

Evaluation of the HVOF Thermal Sprayed Coatings

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Anticorrosion protection forms a large sector of the South African industry because of the scale of the mining industry, general maintenance of infrastructure and due to extra demand for anticorrosion protection in the coastal regions. In order to prolong service life and reduce maintenance costs, essentially all steel structures, bridges, wind power plants, electricity pylons, gas cylinders, air conditioners and heat exchangers need to be coated for protection against corrosion of various kinds. Due to size limitations, galvanizing is often not feasible, therefore large structures are usually painted or thermal sprayed with zinc or aluminium depending on the requirements.

Thermal sprayed metal coatings protect the base material longer than paints, and they also can withstand highly corrosive environments. The quality of metal sprayed coatings depends mainly on the thermal and kinetic energy of the spray particles. High particle velocities result in dense coatings with higher bonding strength due to improved metallurgical bond between the substrate and the sprayed material. Traditional metal spraying techniques, which have been used in industry for decades, such as wire flame and twin-wire arc are classified as low velocity processes because the sprayed material is conveyed by compressed air having subsonic velocity. Recently, a new method, namely the high velocity air flame (HVOF) process, was introduced for thermal spraying for anticorrosion protection.

In this paper, zinc-aluminium (Zn-Al) coatings thermal sprayed using the HVOF method are analysed. The thermal sprayed coatings were characterized by the standard techniques, such as light microscopy, scanning electron microscopy with energy-dispersive spectroscopy, X-ray diffraction, salt spray and bond strength tests. The results show that thermal sprayed coatings have a dense structure, a high bonding strength, low presence of oxides and high resistance to corrosion. This is attributed to high flow/particle velocities and relatively low combustion temperatures of HVOF in comparison with other thermal spraying technologies. High spray rate and good coating quality make the HVOF thermal spray method a viable alternative to the conventional wire flame and twin-wire arc methods.

1. Introduction

Surface protection forms a large sector of the modern industry, especially in the area of anticorrosion protection because steel structures, bridges, communication masts, wind power plants etc. require a protection layer. Thermal spraying technologies have been used for decades for corrosion protection. Thermal spraying is a technique of coating where sprayed material (powder or wire) is melted by a certain heat source (such as electric arc, flame, plasma and laser etc.) and molten droplets are accelerated to impinge on the substrate to form coatings. According to Hangong¹, thermal spray industry output worldwide was about 4 US \$ billion in 2002, and the United States share US \$ 2 billion, Japan US \$ 0.8 billion, Germany US \$ 0.25 billion, China US \$ 0.12 billion.

The most common thermal sprayed materials are zinc, aluminium and their alloys. Zn-Al alloys have an excellent corrosion behaviour in combining the special advantages and characteristics of pure zinc and aluminium, reported by He². While zinc in the spraying layer takes care for the active corrosion protection of steel, aluminium provides the passive protection against corrosive industrial or maritime atmosphere. Zn-Al coatings have the advantage of better mechanical characteristics compared with pure zinc coatings. Salt spray tests under simulated maritime atmosphere show that Zn-Al coatings provide better protection against corrosion than layers with pure zinc or aluminium. In addition, layers made with Zn-Al coatings showed excellent corrosion protection resistance in an SO₂ industrial atmosphere.

2. Theoretical Rational

The most common thermal spray techniques are wire flame and twin-wire arc techniques, which are also cost effective and productive methods. However, they typically produce coatings with relatively low bond strength and high porosity. In recent years, high velocity thermal spraying technologies have been developed to address these shortcomings. Xu³ reported on high velocity wire arc spraying (HVAS) to produce well bonded, low porosity coatings to protect steel structures from corrosion in aggressive conditions. A hybrid high velocity oxy flame and twin-wire arc (HVOF-Arc) system, reported by Kosikowski⁴, is a combination of the processes where consumable wire is molten by electric arc and then accelerated by a high velocity jet generated with HVOF.

The drawbacks of these techniques are high costs, which make them economically unviable in comparison with twin-wire arc, and inability to spray on-site. Another high velocity spray process is the cold spray process, in which a preheated compressed gas is accelerated to a supersonic velocity in a converging-diverging De Laval type nozzle, developed by Papyrin⁵. Cold spray provides coatings of very low porosity and low oxygen content, which is regarded as an advantage for several material properties, such as high electrical conductivity and corrosion resistance, as reported by Stoltenhoff⁶. However,

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Makinen⁷ reported that cold sprayed zinc coatings, despite dense microstructures, are not fully effective corrosion barriers due to some through-porosity.

