Thermal Arc Spray Overview

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Abstract: Usage of protective coating for corrosion protection was on highly demand during the past decade; and thermal spray coating played a major part during that time. In recent years, the thermal arc spray coating becomes a popular coating. Many big players in oil and gas such as PETRONAS, EXXON MOBIL and SHELL in Malaysia tend to use the coating on steel structure as a corrosion protection. Further developments in coating processes, the devices, and raw materials have led to expansion of functional coatings and applications scope from conventional coating to specialized industries. It is widely used because of its ability to withstand high process temperature, offer advantages in efficiency, lower cost and acts as a corrosion protection. Previous research also indicated that the thermal arc spray offers better coating properties compared to other methods of spray. This paper reviews some critical area of thermal spray coating by discussing the process/parameter of thermal arc spray technology and quality control of coating. Coating performance against corrosion, wear and special characteristic of coating are also described. The field application of arc spray technology are demonstrated and reviewed.

Keyword: Thermal spray, aluminium, zinc, coating, wire arc, corrosion

1. Introduction
Corrosion will occur when four things present; anode, cathode, return current path and electrolyte (either water or wet soil). Corrosion will occur when electron flow through electrolyte at different current potential. Potential difference is caused by galvanic action or electrolyte experiences differential aeration or impurities in metal leading to pitting corrosion [1]. There are many consequences of corrosion and failed handling it will result loss of profit (replacement of corroded component), safety issue and damage company reputation. Problem of corrosion on steel structure can be solved by using cathodic protection or proper coating.

Coating technology nowadays has become one of the advanced knowledge and technique in modern country. By manipulating coating material and method, many surface problems could be figured out, and would lead to the saving cost in term of production and maintenance [2]. Since 1900s, thermal spray coating was used, when oxy-acetylene torches were altered for powder and wires application [3]. In 1984 Conoco Hutton TLP used 200 microns of thermal arc spray aluminium with sealer on risers for offshore platform in North Sea and after eight years, the coating on riser was still in good condition [4]. That was the first time application of thermal arc spray used in major offshore
structure. After that, the technology was developed in industry with massive development on material, equipment and application.

Thermal spray process can be classified into two groups: combustion type and electrical type (Figure 1)

![Thermal Spray Process Diagram](image1.png)

Figure 1: Thermal Spray Method [5]

Recently, thermal spray (wire arc) is considered by many industries as the most selected method for corrosion protection due to its economic benefits in term of production and maintenance. A cost comparison was discussed [5] to determine the highest production cost which is the flame spraying process as illustrated in Table 1.

Table 1: Comparison Cost between Flame Spray and Arc Spray Thermal Coating [5]

| Characteristic                        | Flame Spraying | Arc Spraying |
|---------------------------------------|----------------|--------------|
| Liquefaction of zinc, kg/h            | 18             | 35           |
| Energy costs for liquefying zinc, $/h | >28            | >25          |
| Effective use, min/h                  | 40             | 40           |
| Effective use, kg/h                   | 12             | 23           |
| Energy costs, $/m²                     | 2.33           | 0.11         |
| ($kg equals $/m² at 100 µm zinc thickness) |               |              |
| Spraying speed, m³/h for 100 µm zinc | 12             | 23           |
| Wage costs, $/m² at 60 $/h            | 4.17           | 2.17         |
| Total costs, $/m²                    | 6.50           | 2.28         |

2. Process and Variable Parameters of Thermal Arc Spray Technologies
To optimize coating technology usage, the system should consider substrate, coating properties, process, and its application. Those elements are important for development of an economical coated-surface engineering [2].

Thermal arc spray technology involves four main parts namely 1) Spray gun - used to receive the wire and shoot the melted material onto substrate, 2) Air Compressor—to accelerate melted material, 3) Blasting pot – for garnet space when blasting preparation is performed, 4) Thermal Arc Spray Machine – to supply current to wire so that arc can be created [6].

