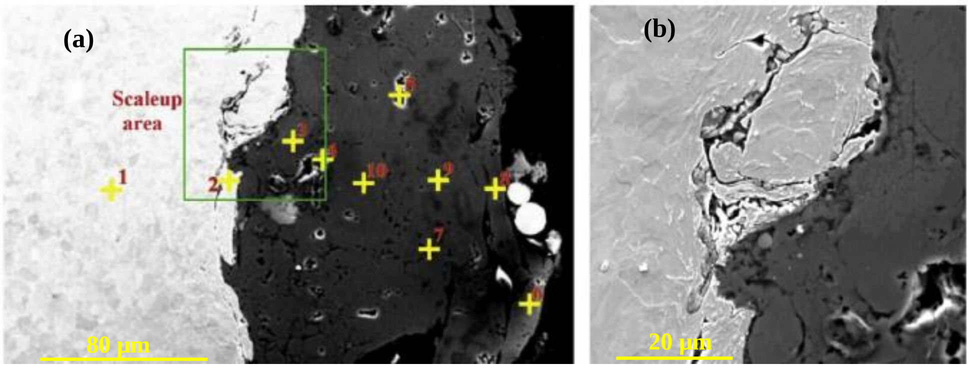

Figure 5. Cross sectional SEM of Al coating (a) Elemental composition, and (b) magnified morphology of Figure 5(a) coating deposited by arc thermal spray process (Chen et al., 2021).

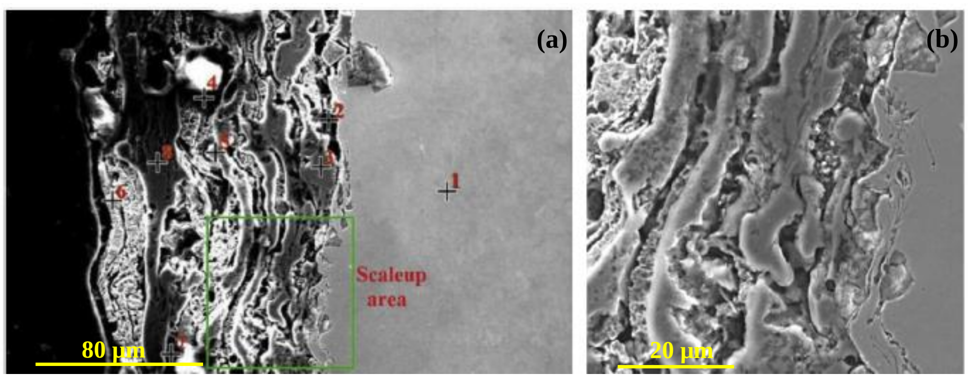

Figure 6. Cross sectional SEM of Al-Zn coating (a) Elemental composition, and (b) magnified morphology of Figure 6(a) coating deposited by arc thermal spray process (Chen et al., 2021).

Table 1. Compositional analysis (wt.%) of points shown in Figure 5 and 6 (Chen et al., 2021).

Points	Al coating			Al-Zn coating				
	Fe	O	Al	Fe	O	Al	Zn	S
1	98.52	1.48	-	98.92	1.08	-	-	-
2	98.68	1.32	-	9.76	2.27	14.14	73.83	-
3	-	-	100	-	-	100	-	-
4	-	11.91	88.09	0.48	0.78	6.17	92.57	-
5	-	-	100	-	9.44	71.95	18.61	-
6	-	-	100	-	-	2.64	97.36	-
7	-	7.23	92.77	-	1.40	11.11	85.71	0.92
8	-	-	100	-	-	92.02	7.98	-
9	-	-	100	-	-	-	-	-
10	-	-	100	-	-	-	-	-

2.1 Deposition of Al Coating and Characteristics

Al coating deposited by arc thermal spray process possesses defects and pores as observed in Figure 7(a) and Figure 7(b) (Lee et al., 2016b). The porosity is formed owing to the high velocity of the molten metal particles and rapid cooling at room temperature, which continuously impinged to the substrate (Min-Su et al., 2009). During cooling of the coating, some air diffused from the coating resulting formation of splashed and defects/pores in the deposited coating (Deshpande et al., 2004; Torres et al., 2007). After deposition of the Al coating, there is no oxidation, therefore, only Al (JCPDS: 85-1327) is observed in XRD as shown in Figure 8 owing to the presence of very less amount of oxygen, which could not form an oxide.