A recently proposed method for thermal spraying of Zn-Al wire utilises the high velocity air flame (HVAF) process, reported elsewhere by the author⁸. In the HVAF thermal gun, wire is melted in the combustion zone (2000 K) and accelerated by supersonic flow in the converging-diverging De Laval nozzle. The high efficiency of the HVAF thermal spraying process can be attributed to the method of injecting the spray material in the high velocity flow. Spray wire enters the combustion zone in such a way that it melts before entering the nozzle and, therefore, molten material gains the most velocity as it is carried in the flow through the highest acceleration zone of the nozzle, which is within approximately the first 50 mm after the nozzle throat as shown in the graph (figure 1), reported in prior work by the author⁹. According to computational fluid dynamics (CFD) modelling, the gas flow reaches approximately 1600 m/s at 70 mm from the nozzle throat and then it decelerates; however, particles reach the highest velocity approximately 50 mm from the nozzle exit, which corresponds with the results reported by Modi¹⁰ and Kwon¹¹. The gain in particle velocity is dependent on the particle size, mass and the loading factor of the multiphase flow. Another example of the efficiency of the thermal spraying process where spraying material is injected before the nozzle is the Cold Spray process, where the powder is injected axially in the flow, and particles reach velocities up to 1200 m/s.

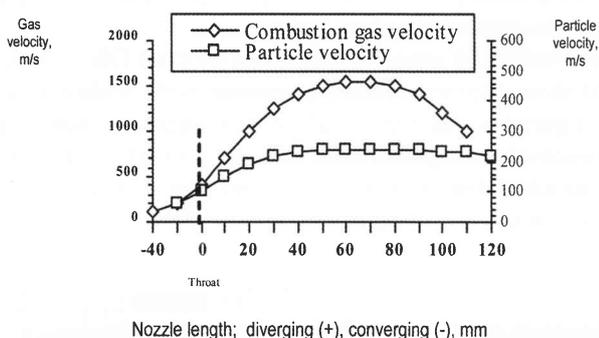


Figure 1: CFD modelled axial gas and particle (200 μm diameter, Al₂O₃) velocities in the nozzle of the HVAF thermal gun⁹

In contrast, in a typical HVOF thermal gun, sprayed material is injected radially into the nozzle after the nozzle throat, therefore the nozzle has to be longer, to allow for particle acceleration. Also, the radial method of powder injection decreases the initial particle velocity, creates turbulence in the flow and causes uneven wear of the nozzle. On the other hand, the axial injection of the spraying material in HVOF results in high oxidation of the material due to high combustion temperature (3300 K) when the material reacts with oxygen in the free stream.

In the twin-wire arc process, two wires are melted by means of an electric arc and then the molten material is sprayed by compressed air delivered through a nozzle, positioned behind the arc. The main drawback of the twin-wire arc process is that the compressed air used for atomising of molten wire material has relatively low velocity, approximately 450 m/s, and spray material does not gain much momentum in the free flow stream, reported by Wilden¹². In order to increase the flow velocity, the de Laval nozzle instead of the straight bore nozzle was suggested by Wilden¹². However, it only increases the particle velocity

by approximately 20 %. The other drawback of twin-wire arc process is the high presence of oxides in coatings due to oxidation of a completely molten material by the air stream jet, which reduces the coating quality and bond strength.

In HVAF thermal spraying, the sprayed material is present in two states, completely or semi molten, when it breaks off the consumable wire and is carried out by the flow through the nozzle, which atomizes and accelerates particles before depositing them onto the substrate. Oxidation of the sprayed material would be minimal as there is little oxygen left in the combustion chamber and the flame temperature is lower than with HVOF, hence reducing the possibility of oxidation in the free stream. Correct spray parameters should minimise or completely eliminate material evaporation during thermal spraying provided the sprayed material is fed fast enough into the combustion zone.

In the experiments, Zn-Al wire was thermal sprayed with the HVAF system on steel substrates (EN3B): flat substrates (100 mm × 20 mm × 5 mm) for cross sectional related properties and cylindrical ($\phi = 25.4 \text{ mm} \times h = 50 \text{ mm}$) for the adhesion test. Following that, the coatings' properties were obtained and analysed in order to compare them with coatings obtained by conventional methods as reported in literature.