Using thermal arc spray process, two consumable coating materials, in wire form, are fed into spray gun. By creating an arc through receiving the current, it enables the wire to be melted and the melted material will be accelerated by compressed air around 4-6 bar [6]. The acceleration will be towards substrate in high velocity, so that molten spray will be solidified and turned as coating on the substrate [7] (as shown in Figure 2). Because of principle of thermal arc spray function, coating material must be electrically conductive so that arc can be created and the material can be melted. The selection of the coating material depends on customer requirement but generally they require zinc, zinc alloy, aluminium or aluminium alloy. The applied arc spray parameters are listed in Table 2.
Before thermal arc spray coating is performed, substrate surface must be cleaned properly. The surface will be blasted by using compressed-air abrasive blasting; since this method is effective for cleaning of mill-scaled and surface preparation for good adhesion of thermal spray coating [11]. Continues impact on steel surface using abrasive particle in high velocity will ensure removal of mill-scaled; efficiency of the process can be up to 100% [11]. In addition of cleanliness efficiency, substrate surface roughness is an important consideration for proper coating bonding. For thermal arc spray, coarse angular surface profile is needed around 110 microns [12] to provide greater adhesion bonding condition and hinder rust spot formation [11]. Before blasting is applied, the surface of substrate must be checked visually and cleaned from any contamination and excessive rust. The abrasive itself shall be free from oil, grease, moisture or any impurities so that abrasive blasting can be performed in an optimum condition [13]. Normally abrasive which used is Garnet 20/40 (non metallic material). It has proved that it can provide desired surface finish and surface roughness [7]. Non metallic abrasive is more preferable compared to the metallic material; metallic abrasive often result in energy being given off as sparks which may cause surface defect. After blasting process, the following conditions must be confirmed before coating can be applied on the substrate surface: 1) Surface finish must be at minimum SA 2.5 according to ISO 8501-1 as it can be measured by visually inspected; 2) Surface roughness must be between 75 -110 microns , this method requires a Replica Tape method. The replica tape is attached on substrate surface which was blasted and is rubbed with a circular ended tool until circular dark colour appears. Then, the replica tape is removed and measured using a dial gauge[12]; 3) Salt contamination of surface shall not exceed 20 mg/m² using Elcometer 138 based on ISO 8502-6 ; [14] 4) Dust level shall not exceed more than rating 1 using cellophane tape according to ISO 8502-3 [15]. Abrasive blasting shall not be performed if humidity of air is greater than 85% or steel temperature is below 3°C above dew point of surrounding air [7]. Failure to comply with these conditions will affect the quality of surface coating which may lead to surface cracking. It may

Table 2: Characteristic or Arc Spray Process Parameter [1, 8, 9, 10]

| Thermal Source | Electric Arc |
|----------------|-------------|
| Particle temperature | Up to 5000°C |
| Particle velocity | 100 m/s –300 m/s |
| Feed Stock Form | 1.6mm-3.2mm |
| Max. Spray Rate | 16 kg/hr |
| Spray distance | 15cm-25cm |
| Power input | 6-80 kW |
| Air flow rate | Up to 60 m³/h |
require coating team to re-work and re-blast the substrate which will increase the production cost. Figure 3 shows process flow of substrate surface preparation.

![Process flow of surface preparation](image)

- Surface Finish ≥ 2.5 SA
- Surface roughness; 75-110 microns
- Salt contamination ≤ 20 mg/m²
- Dust level at Rating 1

**Figure 3: Process flow of surface preparation**

The coating process will be performed if relative humidity of air is less than 85% [7]. Humidity can be measured using hygrometer. Relationship between air temperature, dew point and relative humidity can be observed in Figure 4.

![Relationship between air temperature, dewpoint and relative humidity](image)

**Figure 4: Relationship between air temperature, dewpoint and relative humidity [16]**

From Figure 4, the Dewpoint temperature, $T_{dp}$ and Relative Humidity, RH can be calculated using Equation 1 and 2. This conversion can be used as long as relative humidity is above 50% [16].

