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DEVELOPMENT OF THE MULTIPURPOSE THERMAL SPRAYING SYSTEM

PhD. Prof. Igor A. Gorlach[1]
PhD. Assoc. Prof. Daniela Ghelase[2]
1.School of Engineering, Nelson Mandela Metropolitan University, South Africa
2."Dunarea de Jos" University of Galati, Romania

ABSTRACT

Many components and structures require protection against corrosion, oxidization, excessive heat and wear. This is achieved by applying various types of coatings on the component base material, hence providing the necessary protection and improving performance of aircraft systems. For example, the application of the thermal barrier coatings (TBC), in the last decade, on the aircraft turbine blades, vanes and combustors brought up a substantial increase in the aircraft engine efficiency and reduction of NO_x. Coatings are produced using various deposition techniques of which, thermal spraying technologies play a significant role.
This paper presents a thermal spraying system developed on the principles of the High Velocity Air Flame (HVAF) process, as well as the results of thermal spraying of various materials, such as Zn-Al alloys, 316L stainless steel and WC-Co carbide powders. The anticorrosion Zn-Al coatings sprayed with the HVAF system showed considerably higher bond strength than coatings obtained by the conventional methods, indicating the advantage of this method in areas where the adhesion strength is critically important. The highly dense structure of the coating obtained with HVAF eliminates a need for a top paint coat for anticorrosion protection, which is typically applied on metal sprayed coatings to extend service life.
The developed HVAF system produced high quality coatings of 316L stainless steel and WC-Co carbides as shown by the coating analysis and test results. In addition, the developed HVAF thermal spray system provides competitive spray rates, high deposition efficiency, and the process can be easily performed on-site. Lower operating costs of the HVAF process, in comparison with other high velocity systems, make this technology viable for anticorrosion protection and wear resistance.

KEYWORDS: thermal spraying, HVAF

1. Introduction

At the beginning of the last century, metallization or thermal spraying was invented as a technique for depositing of materials on substrates. In thermal spraying, coating material is molten by a heat source and sprayed onto the substrate using the kinetic energy of the flow to achieve adhesion bonding between the coating material and the substrate surface. Since then, many technologies and processes of thermal spraying have been developed and used for anticorrosion protection, wear resistance and for obtaining various tribological characteristics. Traditional thermal spraying technologies include Wire Flame, Wire Arc, Plasma spraying and High Velocity Oxy Flame (HVOF) processes. In thermal spraying, the coating material is partially or fully melted and deposited on the substrate by means of the gas jet. Materials with a high melting point, such as ceramics and Ti alloys are deposited with the Plasma spray process, which is considered as a low velocity process and as a result the coating porosity can be high. On the other hand, the HVOF process generates the supersonic gas jet and usually highly dense coatings are obtained with it. However, the combustion temperature in the HVOF process (3000K) is not sufficient to melt ceramics in the spray jet. Hence, HVOF is mainly used for thermal spraying

of Cr, WC carbides, yet the process temperature is too high for carbides causing oxidization and decomposition of the sprayed material and, therefore, reducing the coating quality.

The other, less common, high velocity method is the High Velocity Air Flame (HVAF) process, which utilises compressed air for combustion and generates the temperature considerably lower than HVOF.

In this research, the HVAF thermal gun running on liquid fuel and compressed air is used for thermal spraying of Zn-Al wire, 316L stainless steel and WC-Co powders. In the HVAF thermal gun [3], the consumable coating material is fully or partially melted in the combustion zone (2000K), accelerated by the supersonic flow in the converging-diverging de Laval nozzle and deposited onto the substrate, [4].

2. The High Velocity Air Flame System for Thermal Spraying

Figure 1 shows the thermal gun diagram for spraying of powder or wires, which are axially injected into the combustion zone.

Liquid fuel and compressed air mix and combust in the combustion chamber, followed by the gas expansion in the de Laval nozzle. The resultant two-component high velocity jet produces a spray coating deposited onto a substrate.

