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Al-Mg thermal spray: Superior corrosion protection for Bangladesh bridges

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ABSTRACT: Bridges are one of the most important components of modern transportation systems, and thus it is necessary to apply reliable technologies to ensure a long life cycle for these structures. Corrosion is one of the most determining factors affecting the deterioration of bridges, especially in those viaducts located in marine environments, which is something common in Bangladesh. Thus, their important structural members such as bearings and expansion joints must be effectively protected against the detrimental effects of corrosion. The current paper describes several anti-corrosion coatings and discusses their long-term performance under highly corrosive environments. Conducted accelerated corrosion tests reveal that in marine environments a stable and durable anti-corrosion protection could be achieved with a novel technology: the Plasma Arc Al-Mg Thermal Spray. The results of these accelerated corrosion tests and details of the application of this anti-corrosion coating to projects in Bangladesh are discussed in this paper.

1 INTRODUCTION

Bridges are very important components of modern transportation systems, playing a critical role in the transportation networks within cities, or in modern highway networks. Corrosion is one of the most determining factors affecting the deterioration of bridges, causing not only visual degradation but also affecting their safety and serviceability. Given the cost, and importance of these civil infrastructures in our daily life, it seems necessary to apply reliable corrosion methods which can ensure their long life cycle with minimal maintenance. It is thus crucial that important bridge structural members are effectively protected against corrosion.

One of the most critical structural components of a bridge is its bearing supports. Bridge bearings are located between the substructure and the superstructure of the bridge, areas that are poorly ventilated, and have the potential to collect large amounts of dirt, debris, and moisture or standing water, meaning that corrosion is easily triggered (Fig. 1). Besides, bridges located in marine environments, which are very common in Bangladesh, present a higher risk of corrosion.

In Japan, and all around the world, there are innumerable cases of bridges affected by corrosion. In the current paper, the focus is on the protection technologies applied to bridge bearings. Special attention is paid to new protective coatings, i.e. Al-Mg Plasma Arc Thermal Spray, developed to improve the durability of conventional paints and hot-dip galvanized coatings in highly corrosive environments.

Figure 1. Corrosion of bridge bearings

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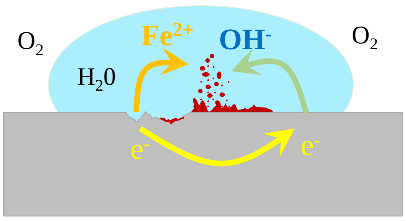

Figure 2. Corrosion mechanism

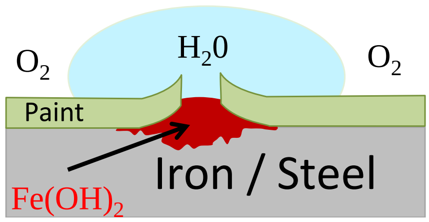

Figure 3. Paint coating protection layer

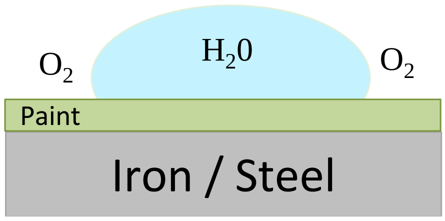

Figure 4. Damaged paint coating

2 CORROSION PROTECTION

2.1 *The mechanism of corrosion*

Corrosion is a process of degradation of metals in which the metal is being oxidized by its surroundings, usually water and oxygen (O_2). The mechanism of corrosion resembles a battery. Under the presence of water and O_2, there is an area (the anode) where electrons are produced and another area, the cathode, where these electrons are consumed. As a result, there is a loss of steel or iron in the anodic area and a compound that we know as rust is formed and deposited on the surface (Fig. 2). This rust is porous and it will not act as a protective layer since it allows water and oxygen to pass through it. As a result, the deterioration of the metal will continue.

