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Development of a semi automated dual feed unit to produce FGM coatings using the HVOF thermal spray process

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Abstract

The application of functionally graded materials (FGMs) is quite difficult, but thermal spray processes like Plasma spray have demonstrated their unique potential in producing graded deposits, where researchers have used twin powder feed systems to mix different proportions of powders. FGMs vary in composition and/or microstructure from one boundary (substrate) to another (top service surface), and innovative characteristics result from the gradient from metals to ceramics or non-metallic to metals. The present study investigates an innovative modification of a high velocity oxy-fuel (HVOF) thermal spray process to produce functionally graded thick coatings. In order to deposit thick coatings, certain problems have to be overcome. Graded coatings enable gradual variation of the coating composition and/or microstructure, which offers the possibility of reducing residual stress build-up with in coatings. In order to spray such a coating, modification to a commercial powder feed hopper was required to enable it to deposit two powders simultaneously which allows deposition of different layers of coating with changing chemical compositions, without interruption to the spraying process. Various concepts for this modification were identified and one design was selected, having been validated through use of a process model, developed using ANSYS Flotran finite element analysis. In the current research the mixing of different proportions of powders were controlled by a computer using LabVIEW software and hardware, which allowed the control and repeatability of the microstructure when producing functionally graded coatings.

***Keywords**: Thermal Spray, Functional Graded Coating, Dual Feed Unit, HVOF*

1. Introduction

Thermal spraying can be described as a coating produced by a process in which molten or semi molten particles are applied by impact onto a substrate. Functionally graded materials (FGMs) are a growing application area with significant promise for the future production of; (a) improved materials and devices for use in applications subjected to large thermal gradients, (b) lower- cost clad materials for combinations of corrosion and strength or wear resistance, and (c) improved electronic material structures for batteries, fuel cells, and thermoelectric energy conversion devices and (d) biomedical implant devices for enhanced bone- tissue attachment. The most immediate application for FGMs is as thermal barrier coatings (TBCs), where large thermal stresses can be minimized. Component lifetimes are improved by tailoring the coefficients of thermal expansion, thermal conductivity, and oxidation resistance.

To date the plasma spray process has produce superior coatings for numerous applications; however the high velocity oxy-fuel (HVOF) process provides deposits with lower porosity, higher bond strength and low residual stress build up compared to Plasma techniques. Because of its high kinetic energy and low combustion temperature design, hence HVOF is overall a more superior deposition process. There are large ranges of materials, which have potential to benefit from graded structures yet to be researched. The current study aims to contribute new knowledge in these areas by depositing nickel base alloy/stainless steel functionally graded coatings on steel substrates using the HVOF process. Nickel base alloy/Stainless steel graded coatings are used in the automotive and marine industry not only to increase strength of the coated system but also for corrosion applications. Functionally graded materials are those materials used to produce components featuring engineered gradual transitions in microstructure and/or composition, the presence of which is motivated by functional performance requirements that vary with location within a component. With functionally graded materials, these requirements are met in a manner that optimises the overall performance of the component reported by Azizpour *et al*. (2012); Hasan and Stokes (2011); Hasan (2004). Wank *et al*. (2010); Suresh and Mortensen, (1998) reported that functionally graded materials have the potential to improve the thermo mechanical characteristics of a component in several ways. Thermal spraying can be used to produce inter layers of FGM coating by two methods; Using premixed powder to produce each different layer and secondly Co-injecting two different powders and varying their relative proportions during deposition. Fu *et al*. (2000); Khor *et al*. (2000); Dong *et al*. (1999); Hu *et al*. (1998); Lima and Trevisan (1997) have used the former method while producing functionally graded coatings; however the latter method is used in this project. However the HVOF does not possess a twin powder feed system, hence such a system was designed to fulfil this application. Figure 1 (a) shows a schematic diagram of computer controlled Powder feed system. This research will discuss the potential of using the HVOF technique to produce FGMs. Hence a functionally graded coating in which the composition, microstructure and properties vary gradually from the bond coat to the topcoat reported by Hasan *et al*. (2009); Dussoubs *et al.* (2001) resembles the graded coating of material R and S is shown in Figure 1 (b).