The main challenge in designing a HVAF system for spraying was to achieve an effective combustion process generating heat for softening or melting the spray material in such a way that it would provide an efficient spraying process with minimum losses due to evaporation or rebound of particles.

The parameters determining the efficiency of the thermal spray process include the combustion process parameters, the wire/powder entry position into the combustion zone, the feeding rate and the nozzle geometry.

Coating quality and the productivity of the spraying process among other are determined by empirical parameters, such as spraying distance, spray pattern, the linear speed of the gun, and coating thickness of a single pass.

The HVAF air/fuel mixture ratio of 30:1 was determined experimentally and modelled using Computational Fluid Dynamic (CFD) software Star-CD [4].

As it can be seen in Figure 2, the CFD simulated temperature distribution inside the thermal spray gun shows the highest temperature of 2059K, which is well in agreement with the data reported in [5, 6]. Although the air/fuel ratio seems to be high and the hot gas flow is diluted with air, it is in accordance with temperatures that the air-cooled chamber housings and the nozzle can withstand, for a prolonged period of time.

The entry position of spray material into the combustion zone influences a number of spraying parameters and ultimately the spraying rate. Consumable wire is fed axially into the combustion chamber through the internal guide (Figure 1).

A wire feeding mechanism can be a "push" or "pull" type depending on the distance between the wire roll and the thermal gun. In the case of spraying powders, a powder feeder is used with compressed air as a carrier gas system.

The gas/powder mixture is also supplied axially into the combustion zone through the internal guide with an injector at the end. The carrier gas feeding to the powder feeder must be moisture free and, therefore, an air dryer is required. The HVAF thermal spray operating parameters are shown in Table 1.