2.2 *Protective layers*

To avoid the appearance and development of corrosion in steel surfaces, the most common approach is to provide a protective coating layer. Its purpose is to physically avoid water and oxygen to come into contact with the steel to avoid the formation of rust (Fig. 3). Paint coatings follow this approach in order to prevent the development of corrosion, and heavy-duty coatings have been proposed and applied in bridges in marine environments. However, this technology presents the following durability issues when applied to bridge bearings:

- The protective layer is degraded due to its exposure to wet and dry cycles of direct sunlight and rainwater. Therefore, regular repainting and maintenance are necessary. This is particularly troublesome for bridge bearings since their location complicates regular inspections and re-painting operations.
- In painted structures rust starts in areas where the coating has been damaged, exposing the steel surface. Bridge bearings, characterized by complicated shapes, are difficult to be evenly coated, and any damage occurred during transportation or installation can easily trigger the appearance of rust in these damaged areas. When the paint coating is cracked, the steel surface is exposed to the corrosive agents and rust starts to form. The expansive nature of this rust will increase the size of the crack of the paint coating, which will accelerate the deterioration process (Fig. 4).

2.3 *Sacrificial protection*

Paint only forms a protective layer, but other technologies have been developed to, besides, provide sacrificial protection to overcome the disadvantages of paint coatings.

Table 1 presents the electrochemical series, which is a classification of metals according to their tendency to lose electrons. Metals with higher ionization tendency than Fe, e.g. Cr, Zn, Al, or Mg, will corrode more easily. When steel is coated with one of these metals (Fig. 5), rust develops faster in the coating and provides sacrificial protection to the base material.

A common anti-corrosion method that applies this principle is hot-dip galvanizing. In this case, the base metal to be protected is immersed in a kettle containing molten zinc (Fig. 6). Since the melting point of Zinc is 420 °C, the majority of materials can be coated using this method, except for high strength materials, which strength could be reduced. In a corrosive environment, Zn will oxidize and form a stable Zn oxide layer that

Table 1. Electrochemical series.

Metal	K	Ca	Na	Mg	Al	Mn	Zn	Cr	Fe	Ni	Sn	Pb
Potential	-2.92	-2.76	-2.72	-2.32	-1.66	-1.18	-0.76	-0.71	-0.47	-0.27	-0.14	-0.13
(V)	Higher tendency to oxidize ←								→ Lower tendency			→
Reactivity with air	Oxidize very easily				Creates and oxide film on the surface							
Reactivity with water	React vigorously				React with steam but not with water, oxidizing					Not reactive		

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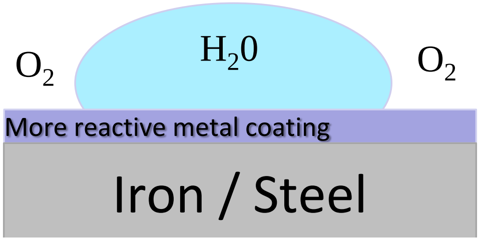