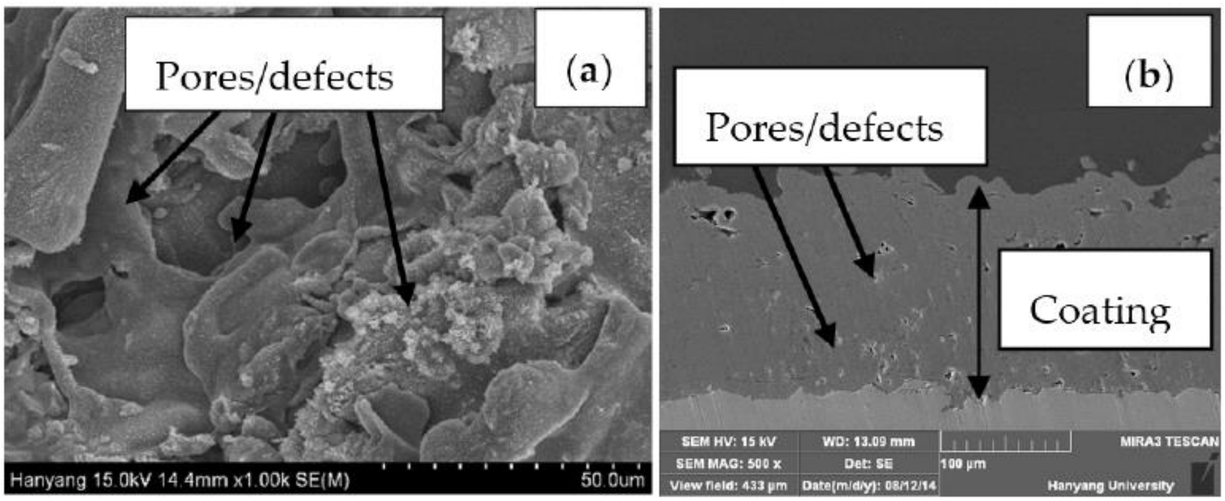

Figure 7. SEM (a) surface, and (b) cross section morphology of the Al coating (Lee et al., 2016a).

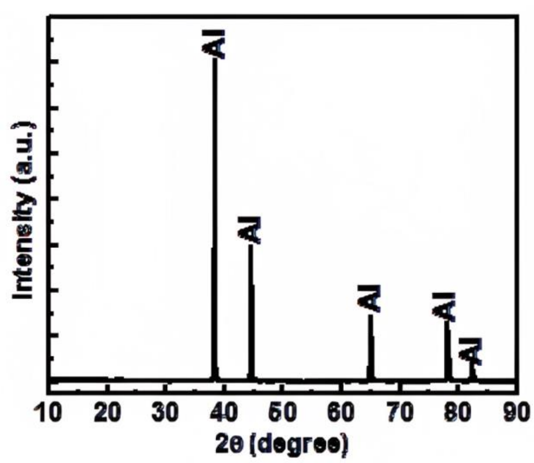

Figure 8. XRD of the Al coating deposited by arc thermal spray process (Lee et al., 2016a).

The corrosion resistance properties of Al coating are assessed in Society of Automotive Engineers (SAE) J2334 and 3.5 wt. % NaCl solutions after 1 hour of immersion and the results are shown in Figure 9(a) and Figure 9(b) (Lee et al., 2016a; Lee et al., 2016c), respectively. It can be seen from Figure 9(a) and Figure 9(b) that bare steel exhibits severe corrosion compared to Al as the quantitative results are shown in Table

3. This result suggests that the Al coating deposited by arc thermal spray process is suitable to be used as coating materials for the protection of steel structures. However, 3.5 wt. % NaCl is more vulnerable for corrosion of bare steel owing to the localized corrosion. On the other hand, the SAE J2334 solution is more dangerous for Al coating where the corrosion rate is greater than 3.5 wt.% NaCl as shown in Table 2. It is attributed to the presence of different aggressive ions such as Cl^- and CO_3^{--}, which enhance the corrosion of Al as well as alkaline pH of this solution. This result suggests that Al is prone to corrosion in alkaline as well as where CO_3^{--} ions are present. Moreover, the Al coating exposed to 3.5 wt. % NaCl solution provides cathodic protection where its corrosion potential (E_{corr}) is greater than -0.870 V vs Ag/AgCl (Park and Kim, 2016) while in SAE J2334 solution, it is gradually corroded.