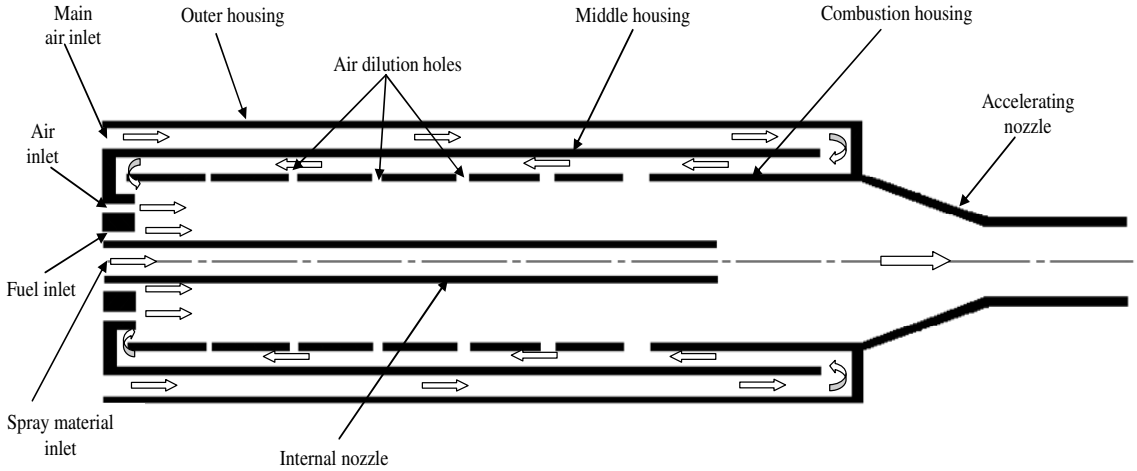


Figure 1. Diagram of the thermal spraying gun

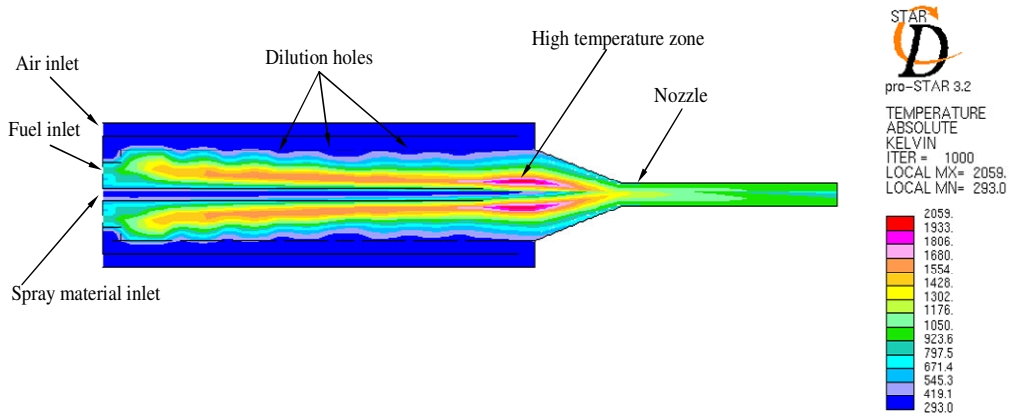


Figure 2. CFD modelled temperature distribution inside the thermal spray gun

Table 1. Parameters of the HVAF thermal spraying gun

Air for combustion		Fuel flow rate (l/min)	Fuel pressure (kPa)	Pressure in combustion chamber (kPa)
Air flow rate (m^3/min)	Air pressure (kPa)			
2.5-3	580-640	0.15-0.20	700	560-620

3. Experimental setup and procedure

Zn-15Al wire, 316L stainless steel and WC-17Co powders were thermally sprayed on metal substrates using the HVAF system. Following that, the coatings' properties were obtained and analysed in order to compare them with coatings obtained by conventional methods as reported in literature. Prior to thermal spraying, samples were grit blasted, which is done to improve mechanical bonding, surface activation and cleaning. Steel plate samples were thermally sprayed for the microstructure analysis and to determine the deposition efficiency.

3.1 Thermal Spraying of Zn-Al

The 2 mm Zn-Al wire (TAFALOY 02A Zn 85-Al) with the melting point of 440 ^{0}C was sprayed using the process parameters shown in Table 2. The example of the sprayed component is shown in Figure 3.

Table 2. Parameters of thermal spraying of Zn-Al wire with HVAF

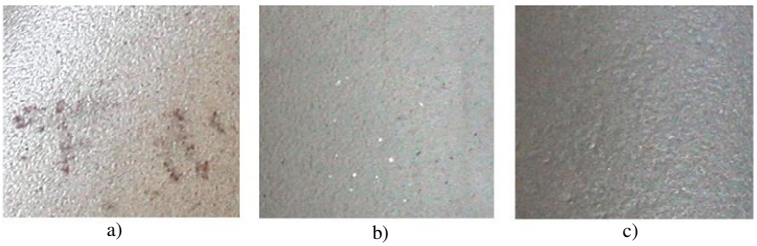
Spraying Parameter	**Value**
Wire feed rate (m/min)	6
Traverse speed (m/min)	0.5
Thickness per pass (μm)	20-50
Spray rate (g/min)	80
Deposition efficiency, appr (%)	70

3.2 Thermal Spraying of 316L stainless steel and WC-17Co powders

316L stainless steel (TAFA 1236F) and WC-17Co (TAFA 1343VM) powders were sprayed on the samples made of low carbon steel and stainless steel with the spraying parameters shown in Table 3. The sprayed samples shown in Figure 4 demonstrate dense coatings especially after machining of the top layer.