Figure 5. Metal coating

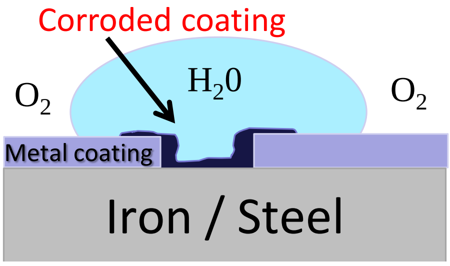

Figure 6. Hot-dip galvanizing

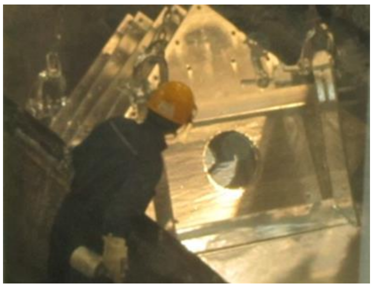

Figure 7. Sacrificial protection

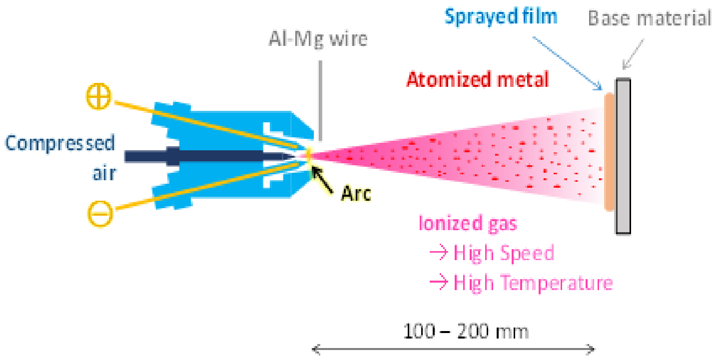

Figure 8. Al-Mg plasma arc thermal spray application

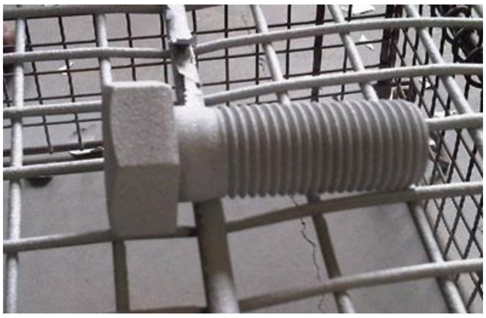

Figure 9. Application to high strength bolts

will prevent the corrosion of the Fe and cover scratches (Fig. 7), conferring a long term corrosion protection.

2.4 *Thermal spray coating using Aluminum – Magnesium alloy*

Apart from Zn, there are two other metals in the galvanic series, i.e. Aluminum and Magnesium, which have the potential to be used as metal coatings. They both have high corrosion potential capability but due to their high melting point (higher than 600 °C), it is costly to melt them and apply them as Zn is applied in the case of hot-dip galvanizing. Besides, high temperatures can affect some materials creating distortions and strength degradation.

To make the most of the excellent anti-corrosion protection characteristics of Aluminum and Magnesium, its application through plasma arc thermal spraying was proposed. This is a process in which a modified gas or electric arc welding equipment equipped with compressed air is used to melt and project a metal wire onto a steel surface, as shown in Figure 8. In this method, surface preparation is a critical step necessary to ensure a very good adherence between the steel base and the sprayed coating layer. Several metals can be sprayed following this technique, including Zn, Al, and Mg. The fact that a metal like Mg, with outstanding corrosion protection characteristics, can be used in this method to create a protective layer could have important advantages. Besides, since this is a cold process, this type of coating can also be applied to high-strength materials, such as high strength bolts (Fig. 9), without creating strength degradation or distortions.

3 PERFORMANCE OF ANTI-CORROSION COATINGS IN MARINE ENVIRONMENTS

As described in the previous sections, several anti-corrosion protection strategies for metals have been studied, developed, and applied during the last decades. To evaluate and compare the anti-corrosion performance of these protection technologies, accelerated corrosion tests with salt spray were and outdoor exposure tests were performed. The results of these tests are described and discussed in the following sections.

3.1 *Accelerated corrosion tests in steel plates and bolts*

An accelerated corrosion test was performed during 9 months (6,000 hours) following the procedure described in JIS K 5600-7-9 (JIS, 2006). Steel plate test pieces and sets of bolts, washers, and nuts were treated with different anti-corrosion coatings, i.e. heavy-duty anti-corrosion paint coating, Zinc hot-dip galvanized coating, and Al-Mg thermal sprayed coating. The test pieces were inserted in a chamber where they underwent wet cycles, i.e. the test pieces were sprayed with water and salt, humid cycles, and dry cycles that were

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Specimen	Start of the test	After 6,000 hours
Al-Mg Plasma Arc Thermal Spray		
Heavy-duty anti-corrosion paint coating (Type C)		
Hot-dip galvanizing		

(a) Steel plate specimens

Specimen	Start of the test	After 6,000 hours
Al-Mg Plasma Arc Thermal Spray		
Hot-dip galvanizing		

(b) Bolt, nut, washer specimens

Figure 10. Results of accelerated corrosion tests performed in steel plates and bolts

cycled automatically to simulate the harsh conditions of a marine environment (Kyushu Electric Power, 2004).