2. Model Design and Experimentation

In this current research the HVOF thermal sprayed facility used is the manually controlled continuous combustion Sulzer Metco Diamond Jet thermal spray system. Sulzer Metco provides a powder feed unit to go with their DJ HVOF thermal spray system. The desired powder is fed from the powder feed unit through a carrier gas, to the DJ gun where combustion occurs. Typically nitrogen is used to carry the powder particles. The powder feed unit comprises a hopper assembly, air vibrator, load cell, feed rate meter and control cabinet as shown in Figure 2 (a). The unit is completely self-contained and is designed to deliver the powder to the gun at a precise flow rate as detailed in METCO/Perkin Elmer (1989 a). The powder material is placed inside the hopper assembly. Due to action of gravitational force, vibration of air vibrator and nitrogen gas pressure within the chamber powder drops into the powder port shaft (Figure 2-b). The nitrogen carrier gas flows through this port shaft and, whilst doing so, carries the powder on its way to the combustion zone of the gun. By adjusting the carrier gas flow meter control, the flow rate of the nitrogen gas is regulated and this is set according to the data outlined in the application charts provided by METCO/Perkin Elmer (1989a). A switch on the gun activates the powder allowing it to flow from the hopper to the combustion chamber within the DJ gun, and the amount flowing is displayed on the feed rate meter (in g min^{-1} or lbs (hour)$^{-1}$), measured by the load cell provided. The feed rate meter has an accuracy of ± 0.1 g min^{-1} and a range of 0-100 g min^{-1}. Further details have been reported by Stokes (2008), hence will not be expanded upon here.

The current research is mainly concerned about the development and re-design of the hopper unit, which has been detailed on the following sections. Spray parameters for stainless steel (Diamalloy 1003) and nickel base alloy (Diamalloy 2001) were taken from Diamond Jet Process manual provided by METCO/Perkin Elmer (1989b).

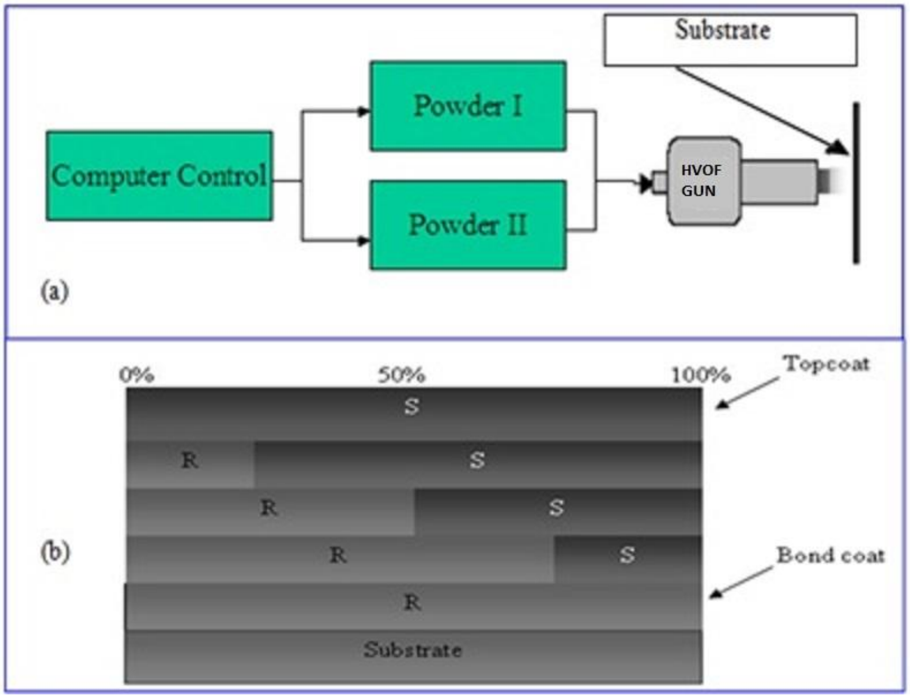

Figure 1. (a) Schematic diagram of computer controlled Powder feed system, (b) schematic diagram of functionally graded coating of material R and S.