Table 3. Parameters of thermal spraying of 316L stainless steel and WC-17Co powders with HVAF

Spraying Parameter	**316L**	**WC-17Co**
Traverse speed (m/min)	0.5	0.5
Thickness per pass (μm)	20-40	10-20
Spray rate (g/min)	150	70
Spray distance (mm)	300	250
Deposition efficiency approx. (%)	70	45



a) b) c)

Figure 3. Picture of the sample; a) grit blasted, b) with Zn-Al coating and c) with sealer coating on top of Zn-Al coating (duplex coating)

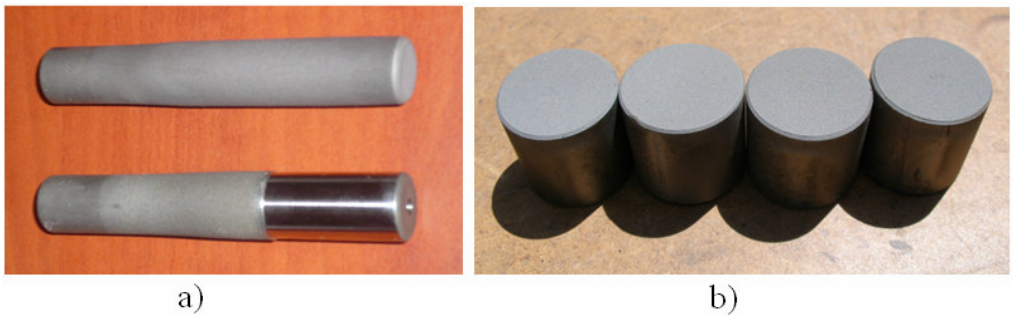


Figure 4. Pictures of the samples coated with a) 316L stainless steel as coated and machined, b) WC-Co coatings

3.3 Analysis and Characterisation of the Coatings

The samples were coated with a 150-200 µm layer of Zn-Al for the adhesion test according to DIN EN 582 and the salt spray tests according carried out at the Institut für Korrosionschhutz Dresden GmbH.

The specimens were tested for 240 hours according to DIN EN ISO 9227-NSS. Every 24 hours (24 hours = 1 cycle) the samples were removed from the test chamber and optically examined.

The deposition efficiency of the thermal spray process was determined according to ISO 17836.

Coating structure was analysed with optical metallography using an Olympus PMG3 optical microscope.

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.

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 40KV and 20mA.

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.

4. Results and Discussion

4.1 Zn-Al coatings

Figure 5 shows the cross-sectional (SEM) image of the Zn85-Al coating with the Energy Dispersion Spectroscopy (EDS).

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.