Figure 10 shows the results of the accelerated corrosion tests. After approximately 9 months (6,000 hours) of exposure in the accelerated test, rust was observed in the cross-cut areas of the steel plate test pieces coated with heavy-duty paint coating, where the steel surface was directly exposed to the corrosive agents. This highlights the lack of sacrificial protection of this type of anti-corrosion coating.

Despite its sacrificial protection capability of hot-dip galvanizing coating, rust developed in the steel plates and bolts treated with this method after 1,000 hours. In this type of specimen, the salt spray stages of the accelerated tests that simulate marine environmental conditions, lead to the formation of unstable white rust. This corrosion product is highly hygroscopic, thick under wet conditions, and powdery under dry conditions. Consequently, the passivation layer cannot properly adhere to the steel surface, and thus zinc is rapidly decomposed. This might be the cause of the loss of the anti-corrosion protection properties of the Zn observed in these specimens during the accelerated test.

On the other hand, test specimens coated with Al-Mg plasma arc thermal spray showed a highly stable protection layer during the whole duration of the accelerated test. During that time no rust formation could be observed, even in the cross-cut area of the plate test specimens or the thread of the bolts. This highlights the suitability of the Al-Mg alloy to provide effective corrosion protection under marine conditions. Therefore, and according to the obtained results from the accelerated test, Al-Mg plasma arc thermal spray coating exhibits excellent anti-corrosion protection, which can be six times more durable than the obtained with hot-dip galvanizing under marine environmental conditions.

3.2 *Accelerated corrosion tests in bridge bearing test specimens*

The previously described test was carried out on steel plate and bolt specimens. Due to the complex shape of bridge bearings, it seems necessary to conduct similar tests directly in these devices to evaluate the suitability of the thermal spray anti-corrosion coating on bridge bearings. Thus, scale-down rubber bridge bearing specimens (Fig. 11) treated with different types of thermal spray coatings were subjected to accelerated corrosion tests simulating harsh environmental conditions (The University of the Ryukyus & Kawakin Core-Tech, 2010).

Two tanks and a dry warehouse were used to simulate wet and dry cycles respectively. The test pieces

(a) Test specimens

(b) Dry warehouse

(c) Tanks

Figure 11. Outline of the accelerated corrosion test on bridge bearings

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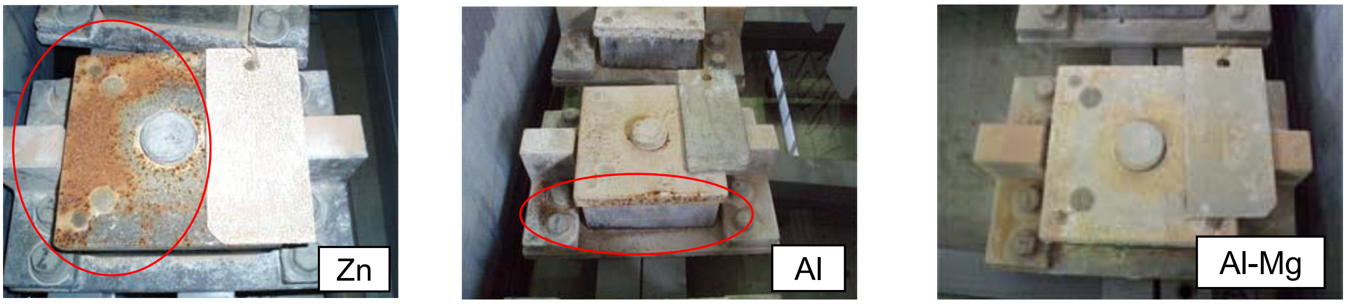

(a) Zn Thermal Spray (b) Al Thermal Spray (c) Al-Mg Thermal Spray

Figure 12. Results of the accelerated corrosion tests on bridge bearings

were alternately placed in both environments for a set amount of time, and the development of corrosion in the test pieces was examined. The specimens were treated with Zn, Al, and Al-Mg thermal spray methods to carry out a comparative analysis.