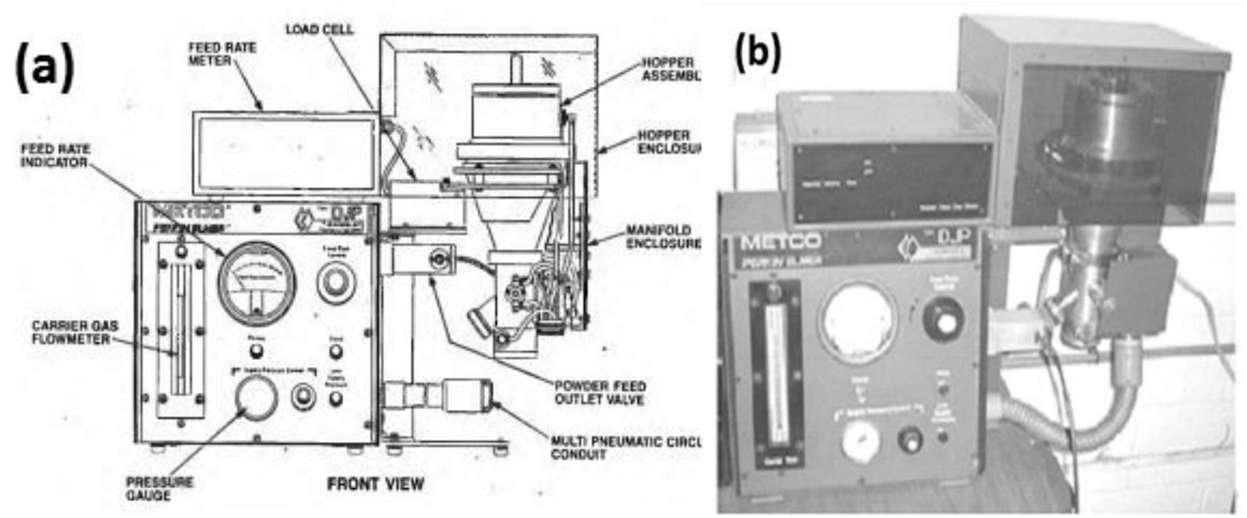

Figure 2. (a) The DJP powder feed unit used in the HVOF process and (b) Schematic cross section of the hopper assembly on the DJP powder feed unit.

2.1 Product Design

The overall aim was to design and manufacture a mechanism, which would provide an automated facility to control the proportion of the powder materials from an existing feed unit device (hopper), in order to produce FGM coatings. The mechanism designed was capable of being integrated into the existing DJ powder feed system. The proposed design where possible interfaced with as much of the existing hardware or software within the facility. To develop a design solution for the current problem certain design specification were considered, such as performance, environmental consideration, maintenance, installation, safety and manufacturability. The lead screw of the linear actuator provides a linear relationship between motor rotation and vertical motion enabling open loop control to be used; that is no sensors are required to define the position of the assembly if the previous amount of motor rotation is known. Due to this linear motion the powder particles are able to flow to the mixing zone from the Chamber ‘A’ and ‘B’. Finally Figure 3 shows the entire Digital picture of the newly designed dual powder feed device.

2.2 Modelling and Software Control

In order to check the effectiveness of the design a finite element analysis was carried out before manufacturing these components using the FLOTRAN CFD ANSYS software the results of which will be described briefly. The objective achievement of entire project depends on the controlling software development. Hence this was an important part of the current project. To control the linear motion of the needle shaped bolts Lab VIEW programming software has been used in this current research.

3. Experimental Analysis

The powder flow bench tests were carried out to calibrate the powder flow with the vertical movement of the needles (Figure 3), which are coupled with two linear actuators and controlled with LabVIEW software from a PC. The bench tests were carried out to calibrate the movements of the bolts inside the powder holders, named as chamber ‘P’ and ‘Q’. These needle shaped bolts moves upwards and downwards according to the users’ requirement inside the chamber. When the bolts are in a fully closed position or zero position, no powder flows. With the increase of the vertical movement powder starts to flow from the chamber into the mixing zone (Figure 3) and vice versa. Initially the dual feed powder holder was placed inside the powder hopper and then needle shaped bolts were placed inside the both chambers. Stainless steel powder (Diamalloy 1003) was poured into the chamber ‘P’ and the hopper cover was attached. After that the linear actuators were coupled with the needles. Variation of vertical movement was carried out controlling from the Lab VIEW Programme to check the flow of powder through the hole at the bottom of the chamber. During this process, powder particles were collected into a pre-weighted container at each stage of vertical increment from the bottom of the powder flow tube. The mass of powder flow was measured over a 10 second time period. Therefore the needle was opened for 10 seconds at every stage of vertical increment and weight of the powder flow was calculated subtracting the weight of the container from the total weight. For each step vertical increment three readings were taken. Next the nickel base alloy Diamalloy 1005 and Diamalloy 2001 were poured