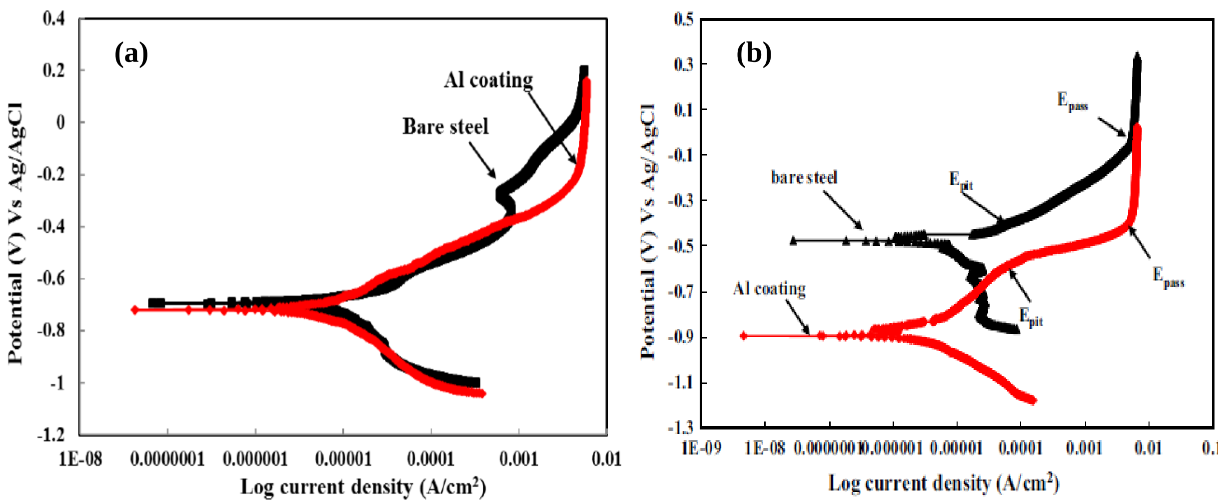

Figure 9. Corrosion performance (potentiodynamic polarization curve) of Al coating deposited by arc thermal spray process in (a) SAE J2334 and (b) 3.5 wt.% NaCl solution after 1 hour of immersion (Lee et al., 2016a; Lee et al., 2016c).

Table 2. Electrochemical parameters obtained after fitting of potentiodynamic polarization curve in Tafel regions (Lee et al., 2016a; Lee et al., 2016c).

Solution	Sample ID	Electrochemical parameters		
		E_{corr} (V) vs Ag/AgCl	i_{corr} (μA/cm^2)	Corrosion rate (μm/year)
SAE J2334	Bare steel	-0.689	15.22	176.82
	Al coating	-0.717	12.96	141.26
3.5 wt. % NaCl	Bare steel	-0.511	150.32	1740.71
	Al coating	-0.896	4.86	52.97

2.2 Deposition of Al-Zn Coating and Characteristics

The Al-Zn alloy coating is deposited by arc thermal spray process to control the corrosion of steel structures. The Al-Zn alloy coating exhibits lesser bond adhesion i.e. 3.91 MPa compared to Al coating (4.86 MPa). The reduction in bond adhesion of Al-Zn alloy coating attributed to the presence of severe defects caused by splat particles in the coating. The SEM of the coating is shown in Fig. 10 along with EDS analysis (Lee et al., 2019). This coating exhibited splat zone, plate like morphology with cracking, pores and inflight particles. The inflight particles caused due to the difference in melting and density of Al and Zn where Zn become very small but due to high density, during melting process, they settle down early and partially oxidized the coating. Therefore, the oxygen content is greater than pure Al coating. However, only Al (JCPDS: 85-1327) and Zn (JCPDS: 87-0713) is observed in XRD as shown in Figure 11 while there is 3.68 wt.% oxygen is observed (Figure 10). There is possibility to partially oxidized the coating but XRD cannot detect lower phases of oxides (Blanton et al., 1991; Lin et al., 2002; Güleryüz and Çimenoğlu, 2004).

The corrosion performance of Al-Zn alloy coating is determined by potentiodynamic polarization curve after 1 hour of exposure in 3.5 wt. % NaCl solution. The results are shown in Figure 12 and Table 3. There is enhanced cathodic polarization observed in Al-Zn coated samples attributed to the oxygen reduction reaction. In this case, the OH^- ion enrichment occurs and increase the local pH in the pits of the coating result in dissolution. This coating is under active dissolution, therefore, provide cathodic protection where the E_{corr} value is found to be -1.123 V vs Ag/AgCl. During exposure in solution, the coating reacts and form corrosion products, therefore, the cathodic current density of Al-Zn coating is greater than bare steel. The corrosion rate of Al-Zn coating is greater than Al coating i.e. 52.97 µm/year (Table 2), attributed to the severe defects/pores formation in the coating as well as galvanic coupling.

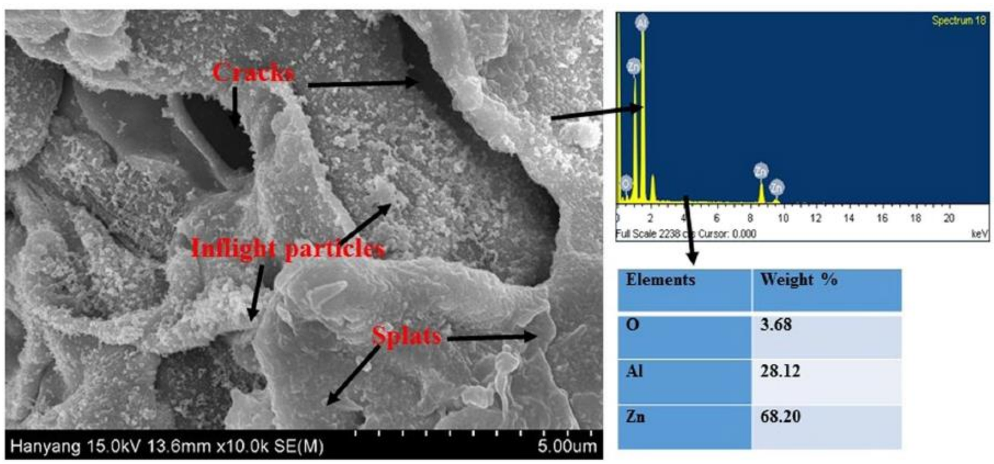

Figure 10. SEM and EDS of Al-Zn alloy coating (Lee et al., 2019).