As shown in Figure 12(a), rust appeared and was rapidly developed in the test specimen coated with Zn thermal spray. The test piece coated with aluminum, a metal with a higher tendency to lose electrons than Zn corroded but to a lower extent, as it can be appreciated in Figure 12(b).

In the specimens threated with Al-Mg plasma arc thermal spray, although some traces of rust could be observed on the surface of the steel members (Fig. 12(c)), it was found out that they were not developed in these test pieces. The rust that appeared in the previous bearings remained inside the tank and was adhered to the bearings treated with Al-Mg Plasma Arc thermal spray, once they were dipped in the tub. Therefore, the test results confirmed the stability and satisfactory performance of Al-Mg thermal spray, when applied to bridge bearings.

3.3 *Long-term outdoor exposure tests*

In some cases using the combination of accelerated test results with long-term outdoor exposure tests could help to understand the life expectancy of coatings in real conditions. This highlights the importance of outdoor tests to complement the information obtained with accelerated testing. On the other hand, coatings systems that perform effectively in one specific environment, might not exhibit the same performance under a different one. Outdoor exposure tests carried out in that particular environment could be useful to address this issue.

Table 2. Test specimens

Code	Material	Specimen type	Anti-corrosion method
SS-1~8	SS400	Steel plate	Al-Mg Plasma Arc Thermal Spray
SM-1~8	Weathering steel (SMA400)	Steel plate	Al-Mg Plasma Arc Thermal Spray
FC-1~8	Cast iron (SCW480N)	Steel plate	Al-Mg Plasma Arc Thermal Spray
HDZ-1~2	SS400	Steel plate	Zn hot-dip galvanizing
ZC-1~2	SS400	Steel plate	ZC-1 Paint
C5-1~2	SS400	Steel plate	C-5 Paint
SS-9~10	SS400	Steel plate	Bare steel plate
Al-Mg~1-4	-	Bolts, nuts, and washers	Al-Mg Plasma Arc Thermal Spray
HDB-1~4	-	Bolts, nuts, and washers	Zn hot-dip galvanizing

Based on this, a series of outdoor exposure tests are being carried out in test specimens treated with Al-Mg Plasma Arc Thermal Spray and other corrosion protection technologies. These tests are being conducted in countries characterized by harsh marine environmental conditions such as Japan, Vietnam, or Myanmar.

The current section focuses on the description of the outdoor exposure tests that were set in the Mawlamyine University of Technology in Myanmar in September 2015. In this ongoing test, steel plate specimens and bolt, washers, and nuts are being tested to evaluate the progression of corrosion in the typical steel components of bridge bearings (Table 2). These specimens are made by a different type of steel to carry out a comparative analysis regarding this aspect. Besides, the influence that a sealing treatment (paint) applied on top of the main coating has in the anti-corrosion performance is also being evaluated. Figure 13 show the appearance of the specimens at the beginning of the test, as well as their code names.