$T_{dp} = T - \frac{100 - RH}{5}$  \hspace{1cm} (1)

$RH = 100 - 5[T - T_{dp}]$ \hspace{1cm} (2)

After blasting is done, at least one layer of coating must be performed on substrate within four hours. If holding period exceeds 4 hours, the surface needs to be cleaned and re-blasted [7, 17].

Skilled sprayer is required to perform the coating work. Normally spraying shall be performed in block pattern of 2ft squares. A sprayer nozzle stand-off distance shall be at maximum of 25 cm since excessive stand-off distance could produce more porous coating due to cooling and deceleration of...
particle projected on substrate surface. Too close stand-off distance may lead to poor coverage on coating thickness due to overheating and producing internal stress inside the coating [5, 18, 19]. So, it is important to find optimum stand-off distance since it will influence adherence of coating bonding [19]. The spraying shall overlap with the previous pass to achieve required thickness i.e. 200 microns. The angle of spray nozzle must be perpendicular to the substrate surface for better quality coating. Overall coating needs to be completed within 8 hours after blast cleaning process. Before subsequent layer of coating is conducted, the coated layer should be inspected visually to check for any contamination [7].

3. Qualification Test and Quality Control
The coating thickness needs to be measured after spraying process. Since melted material of thermal spray turns to solid state once it hits the surface metal, so it is easier to measure coating thickness by using a magnetic or electronic thickness gauge [20]. Bend test is required to check any coating failure. It means if major cracking with lifting appears on substrate surface, the coating is considered failed and correction action must be taken [21]. The bend test requires at least 3 samples (150mm x 50mm x 1.8mm). The sample needs to be bent at 90 degrees so that any defect on the surface can be observed immediately as illustrated in Figure 5 [21]. The other test is called pull-off test, and the test is important to determine adhesion of metal coating onto the substrate with a recommended minimum value is 7.0 Mpa [20]. Dolly is used to pull the coating on plate and epoxy glue acts as adhesion medium between the dolly and thermal spray coating [21]. An example of a test panel with a size of 1 m² was selected for a particular test [21]. Both tests (bend test and pull-off test) must be performed once per 100m².

![Figure 5: Bend Test Determination](image)

A sealer is normally applied on the coating as additional protection after thermal spray is performed and to seal the coating from any porosity [23]. It must be carried out within 24 hours after thermal spraying, but it is better to be done immediately after thermal spraying to reduce any opportunity of moisture or pollutants creation resulting penetration reduction of sealer [24]. Usage of sealer is essential since it can perforate due to low viscosity, so extend the life of substrate and leading to reduction of total area of the exposed metal. Normally sealer is epoxy (up to 120 °C) or silicone (up to 450 °C) [21]. Theoretically, thickness of applied sealer is 38-40 microns. However it may be inspected at 30X power magnification to ensure porosity is filled by sealer [25]. The sealer also provides smooth surface and attractive look. Sealer could be pigmented in colour code and make it easy for coating inspector to differentiate between coating and sealer [4].

As precaution during coating, coating process must be carried in a closed chamber to avoid reaction between sprayed material and component of ambient air [8]. Sprayed particle will oxidize if reaction occurs with the components of ambient air which leads to reduction of corrosion resistance of the coating [8, 26].
4. Material Usage and Characteristic of Thermal Arc Spray

Factors which need to be considered before applying coating are; operating temperature, structural application, environment condition and surface preparation aspects [1].

In thermal spray technology, zinc, aluminium and its alloy are commonly used as coating material. Both materials give excellent corrosion protection in natural environments. Generally, aluminium and its alloy are used as coating material for arc spray while zinc used in flame spray method [4]. The condition can be vice versa depending on client requirement.