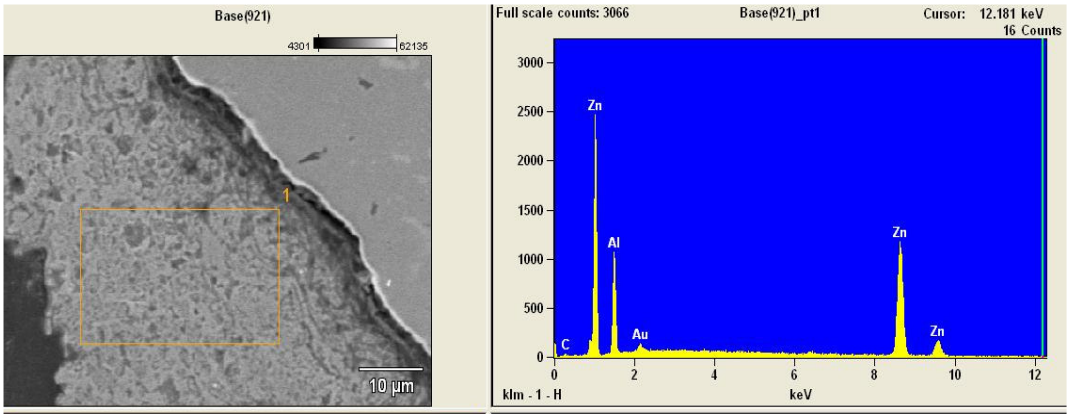


Figure 5. SEM image and the EDS of the cross section of the Zn 85-Al coating

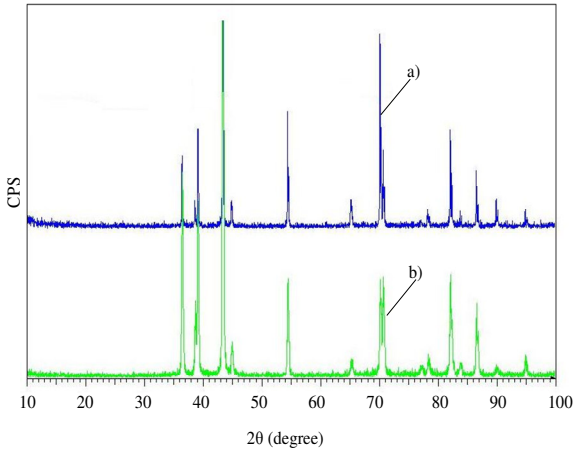


Figure 6. X-Ray diffraction patterns of: a) Zn-Al feedstock material, b) Zn-Al coating

The results of phase identification by EDS analysis showed: 80 wt% Zn, 16.6 wt% Al and the rest C, which is close to the phase composition of the feedstock material. This was also confirmed by the X-ray diffraction (XRD) analysis (Figure 6).

Adhesive tensile strength of the Zn85-Al coating was measured with a pull test.

The measured bond strengths were 12-18 MPa. In comparison, a typical bond strength with Twin-Wire Arc is 9 MPa, [7], 14 MPa is obtained with a hybrid HVOF-Arc system for Zn-Al-Mg coating reported in [8], and 13 MPa is obtained for Zn coating sprayed by Cold Spray, [9].

For characterization of the corrosion behavior, the performance of the coated specimens was evaluated by a salt spray (fog) test.

The results of optical observation of the specimens' coatings showed no signs of corrosion on the coated surfaces after 240 hours of tests, indicating that the coatings are free of pores even without a layer of sealer, which would be applied as a final coat.

4.2 Stainless steel coatings

The composition of 316L stainless steel powder (TAFA 1236F) is as follows: 12% Ni, 17% Cr, 2.5% Mo and the balance is iron.

The composition of the coating is similar to the powder as represented in Figure 7 showing the cross-sectional SEM image of the coating with the EDS analysis.

The coatings appear to be free from oxides.

The presence of small quantities of carbon can be attributed to the moulding and coating materials used for the sample preparation.