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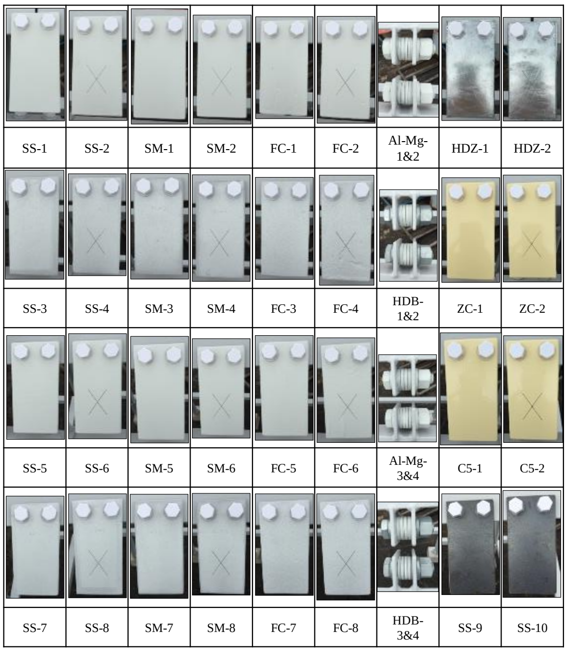


Figure 13. The initial condition of the test specimens

Figure 14 shows the appearance of the testing specimens 3 years after the beginning of the exposure tests. Since the exposure time is relatively short, rust has developed only on the bare steel specimens. In these steel plates, corrosion quickly appeared and led to a weight loss of around 1% in only 3 years. On the other hand, all the specimens coated with Al-Mg plasma arc thermal spray were in a good condition, and no progression of rust was observed even from the cross-cut that was purposely done to the steel plates to test the sacrificial protection capacity of the coating. Subtle marks of rust could be appreciated on the washers treated with Zn hot-dip galvanizing, but not on those treated with Al-Mg plasma arc thermal spray. There was an overall green discoloration, which was particularly noticeable in the test specimens that had been subjected to a sealing treatment applied on top of the coating. However, when the test pieces were cleaned to measure their weight, the deposits were easily peeled off, and the weight of specimens was almost the same as at the beginning of the tests.

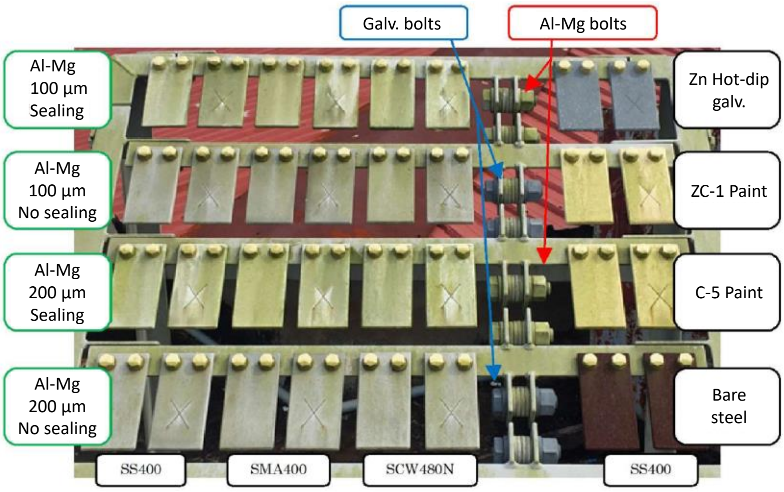


Figure 14. Condition of the test specimens after 3 years

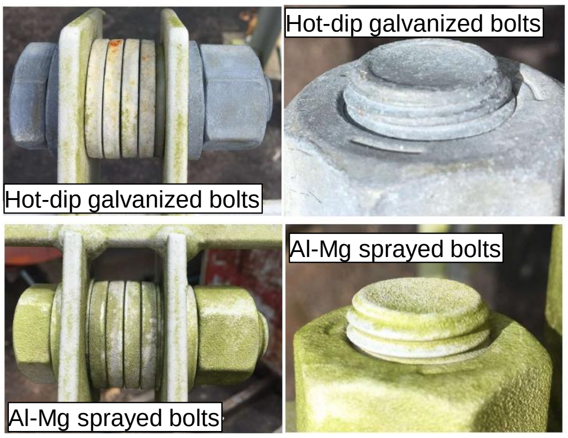


Figure 15. Bolt specimens

4 APPLICATIONS OF AL-MG PLASMA ARC THERMAL SPRAY IN BANGLADESH

Al-Mg Plasma Arc Thermal Spray is a Japanese technology. NEXCO, i.e. the company that manages the Japanese highway network, in its design and construction standards officially adopts the use of this technology for the anti-corrosion protection of bridge bearings.