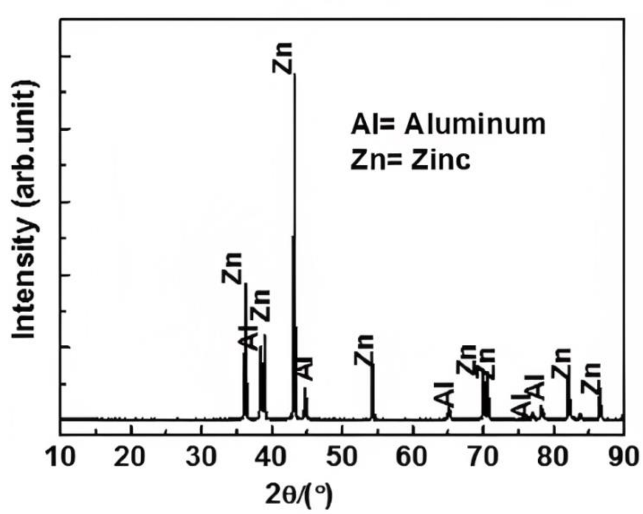

Figure 11. XRD of AL-Zn alloy coating (Lee et al., 2019).

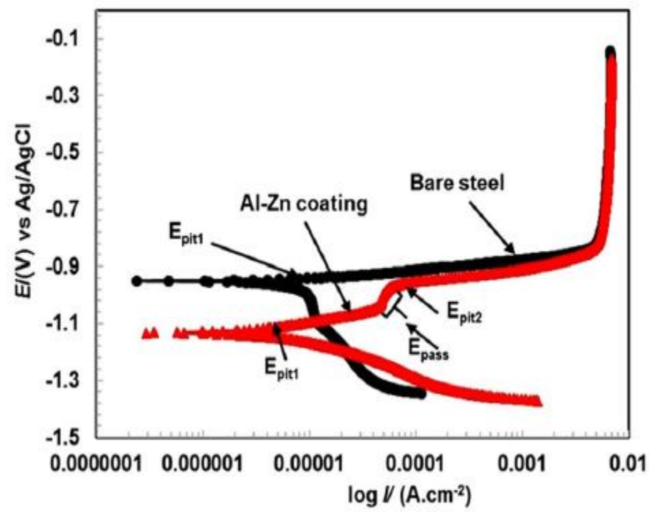

Figure 12. Potentiodynamic polarization curve of Al-Zn alloy coating in 3.5 wt.% NaCl solution after 1 h of exposure (Lee et al., 2019).

Table 3. Electrochemical parameters obtained after fitting of potentiodynamic polarization plots in Tafel regions.

Sample ID	Electrochemical parameters		
	E_{corr} (V) vs Ag/AgCl	i_{corr} (µA/cm^2)	Corrosion rate (µm/year)
Bare steel	-0.950	20.10	233.17
Al-Zn coating	-1.123	7.19	120.40

3. Protection of Reinforced Concrete from Corrosion in Waste Water Reservoir

The steel rebar reinforced to concrete to provide strength. It is used in construction of waste water reservoir where many aggressive ions present. Due to contamination of waste water with sulfur reducing bacteria, hazardous elements such as Pb, As, Sn and Cd as well as acidic elements, they ingress through the concrete and reach at the concrete/steel rebar interface and cause corrosion (Guo, 1997; Giergiczny and Król, 2008; Lupsea et al., 2014). Therefore, different techniques such as polymeric coating (Swamy and Tanikawa, 1993; Rosa et al., 2013), stainless steel plating (Bhalerao and Arceivala, 1971; Crowe and Nixon, 2016) have been used to reduce the corrosion of embedded steel rebar in the concrete. However, polymeric coating cannot sustain in aggressive condition as well as stainless steel grouting is very expensive to be used to control the corrosion of steel rebar embedded in the concrete. Therefore, stainless steel coating is used on the concrete surface by arc thermal spray process to control the corrosion. Lee et al. (2016a) have used 316L stainless steel (SS) on concrete surface to mitigate the corrosion of waste water reservoir (Lee et al., 2016a). Figure 13 shows the SEM images of the coating as well as some post-treatment on the coating surface applied (Lee et al., 2016a). As described above that arc thermal spray process exhibits defects/pores formation in the coating, therefore, these are observed in Figure 13(a). To reduce the porosity, abrading was applied by emery paper on the coating (Figure 13(b)). However, even after abrading some porosity is still observed. Therefore, epoxy coating was used on deposited coating where coating become smooth but still defect is observed (Figure 13(c)). For the comparison, a 316L SS plate is considered for the studies where the surface is smooth and defects free (Figure 13(d)). Figure 13(e) shows the morphology of the concrete where micro and macro pores are observed through which the aggressive solution penetrate and reach at the steel/concrete interface and cause the corrosion.