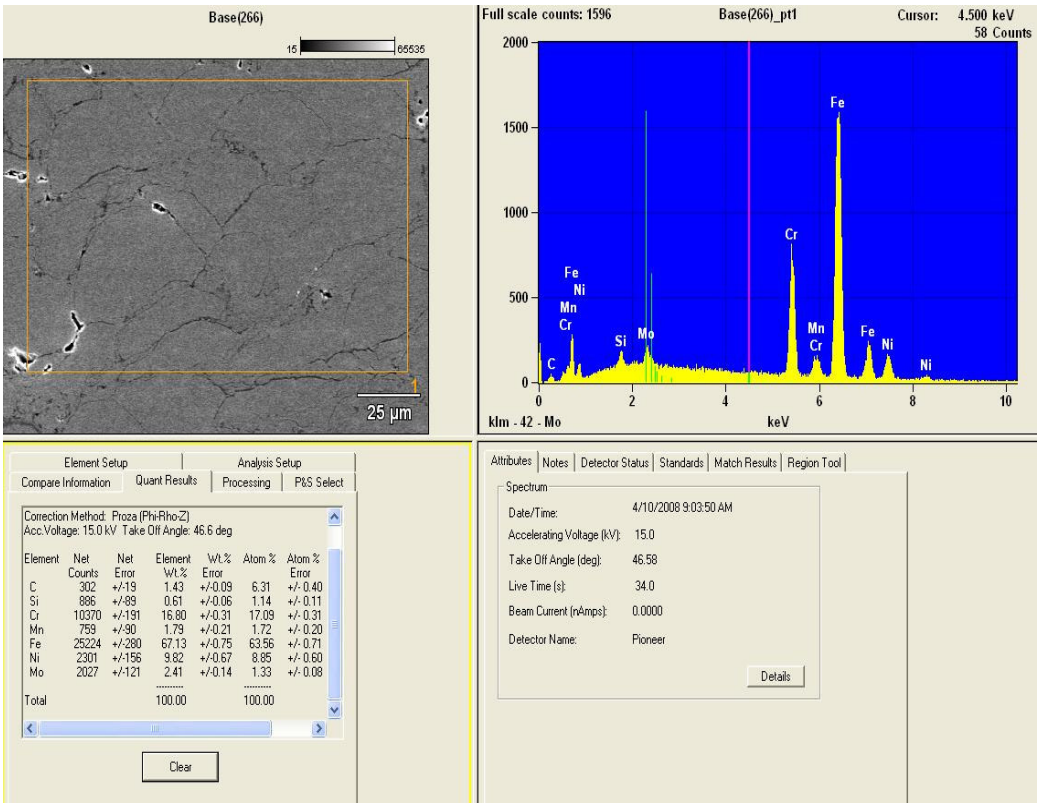


Figure 7. SEM image and the EDS of the cross section of the stainless steel coating

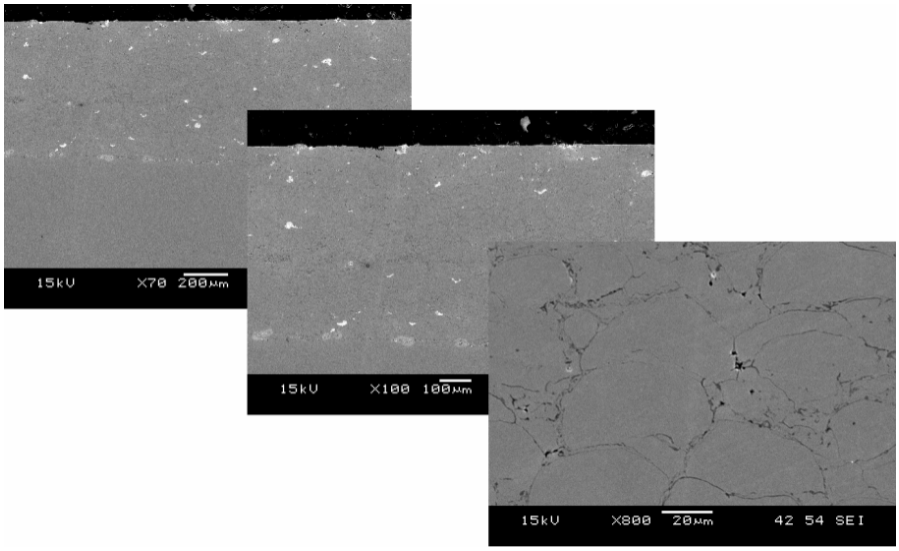


Figure 8. Micrographs of the cross section of the stainless steel coating

The 316L stainless steel powder was thermally sprayed on a 316L stainless steel plate. Similarity of the coating and substrate materials are seen on the micrograph (Figure. 8).

The coating is dense and homogeneous indicating the complete melting of the spray elements.

The coating hardness was HB360 for a 172.5 kg load and a 2.5 mm ball, which is almost twice higher than the stainless steel plate.

This is attributed to the hardening effect of steel from the heat of the thermal spray jet.

4.3 WC-Co coatings

The thermal sprayed WC-Co coating is dense and homogeneous as it can be seen with a X200 magnification shown in Figure 9. For a higher magnification, the analysis reveals that the WC particles did not melt or deformed, while the Co matrix appears to be softened due to melting or on the impact, which is typical for thermal sprayed carbide coatings obtained during high velocity processes. The absence of oxides in the coating, confirmed by the EDS analysis, indicates that the thermal jet temperature of the HVAF process is not excessive (Figure 10). However, the main advantage of the HVAF spraying of WC-CO, according to the X-ray diffraction analysis (Figure 10), is that there is no detectable decomposition of the WC phase into W_2C that would typically lead to poor coating performance in wear, which is the major drawback of HVOF and plasma spraying processes, [10].