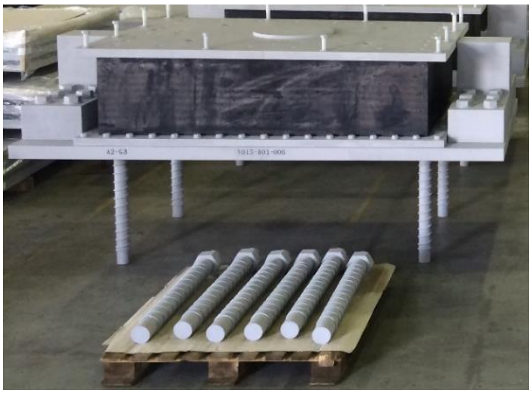
Apart from Japan, this anti-corrosion coating has been applied in important bridge projects in Asia due to its capacity to prevent the appearance of rust in steel bridge members located in harsh environments. In Bangladesh, where marine environmental conditions are common and important concentrations of airborne salinity are observed in large areas of the country, the use of this anti-corrosion coating could bring important benefits such as the increase in the life cycle of bridges and the reduction of the life cycle costs. Aiming to this, critical infrastructure projects in the country such as the Western Bangladesh Bridge Improvement Project, or the 2nd Kanchpur, Meghna, and Gumti Bridge Project have applied this technology in critical bridge members.

The 2nd Kanchpur, Meghna, and Gumti Bridges are located in the most important economic corridor of Bangladesh. They were opened to traffic in 2019 and they are critical to solving the traffic bottleneck of the area, where the traffic capacity was exceeded by 60%. To reduce maintenance costs and ensure the serviceability of these important bridges and their long life cycle, critical bridge members such as bridge bearings (Fig. 16) and expansion joints (Fig. 17) were treated with Al-Mg plasma arc thermal spray.

The bridge bearings of this project (Fig. 16) are rubber seismic isolation bridge bearings known as High Damping Rubber Bearings (Lopez Gimenez et al., 2018). The main body of the bridge bearings is made of a special rubber compound to absorb the energy of the earthquake and prevent structural damage in the event of a strong earthquake. The connection hardware of the bridge bearing, i.e. steel plates, bolts, anchorages, etc., was treated with Al-Mg plasma arc thermal spray.

The expansion joints (Fig. 17) installed on the new bridges of this project are waterproofed steel finger joints. The joint movements that they can accommodate vary on the location, e.g. +/- 215 mm in the central hinge of the 2nd Gumti Bridge. All the steel parts of these expansion joints other than those in contact with the road surface and concrete were protected against corrosion with Al-mg plasma arc thermal spray.

The bridge bearings of this project (Fig. 16) are rubber seismic isolation bridge bearings known as High Damping Rubber Bearings (Lopez Gimenez et al., 2018). The main body of the bridge bearings is made of a special rubber compound with a highly nonlinear response (Amin A.F.M.S. et al., 2014) that absorbs the energy of the earthquake and prevent structural damage in the event of a strong earthquake. The connection hardware of the bridge bearing, i.e. steel plates, bolts, anchorages, etc., was treated with Al-Mg plasma arc thermal spray.