The corrosion of 316L SS coating deposited by arc thermal spray process, abraded coating and the same steel plate is considered at different pH of H_2SO_4 solution and the potentiodynamic polarization results are shown Figure 14 (Lee et al., 2016b). The sealed 316L SS sprayed coating with epoxide exhibits lower cathodic and anodic current density followed by plate, abraded and sprayed in pH 6, 5 and 4 as shown in Figure 14a, b and c, respectively. The epoxide coating causes a barrier where solution cannot react with polymer and show lower corrosion rate. Alternatively, the plate surface does not contain any defects, therefore, the native oxide film presents on the surface, cause barrier but these are metallic and react with solution and initiate the corrosion. Moreover, the abraded and sprayed coatings exhibit pores/defects, which act as active center for the corrosion where solution easily penetrate and cause the corrosion. Therefore, these samples show greater cathodic and anodic current density. In another studies, Lee et al have found that Ti coating is the exhibiting better corrosion resistance that 316L SS coating at pH 4 due to formation of rutile and anatase phase as the passive film (Lee et al., 2018).

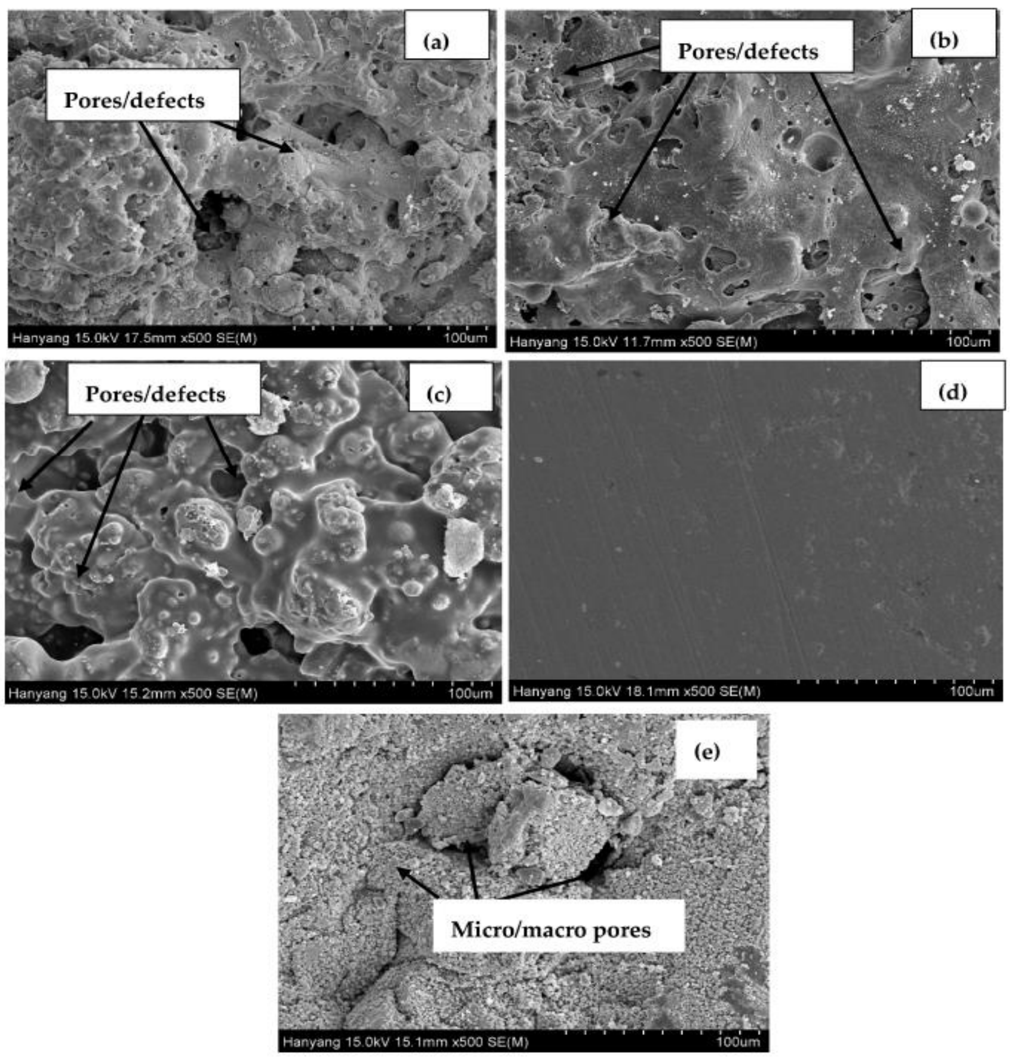

Figure 13. SEM images of 316L stainless steel coating (a) sprayed; (b) abraded; and (c) sealed; (d) stainless steel plate; and (e) OPC concrete (without coating) (Lee et al., 2016b).