The compositions of WC-17Co powder (TAFA 1343VM) and the coating can be compared in Figure 11, showing the cross-sectional SEM image of the coating with the EDS analysis with the composition of 82 wt% WC, 15.6 wt% Al and 2.37 wt% C. The coating is free from oxides and impurities and highly dense. The average micro Vickers hardness of the sprayed WC-17Co coatings by HVAF was 960 HV_{300}, which is similar to HVOF. It was observed that the hardness increased with the decrease of the spray distance.

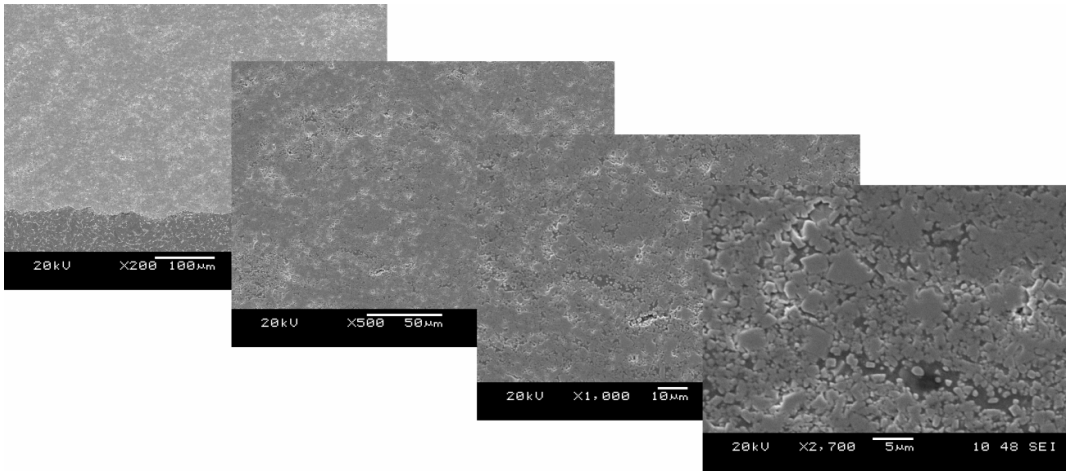


Figure 9. Micrographs of the cross section of the WC-Co coating

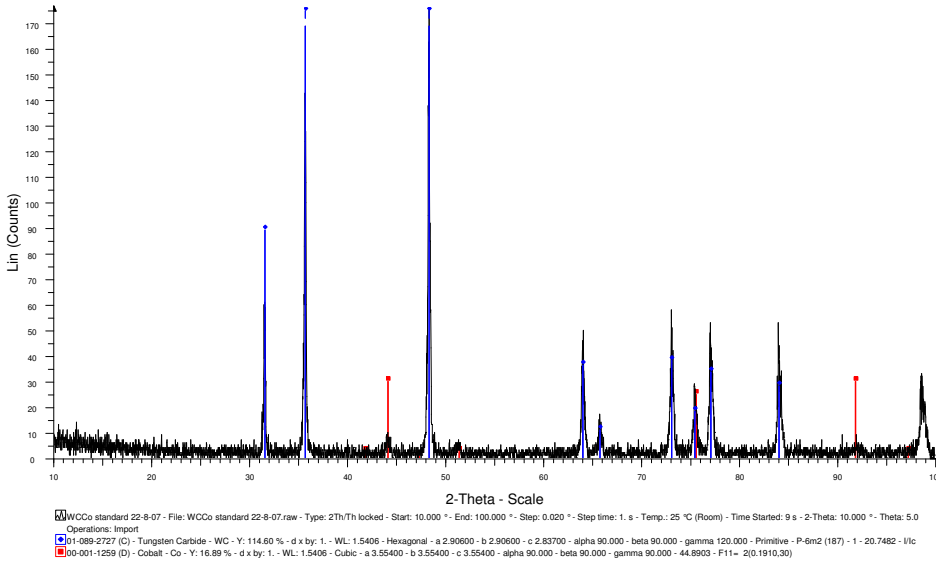


Figure 10. X-Ray diffraction patterns of the WC-17Co coating and feedstock material