(a) High Damping Rubber Bearings after assembly

(b) High Damping rubber bearings installed in the 2nd Meghna Bridge

Figure 16. Bridge Bearings for the 2nd Meghna Bridge

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(a) Application of plasma arc thermal spray on the steel finger joints (b) After plasma arc thermal spray application
Figure 17. Steel finger expansion joints with Al-Mg plasma arc thermal spray for the 2nd Meghna, Gumti, and Kanchpur bridges

The details of the anti-corrosion system applied in this project are described in Table 3. Before the application of the coating, the surface of the base steel material was treated to remove rust and to create a rough surface (Fig. 18) that will ensure good adhesion between the base steel and the sprayed coating. After finishing the surface preparation, thermal spraying needs to be conducted in a specific time to prevent oxygen or water to affect the metal surface. Al-Mg alloy was sprayed on the steel plates and bolts until obtaining a coating thickness of at least 100 μm. The thickness of the applied coating was confirmed using magnetic methods (Fig. 19). Finally, a sealing treatment was applied to prevent environmental agents, e.g. water or water vapor, to infiltrate through the microscopic voids that could have been formed in the coating layer during the thermal spray process. Special attention needs to be paid to the material used for the sealing treatment to ensure compatibility.

The application of Al-Mg plasma arch thermal spray following strict quality control standards is of critical importance to ensure its durability and to prevent the appearance of corrosion due to an uneven application of the coating, or to the delamination of the sprayed coating due to lack of adhesion (Himeno et al. 2018). The adhesion of the coating to the base material, which had to be at least 4.5MPa for this project, can be confirmed through tensile adhesion tests as the ones shown in Figure 20.

Table 3. Anti-corrosion protection system

Procedure		Requirement
Surface treatment	Rust removal	Sa3 (ISO 8501-1)
	Roughness	Ra > 8 μm Rz > 50 μm
Thermal spray	Metal alloy	Aluminum Magnesium alloy (95%: 5%)
	Sprayed layer thickness	≥ 100 μm
Sealing	Primary sealing	Sealant (mist coat)
	Secondary sealing	Sealant

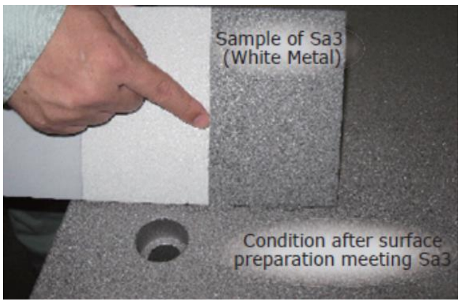

Figure 18. Roughness

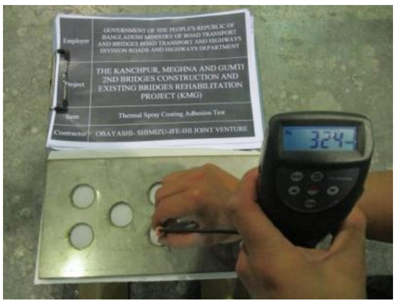

Figure 19. Coating thickness

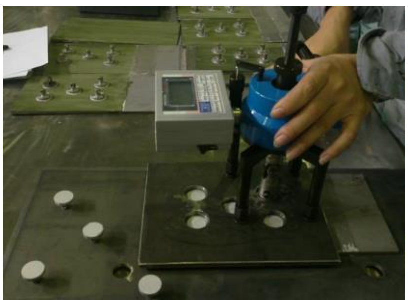

Figure 20. Adhesion test

5 CONCLUSIONS

Corrosion is one of the most determining factors affecting the deterioration of bridges especially in those viaducts located in marine environments, which is something common in Bangladesh. In the current manuscript, different anti-corrosion protection methods for bridge bearings were described and their performances in marine environments were compared through accelerated corrosion and outdoor exposure tests. The following conclusions can be withdrawn from the information described in this paper:

- The results of the accelerated tests highlighted the stable and long term protection capability of Al-Mg plasma arc thermal spray, a Japanese technology widely used in the Japanese highway system.
- This technology has also been applied in the bridge bearings and expansion joints of important bridge projects in Bangladesh to decrease the life cycle cost of the structure.
- The application of Al-Mg Plasma Arc Thermal Spray must be carried out following a strict quality control to ensure the long performance of the coating in harsh environments.

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