Zinc coating provides better corrosion control in most environments as a protective coating. The performance is due to its ability to form dense coating. Zinc density is 7.14 g.cm$^{-3}$; two times higher compared to aluminium (2.70 g.cm$^{-3}$). Zinc also has a low rate of corrosion, which is around 10 to 100 times below than ferrous metal. Because of high sacrificial action of zinc, it becomes a good corrosion prevention for steel [5]. Furthermore, the sacrificial action of zinc produces insoluble corrosion product which will block any empty void in coating (porosity) and prevent the corrosive media to directly contact with substrate [27]. So it will become more resistant to mechanical damage. This action, however will lead to rapid depletion of coating [3]. Naturally, zinc performs in the range of 6 – 12 pH, which is more suitable in alkaline [1].

In industrial environment such as in freshwater, marine environment, under thermal insulation or hot surface area, thermal spray aluminium is the most chose due to its superior performance. American Welding Society has concluded that aluminium as an outstanding material based on the report, Corrosion Test of Flame Sprayed Coated Steel-19 Year [28]. Aluminium has been found as the most effective for steel protection in offshore field [29]. Aluminium performance pH is in the range of 4-11 [1]; it can withstand either in acidic or alkaline condition. Aluminium coating advantages come from its ability to form passive film formation, thus giving a lower corrosion rate [3]. However its sacrificial protection is greatly low due to this reason. Aluminium also offers less weight and cheap price compared to zinc [30]. One of the key factor aluminium is more preferable rather than zinc because of its high temperature resistance, up to 550 °C. It has lower tendency to build up pits and blister due to formation of aluminium oxide when it interacts with air, thus preventing further corrosion [4]. Coating thickness from 100 microns till 250 microns are normally used for corrosion protection [4]. The process temperature is from 200°C – 500 °C. If the process temperature is more than 550 °C (i.e. 550 °C – 900 °C), a heat treatment process is required before the aluminium can be sprayed onto the substrate surface. The heat treatment process is necessary to partially diffuse aluminium into steel surfacet [31]. Minimum thickness of 150 micron is needed to ensure enough inter-diffusion of aluminium with the substrate during heat treatment.

Table 3 shows coating properties comparison between flames spray (FS) and arc spray (AS). It justifies that the arc spray application produces better coating quality for oil and gas industry.

| Characteristics & Properties | FS | AS |
|-----------------------------|----|----|
| Porosity (%)                | 10.97 | 8.85 |
| Oxide (%)                   | 14.64 | 15.01 |
| Hardness (HV$_{100}$)       | 244   | 295   |
| Wear rate (mm$^3$/m)x10$^4$ | 2.51  | 0.83  |

From Table 3, it can be explained that by using the arc spray method, the produced coating have the highest hardness due to low porosity (8.85%) and also high percentage of oxide content (15.01%).
Generally, temperature and velocity will affect porosity level. Increasing particle velocity will result in a dense microstructure [33]. The arc spray method normally produces less porosity coating compared to flame spray technique as shown in Figure 6. The reason is that the particle velocity of flame spray is slightly lower around 180 m/s compared to particle velocity of arc spray 300 m/s [10]. A study [33] has suggested that the chemical composition of coating influences substrate hardness since hard phase is formed during solidification state. The phase is due to the presence of Boron element in the coating material.

5. Coating Performance
Currently, thermal spray coatings are frequently applied on offshore structure such as for valves, risers, and platform above sea level. Thermal arc spray aluminium had been proven of providing corrosion protection over than 30 years by using a thickness of only 200 microns [4]. Aluminium coating and zinc coating both can offer complete protection of corrosion but the usage of coating differs in term of thickness applied. America Welding Society has reported that zinc coating thickness used is at minimum of 300 microns [30]. In offshore platform, mostly coating is used in atmospheric zone and tidal zone [3]. Combination of coating with sealer will enhance lifetime and performance of thermal spray aluminium coating due to reduction of exposed area when porosity is filled by the sealer. Due to ease in predicting coating lifetime, it makes maintenance programme easy. It provides an advantage in terms of cycle cost even though the initial investment cost is high; therefore, it leads to cost saving. As an example in 1978, US Navy launched an evaluation method of testing the corrosion performance of thermal spray using aluminium at 515°C for steam valves. As reported after 8 years, 3000 steam valves had shown no sign of corrosion and the result benefited in term of cost saving by USD 800,000 [1]. This gives advantages in reduction of corrosion allowance. Currently steel structure in splash zone is designed with corrosion allowance from 3 mm until 12 mm [4]. In theory, using thermal arc spray with aluminium offers zero corrosion allowance, and this could save another production cost. Furthermore, thermal arc spray coating can dry immediately after coating is applied, and the steel structure is ready in a short time [29]. The simplicity of process makes the process and quality control easy to handle.