3. Experimental Setup and Procedure

The schematic diagram of the thermal spraying experimental set-up is shown in figure 2. The equipment used in the experiments was the HVAF thermal spray gun developed specifically for Zn-Al wire spraying. The thermal gun operates on paraffin Jet A-1 and compressed air. Fuel is supplied to the thermal gun by a fuel pump. The compressed air requirements are similar to grit blasting, however, there is no need to dry compressed air, hence a basic water trap is sufficient. The required fuel/air ratio for the combustion process is set on the controller as specified. The thermal gun operating parameters are shown in table 1.

For spraying material, Zn-Al wire made by Praxair was used, having properties shown in table 2. Wire is fed into the thermal gun by an electric wire feeder used for welding. The feeding mechanism operates on a "push" type principle, which allows a distance between the wire feeder and the thermal gun of up to 5 m.

Prior to thermal spraying, samples were grit blasted, which is done to improve mechanical bonding, surface activation and cleaning. Steel plate samples were thermal sprayed for the microstructure analysis and to determine the deposition efficiency. The cylindrical steel samples were coated with a 150-200 μm layer for the adhesion test according to DIN EN 582 and the salt spray tests according to ISO 9227. The deposition efficiency of the thermal spray process was determined according to ISO 17836.

Air flow rate (m ³ /h)	Air pressure (kPa)	Fuel flow rate (l/h)	Fuel pressure (kPa)	Pressure in combustion chamber (kPa)
180	550	18	550	500 - 510

Table 1: Parameters of the HVAF thermal spraying gun

The thermal spraying process was performed manually with consecutive vertical and horizontal passes. Table 3 shows the process and coating parameters of thermal spray of Zn-Al wire

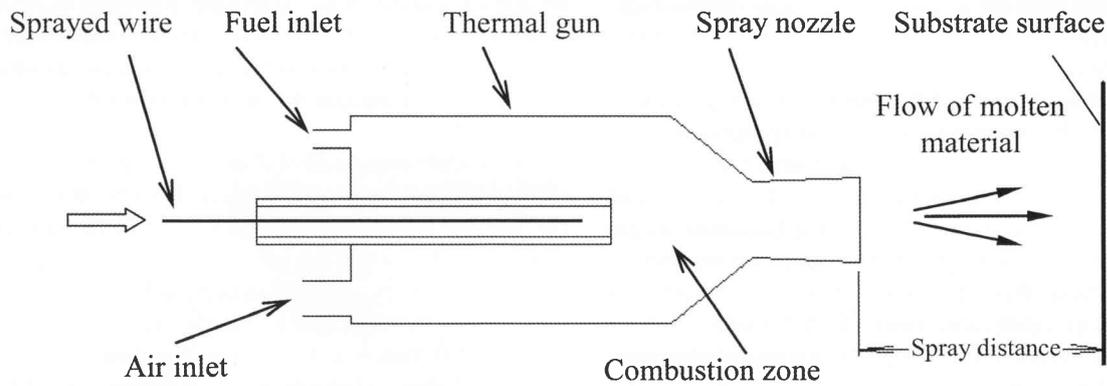


Figure 2: Schematic of the experimental set-up

Composition (%)		Diameter (mm)	Melting temperature (°C)	Specific weight (g/cm ³)	Temperature of potential inversion of metals (°C)
Zn	Al				
85	15	2	382-450	5.73	315

Table 2: Characteristics of the spray wire

using HVOF. The spraying distance was set to 300 mm. No cooling of the substrate was employed during or after thermal spraying.

Spraying Parameter	Value
Wire feed rate (m/min)	5
Traverse speed (m/min)	0.5
Thickness per pass (µm)	80-100
Spray rate (g/min)	100
Deposition efficiency (%)	70

Table 3: Process and coating parameters of thermal spray of Zn-Al wire using HVOF

4. Results and Discussion

Coating structure was analysed with optical metallography using an Olympus PMG3 optical microscope. Figure 3 shows the cross-sectional morphologies of the HVOF sprayed coating having a 150-200 µm thickness. The coating structure is homogeneous, nonporous and dense without visible lamellae, which is typical for other methods, indicating that complete melting of sprayed layers takes place during spraying since a number of passes are usually required to produce coatings. A rough interface between the coat-