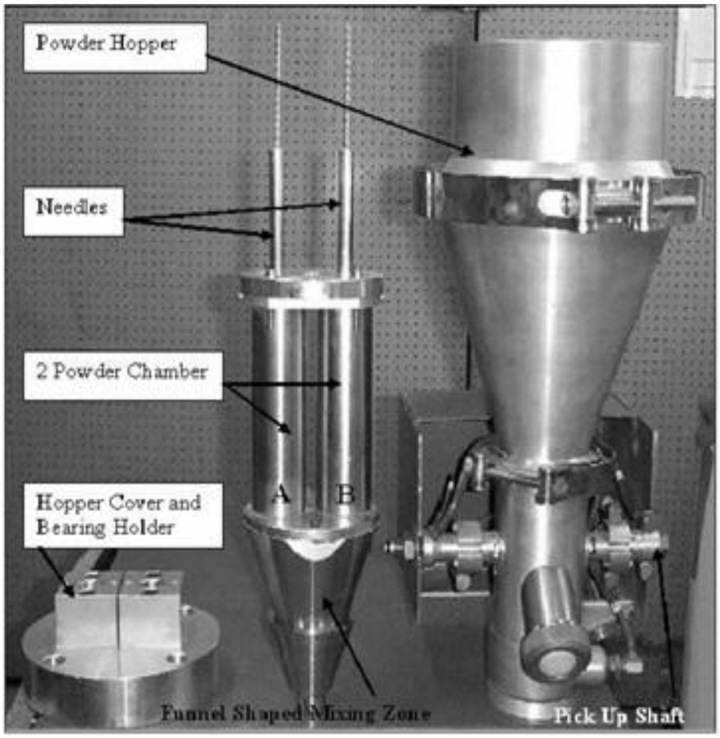

Figure 3. Digital picture of the designed dual powder feed device.

separately into the chamber ‘Q’ and the above procedure was repeated. To verify the results, chamber ‘Q’ was filled with Diamalloy 1003 and chamber ‘P’ was filled with Diamalloy 1005 and Diamalloy 2001, to justify if there was any difference between the two chambers results. Another test was carried out to check the mixing ability of the re-designed mixing zone. In order to test this, two powders, Diamalloy 1003 (light in coloured compared to Diamalloy 2001) and Diamalloy 2001 powders were poured into chamber ‘P’ and ‘Q’ respectively. During this test the feed unit system and the nitrogen gas flow were operated under running mode. A container was placed to collect the resulting powder mixture from the tube connected to the pickup shaft. Visual inspection was carried out to confirm that the light coloured and dark coloured powder particles were mixed properly. Post bench test, FGM were deposited by spraying the powders mixture varying the composition from Bond to Top coat. This was used to validate that the device worked where these coatings were analysed using EDX (SEM) technique.

4. Results and Discussion

This section briefly describes all the results and discussion of them related to this research. The following section describes the qualification procedure used to assess the functionality of the dual powder Feed device. Hypothesis of the current project was used to control the flow of two different powders at a certain ratios, which would give a desired coating composition as showed in Table 1. To achieve this objective a number of experimental tests were carried out on the current project design; manufacturing and installation processes. This section describes the calibration test on the design finally chosen to fulfil the project objective.

4.1 Simulation Results

This ANSYS simulation was carried out mainly to verify the following two questions; whether the design parts would be able to carry the powders into the mixing zone (inside the parts) where they are supposed to mix, whether the mixed powder particles would then be carried out by the nitrogen gas flow inside the pickup shaft towards the spray gun. During the FEA simulation approach different nitrogen gas pressure ratios (ratio between the top of the pressure inlet tube to pick up shaft, 1:1, 2.25:1 and 1.8:1) were applied and an approximate nitrogen gas pressure ratio was determined to cause powder mixing and to force the mixed powder into the carrier gas flow (nitrogen gas) inside the pickup shaft. To meet the requirements of the current

Table 1. Hypothesis of the two different powders flow controlling the vertical movement of the linear actuators ‘A’ & ‘B’.

	Initial position of both needles is close or zero.		Desired composition of FGM coating of different powder (%)	
	A	B	P (SS)	Q (Nickel base alloy)
Vertical movement of linear actuators (mm)	4	0	100	0
	3	1	75	25
	2	2	50	50
	1	3	25	75
	0	4	0	100
	0	0	Reset to the initial position	
Considering, travelling Distance is 4 mm and time delay for each step is equivalent to eight passes of the spray gun in front of the substrate.				

project objective it was necessary to compare with the velocity and particle flow trace found in each of the ANSYS models. Figure 4 shows the flow trace of nitrogen gas and powders for a pressure ratio of 2.25:1 where the optimum maximum velocity was found at the outlet ranged from 130 to 147 m/s and this analysis shows that the powder particles are able to mix with each other in side the mixing zone at a velocity range of 0 to 16 m/s and these were shown to perform better than the previous research by Hasan (2004).