Table 4: Corrosion rate comparison between coated steel (TSA) and uncoated surface [5]

| Temperature (°C) | Corrosion Rate (mm/year) |
|-----------------|--------------------------|
|                 | Thermal Spray Coating    | Bare Steel               |
| 60              | 0.0511                   | 0.1872                   |
| 70              | 0.3025                   | 0.1718                   |
| 80              | 0.0454                   | 0.1099                   |

Table 4 and Figure 7 show comparisons of corrosion rate performance between bare steel (without coating) and structure with thermal spray coating. From the result, thermal arc spray aluminium offers...
a great corrosion protection. Based on America Petroleum Institute (API) 581, the estimated corrosion rate for carbon and alloy steel in marine environment is 0.13 mm/year at 60 °C, so the difference is about -0.0789 mm/year giving a signal that the thermal spray aluminium coating is a better method to reduce corrosion on steel structure [5, 22].

![Graph of corrosion rate versus temperature](image)

**Figure 7: Graph of corrosion rate versus temperature [5]**

### 6. Application of Thermal Spray Coating
Thermal spray coating has been used mostly as a corrosion protection. Other than offshore field, some power plants also applied the coating for their machinery such as boiler tube, gear box, shaft and crankshaft [8]. Examples of products are listed in Table 5.

| Application                  | Material                   | Thermal Spray Process   |
|------------------------------|----------------------------|-------------------------|
| Pipe section for salt water pump | Aluminium                 | Arc Spray               |
| Bridge                       | Zinc, Zinc-Aluminium, Aluminium | Flame or Arc Spray     |
| Chemical & Water Storage Tanks | Aluminium, Zinc | Flame or Arc Spray     |
| Piping in Water Plant        | Aluminium, Zinc-Aluminium | Arc Spray               |
| Cooling Water Pump           | Zinc, Zinc-Aluminium       | Arc Spray               |

Application of thermal spray coating is not only on steel structure, it also can be used on concrete to protect steel rebar (Figure 8). Theoretically, corrosion damage of steel rebar in reinforced concrete structure can be prevented due to high pH (more than 12) electrolyte contained in the pores of concrete [34]. The condition can ensure passivation of the steel surface. However due to unfavourable environment, repair work and presence of carbonation/chloride contamination, [35] corrosion mechanism can occur and in worst case, corrosion on reinforced steel can take up five times the volume of steel (in case concrete is spalling) [34, 36]. In 1997, the thermal arc spray zinc was applied on steel reinforced concrete structure located at Arabian Gulf since the structure experience severe problem. After one and half year, there is no sign of rebar corrosion [34].

In this coating type, bonding between coating and concrete can be maximized by ensuring concrete is dry, concrete shall be pre-heated at least at 50 °C and coating usage should be in multiple pass [1].
installed so that patching of the structure can be carried out. After that fitting of electrical contact for zinc coating is performed and arc spraying of the zinc anode is applied [36].

Figure 8: Arc spray application on concrete at San Luis Pass Bridge, Texas [35].

7. Conclusion
In summary, thermal arc spray coating should be considered to be chose as a coating for an effective corrosion protection medium. Zinc and Aluminium are both suitable in atmospheric condition. However aluminium is the most selected due to its property and advantages offered. Further research need to be conducted to analyze the entire potential of arc spray technology as a corrosion protection so that massive improvement in coating technology can be explored. Extensive research in tidal zone or immersion zone may be carried out for new development in thermal arc spray technology. New material usage may be tested in future research.

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