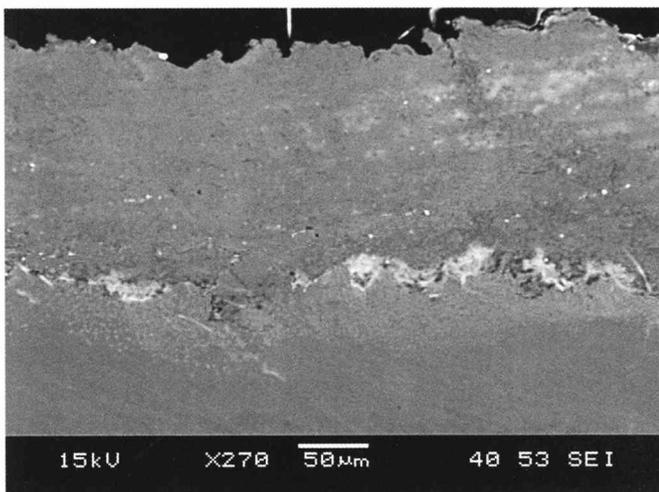


Figure 3: Micrograph of the polished cross-section of coating with Zn/85 Al/15

ing and the substrate is due to grit blasting, which possibly caused some surface contamination with visible grit media embedded in the substrate surface profile. The indication of through-porosity was also obtained by testing corrosion resistance of the coatings.

The characterization of microstructure of the coatings was examined through scanning electron microscopy (SEM) coupled with energy dispersion spectroscopy (EDS) using a Philips XL30 electron microscope to determine the coating purity. The cross-sections were prepared metallographically after embedding the samples in epoxy resin. The sections were coated with thin gold films prior to the SEM observations. Figure 4 shows the cross-sectional SEM image of the Zn-Al coating. Although the microstructure revealed micro pores, they are not critical for corrosion resistance because of their small sizes and that they do not penetrate the coating layer.

The results of phase identification by the EDS analysis in SEM shows the same phase composition as the feedstock material (figure 5). The coating is free from oxides as shown. The presence of small quantities of carbon (less than 3 %) and gold can be attributed to the moulding and coating materials used for the sample preparation.

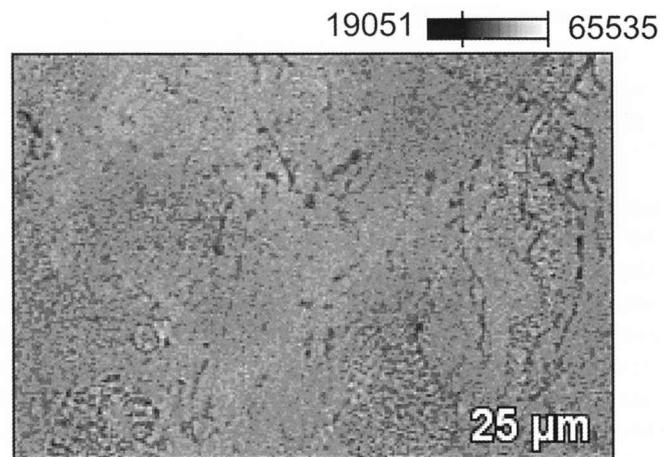


Figure 4: SEM image of the cross section of Zn/85 Al/15 coating

To determine the crystallography of phases present in the coatings, X-ray diffraction (XRD) was carried out on a Bruker AXS X-ray diffractometer D8 with CuKα radiation operating at 40 KV and 20 mA. The results of XRD analyses of the feedstock material and the Zn-Al coating presented in figure 6 shows no phase changes indicating that the crystallinity of Zn-Al does not change in the thermal spraying process.

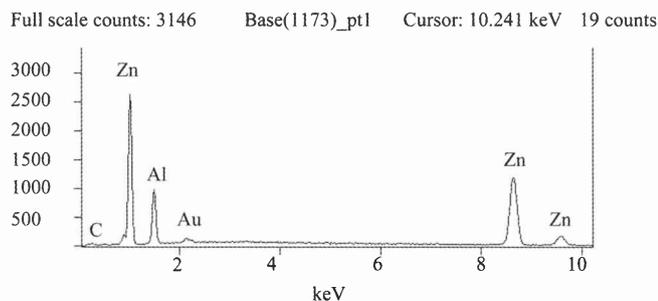


Figure 5: Energy dispersion analysis of Zn/85 Al/15 coating

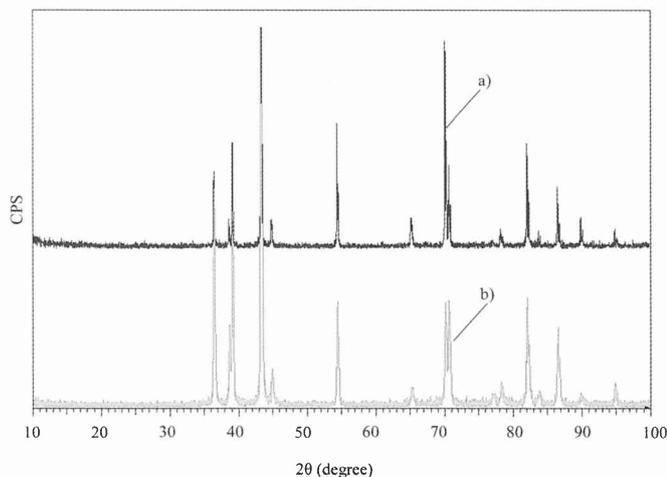


Figure 6: X-Ray diffraction patterns of: a) Zn-Al feedstock material, b) Zn-Al coating