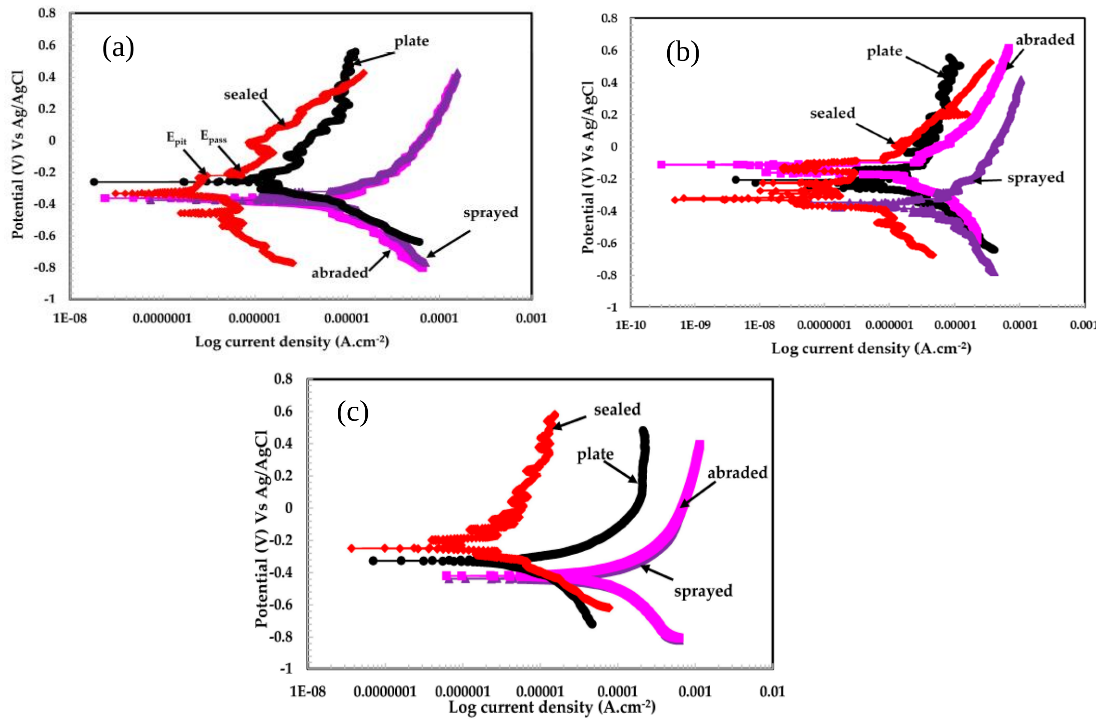

Figure 14. Potentiodynamic polarization plots of 316L stainless steel coating at pH (a) 6, (b) 5 and (c) 4 H_2SO_4 solution (Lee et al., 2016b).

The schematic representation as shown in Figure 15 depicts the formation of passive film on the stainless steel coating surface in inner surface of waste water reservoir (Lee et al., 2016b). In this coating, the acidified water reacts with stainless steel and form a passive film, which further provide protection. This passive film can sustain in a mild acidic condition while highly acidic solution destroy the passive film and cause corrosion. Therefore, at pH 4, the coating exhibits severe corrosion.

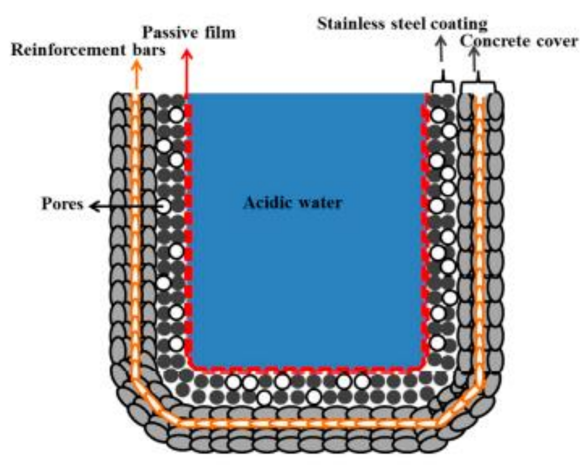

Figure 15. Schematic of the formation of a passive film on the stainless-steel coated surface of a water treatment reservoir (Lee et al., 2016b).