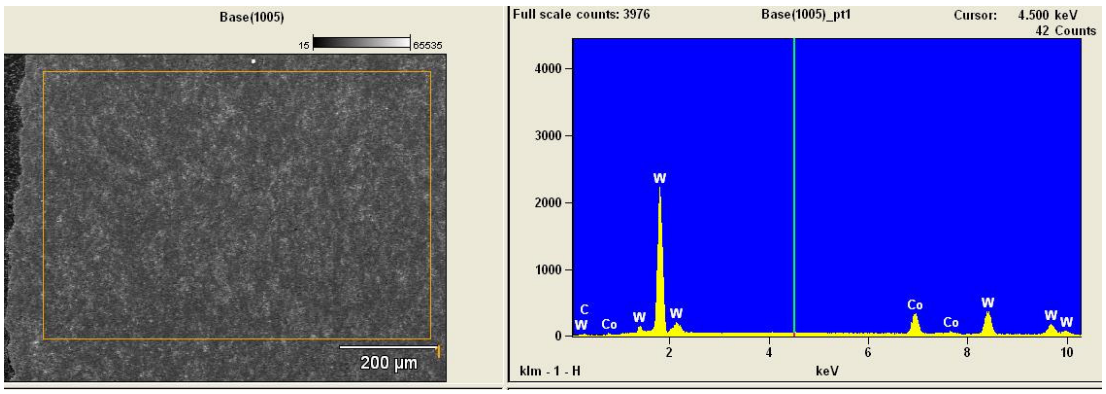


Figure 11. SEM image and the EDS of the cross section of the WC-17Co coating

5. Conclusion

- The HVAF process can be efficiently used for thermal spraying of Zn-Al wire, nickel alloys and WC-Co powders to produce coatings of high quality as shown in the microstructure analysis.

- In thermal spraying of Zn-Al wire, the spray rate of 9 kg/h was achieved using a 2 mm diameter wire without compromising coating surface finish. 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 300-350 mm prevents overheating of the substrate and therefore cooling is not required. The coatings obtained have less than 3% porosity and possess high adhesion to steel substrates, with an average 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 Zn-Al 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.

- Stainless steel coatings were obtained by thermal spraying of 316L powders (TAFA 1236F). The coating showed high quality with the hardness, which is considerably higher than for conventional stainless steel. This is attributed to a high velocity of the jet and particles, and due to the heat of the combustion process. Thermal sprayed stainless steel coating can be an economically viable solution in many industrial applications, as a replacement of the complete stainless steel components with cheaper base materials.

- The WC-17Co powder (TAFA 1343VM) was thermal sprayed using HVAF producing highly dense, homogeneous and hard coatings, which are superior to coatings obtained by HVOF. In addition, the HVAF process is considerably cheaper than HVAF as it runs on compressed air and not oxygen, no cooling is required and the generated temperatures are lower reducing a possibility of the decomposition of WC-Co.

- The coated samples were also examined using optical microscopy, SEM, X-ray diffraction, bond strength and salt spray testing (Zn-Al coatings). The analyses showed that HVAF sprayed coatings consist of similar phases to the feedstock materials without detectable oxides or impurities present. This can be attributed to the characteristics of the combustion process of the developed HVAF system.

- HVAF thermal spraying is an economically viable alternative to costly HVOF. And HVAF can be applied in many fields of industry, including in the aerospace industry for anticorrosion protection, heat and wear resistance in the main.

Acknowledgements

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