Adhesive tensile strength was measured with a pull test (Instron 1185 mechanical testing machine) according to the DIN EN 582 as an average of six carbon steel samples, grit blasted before thermal spraying. The specimens were bonded with cylindrical counterparts with the adhesive “Ultrabond 100”, with a specified strength of over 100 MPa on steel. The measured bond strength ranged from 13.8 MPa to 18.2 MPa, with the average of 16.5 MPa. In comparison, a typical bond strength with twin-wire arc is 9 MPa, reported by Varacalle¹³, 14.2 MPa is obtained with a hybrid HVOF-Arc system for Zn-Al-Mg coating reported by Xu³, and 13 MPa is obtained for Zn coating sprayed by cold spray reported by Makinen⁷.

For characterization of the corrosion behaviour, the perfor-

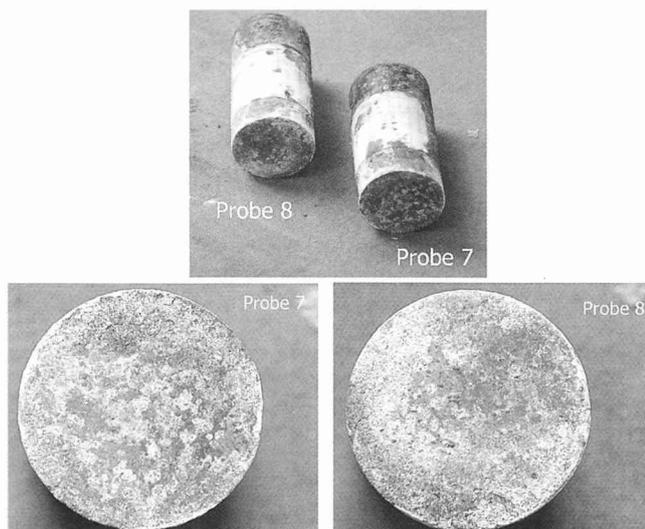


Figure 7: Overview of the samples tested in salt spray test

mance of the coated specimens was evaluated by a salt spray (fog) test. Eight specimens having 150-200 μm thick coatings were tested for 14 days according to ISO 9227. Every 24 hours (24 hours = 1 cycle) the samples were removed from the test chamber and optically examined. The results of optical observation of the coatings show no signs of corrosion, only white rust on the coated surfaces after 14 days of tests, indicating that the coatings are free of pores even without a layer of sealer, which would be applied as a final coat (figure 7).

5. Conclusion

The HVAF process can be efficiently used for thermal spraying of Zn-Al wire to produce coatings of high quality as shown in the microstructure analysis. The spray rate of 9 kg/h is achieved using a 2 mm diameter Zn/85 Al/15 wire without compromising coating surface finish. Bigger wire diameters could be used to increase spray rates. A typical coating thickness of 150-200 μm with the spray pattern of 50 mm in diameter is obtained in two passes of the thermal gun with a 0.5 m/s traverse speed, while thicker coatings can be easily obtained by adding layers of material. A long spray distance of 300-400 mm prevents overheating of the substrate and therefore cooling is not required.

The coated samples were examined using optical microscopy, SEM, X-ray diffraction, bond strength and salt spray testing. The analyses showed that HVAF sprayed coatings consist of similar phases to the feedstock wires without detectable oxides present. This can be attributed to lower combustion temperatures (less than 2000 K) of HVAF in comparison with other thermal spray processes, such as plasma and HVOF. The coatings obtained have low porosity and possess very good adhesion to steel substrates, with an adhesion tensile strength of 16.5 MPa, which is considerably higher than for coatings typically obtained with wire-arc systems. The tests also indicated that the coatings have good corrosion resistance, which can be attributed to a dense and homogeneous layer morphology as a result of high particle velocities obtained in the HVAF spray jet. It was also observed that large thickness coatings can be easily obtained with HVAF thermal spraying.

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