4. Application of Arc Thermal Spray Process in Electromagnetic Pulse (EMP) Shielding

The electromagnetic wave (EM) destroys the building, electronic and big structures. Moreover, the interaction of EM wave with materials depends on materials properties. In EM, when waves are incident on the materials, there is reflection, absorption and transmission phenomenon occur as shown in Figure 16 (Faisal et al., 2022). Due to materials impedance difference, the reflection and transmission of waves occur. In this process, reflection and/or absorption of EM wave occur (Kim, 2009; Nam et al., 2011; Singh et al., 2018), which prevent the penetration of harmful EM radiation into the materials (Chung, 2000). Therefore, the thermal sprayed coating can be considered as the EMP materials where the incident wave attenuates by the complex refraction and scattering phenomenon, which cause the dielectric loss in the coated materials. For the security purpose, EMP needs minimum 80 dB shielding value at 0.1 to 1 GHz. The metallic coating can obtain the minimum values deposited by arc thermal spray process. Jang et al have found that use of Zn in Cu coating improve the EMP shielding value and obtain minimum 80 dB compared to pure Cu or Cu-Ni coating even the thickness is 100, 200 and 500 µm as shown in Figure 17(a), (b) and (c), respectively (Jang et al., 2020). It is attributed to the increase in conduction loss. However, at low coating thickness, there is porosity observed, where the EM waves are leaked and reduce the EMP value. Once, the thickness is increased, the porosity of the coating is decreased result in increase in EMP value attributed to the increase in electrical conductivity and absorption loss.

The Al-Zn coating deposited by arc thermal spray process exhibits the identical EMP shielding compared to metal plate as shown in Figure 18 (Lee et al., 2017). At low frequency, the coating exhibit lower in shielding value compared to Fe and Cu plate but as the frequency is increased, the shielding value is found to be identical or greater.

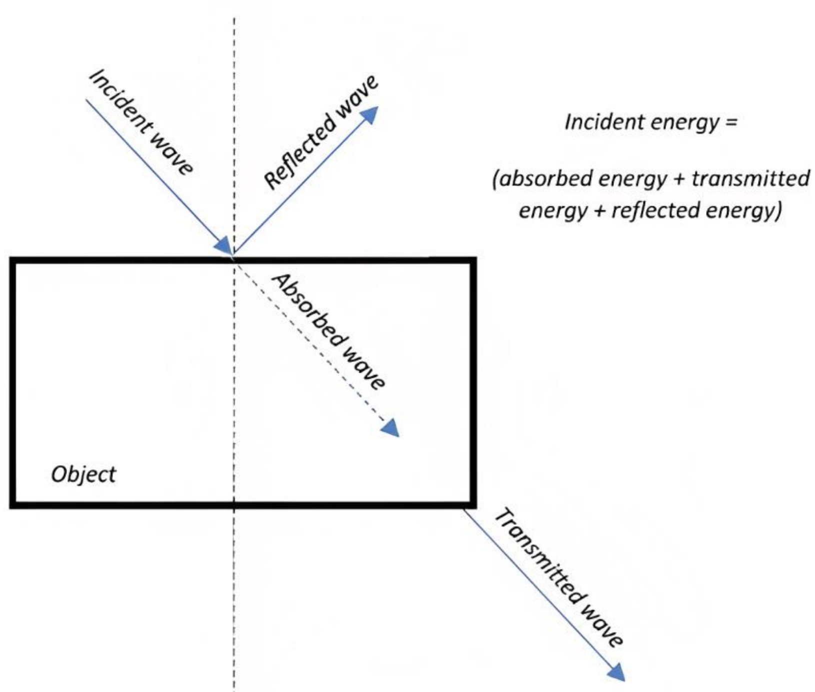

Figure 16. EM wave reflection, absorption, and transmission (Faisal et al., 2022).

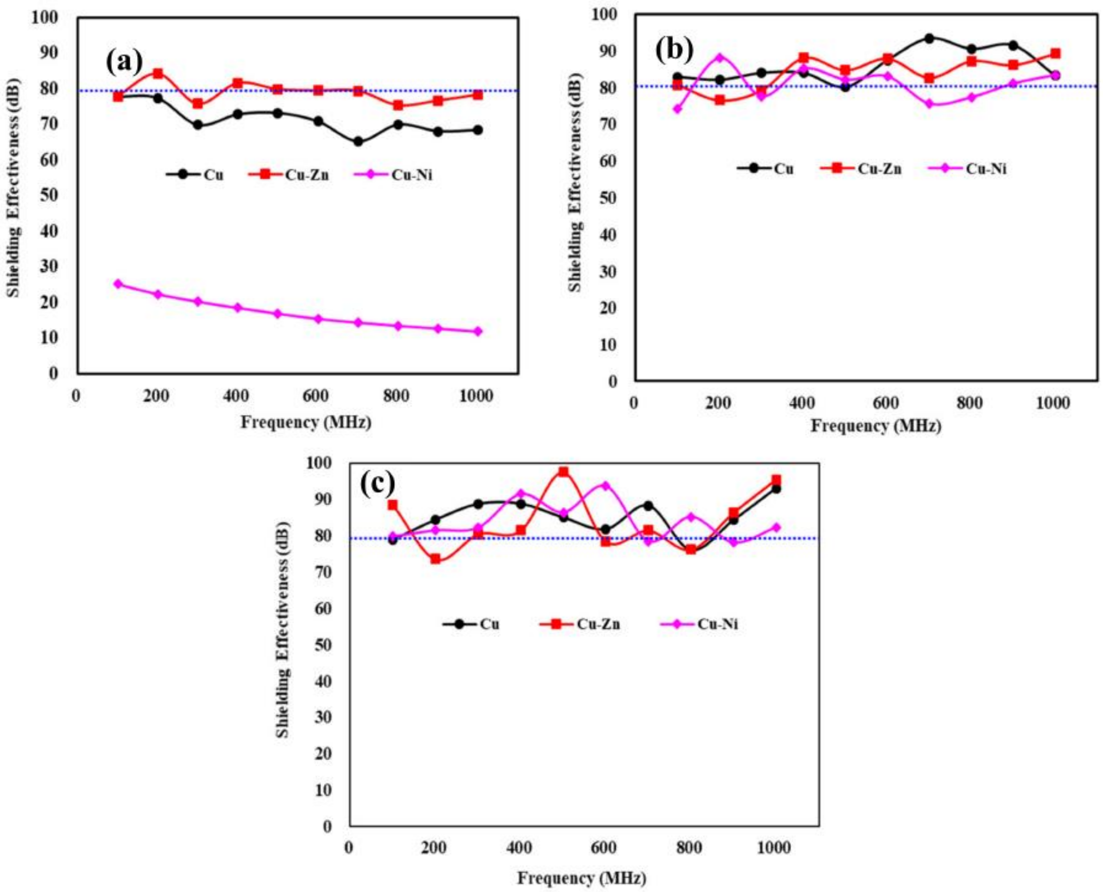

Figure 17. Shielding effectiveness value of Cu, Cu–Zn, and Cu–Ni coatings, each with thicknesses (a) 100 µm, (b) 200 µm, and (c) 500 µm at different frequencies (Jang et al., 2020).

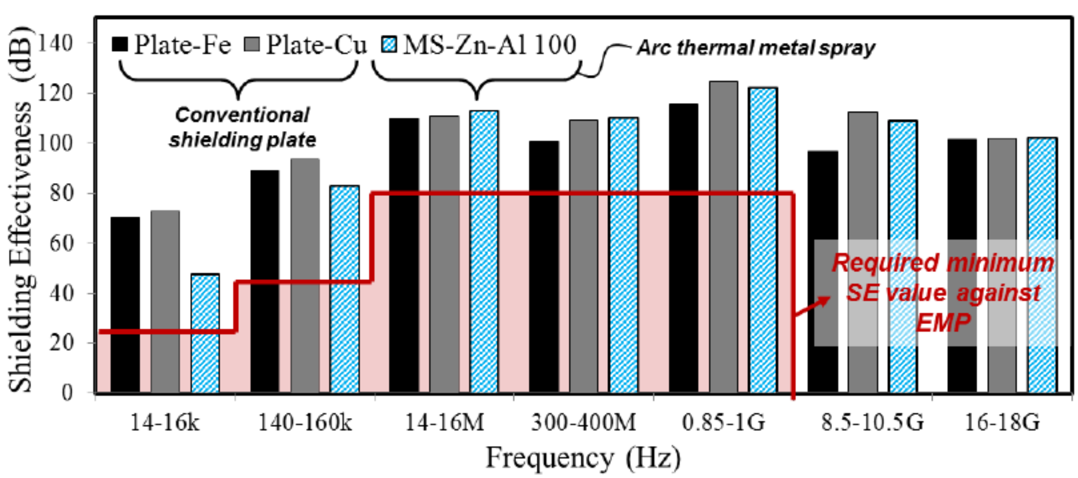

Figure 18. Shielding effectiveness result of metal plate and Zn-Al coating deposited by arc thermal spray process (Lee et al., 2017).

5. Conclusion

The arc thermal spray coating system is used in different applications specially it has excellent performance in corrosion protection of steel structures and EMP shielding. The arc thermal spray process possesses porosity and defects formation, which reduce the performance of the coating. The Al coating deposited by arc thermal spray exhibit excellent corrosion resistance performance in SAE J2334 as well as 3.5 wt.% NaCl solution. However, it is more prone to corrosion in SAE J2334 solution owing to the presence of Cl^- and CO_3^{--} ions in solution, which cause localized and pitting corrosion. Moreover, it is suitable to be used in saline environment where it can provide sacrificial protection. The Al-Zn coating is more susceptible to corrosion compared to pure Al owing to the presence of severe defects formation where the inflight and splat particles act as active center as well as form galvanic cells for the corrosion in 3.5 wt.% NaCl solution. The stainless steel could be used as coating materials to reduce the corrosion of steel rebar embedded in waste water reservoir concrete surface. However, it can sustain in mild acidic pH whereas if the pH is become acidic then it causes corrosion. In this case, Ti coating could be useful for extended service condition. The Al-Zn is the coating, which provide excellent EMP shielding compared to Fe and Cu plate. Zn can enhance the EMP properties of the materials once used with Al or Cu. However, there is task to improve the properties of arc thermal sprayed coating by reducing the porosity. It is recommended to select a proper pore sealing agent for the arc thermal sprayed coating, which enhance the properties of the coating and could be more efficient for corrosion protection and EMP shielding.

Conflict of Interests

The author declares there is no conflict of interest.

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