4.2 Bench Tests of Powder Flow

Figure 5 shows the combine graphical representation of the powder flow through the mixing zone during the 4 mm increment of needle movement in chamber ‘A’ and chamber ‘B’ for all powders. From visible observations it was found that the powder particle of Diamalloy 1003 and Diamalloy 1005 are more or less same sized, shape. Diamalloy 1003 and Diamalloy 1005 powders have a tendency to agglomerate due to their fine shape where as Diamalloy 2001 is more granular but flows easier compare to the other two types. However the Diamalloy 2001 flowed at high rate compare to Diamalloy 1003 and Diamalloy 1005. Flowability or density measurement tests and optical microscope image analysis also confirmed these reasons for difference in flow of each powder. From the powder flow bench test results it has been determined that during the coating process to get the 100% flow of powder particle vertical increment of the needle shaped bolts was 4 mm from zero position using any chamber either ‘A’ or ‘B’. Each stage of vertical increment or decrement was 1 mm to achieve 25% powder composition. Hence to obtain a 1000 µm (approximately 1 mm) thick coating, the spray gun needs to produce 32 layers on the substrate, which is 16 passes (as each layer is 30 µm thick). Hence the Lab VIEW Programme limit switch was designed to send a signal to create the vertical increment or decrement of the needle shaped bolts every 8 layers (1/4 of overall coating thickness). The above procedure is applicable when the flow ability of the two powders is almost same, for example here, base powder material Diamalloy 1003 and coating powder material Diamalloy 1005. But when the flow ability of two powders (for example base powder material Diamalloy 1003 and coating powder material Diamalloy 2001) is dissimilar then it is necessary to calibrate the powder composition ratio with the vertical increment or decrement of the needle shaped bolts. For the current research Diamalloy 1003 was used as a base material powder (similar to the substrate). Table 2 shows the vertical increment or decrement of each needle shaped bolt according to the amount (mass) of powder found in the mixture as determined by the powder bench test for Diamalloy 1003, 1005 and 2001. Hence, these increment (or decrement) values for each powder-controlling needle, yields the desired functionally graded coatings.

4.3 Experimental Results

A 1 mm thick Stainless steel substrate has functionally grad coated with Diamalloy 1003 and Diamalloy 2001 using the designed semi-automated system and chemical composition of five layers was determined using the energy dispersive X-ray (EDX) spectroscopy. The chemical composition of Diamalloy 1003 and Diamalloy 2001 are shown in Table 2.

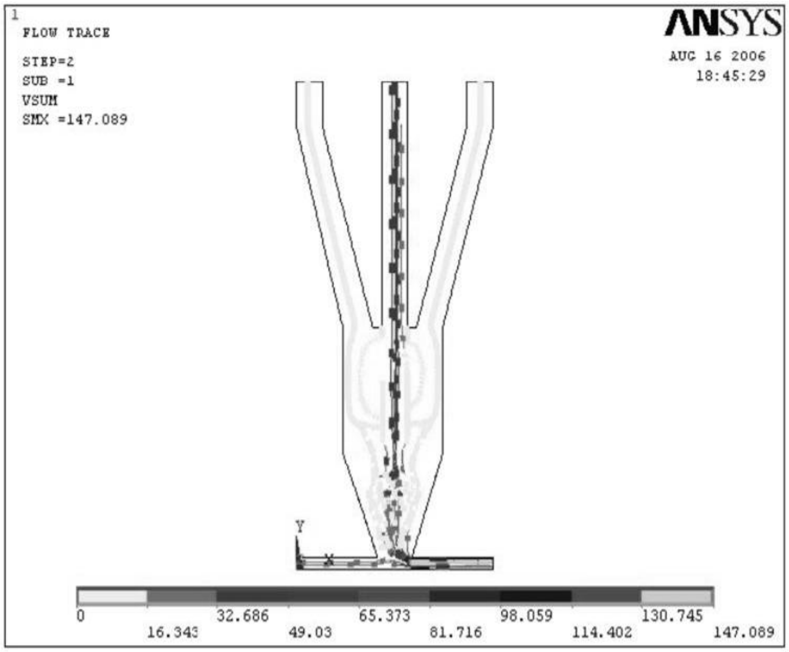

Figure 4. Particle flow lines for the nitrogen gas and powders for a pressure ratio of 2.25:1.

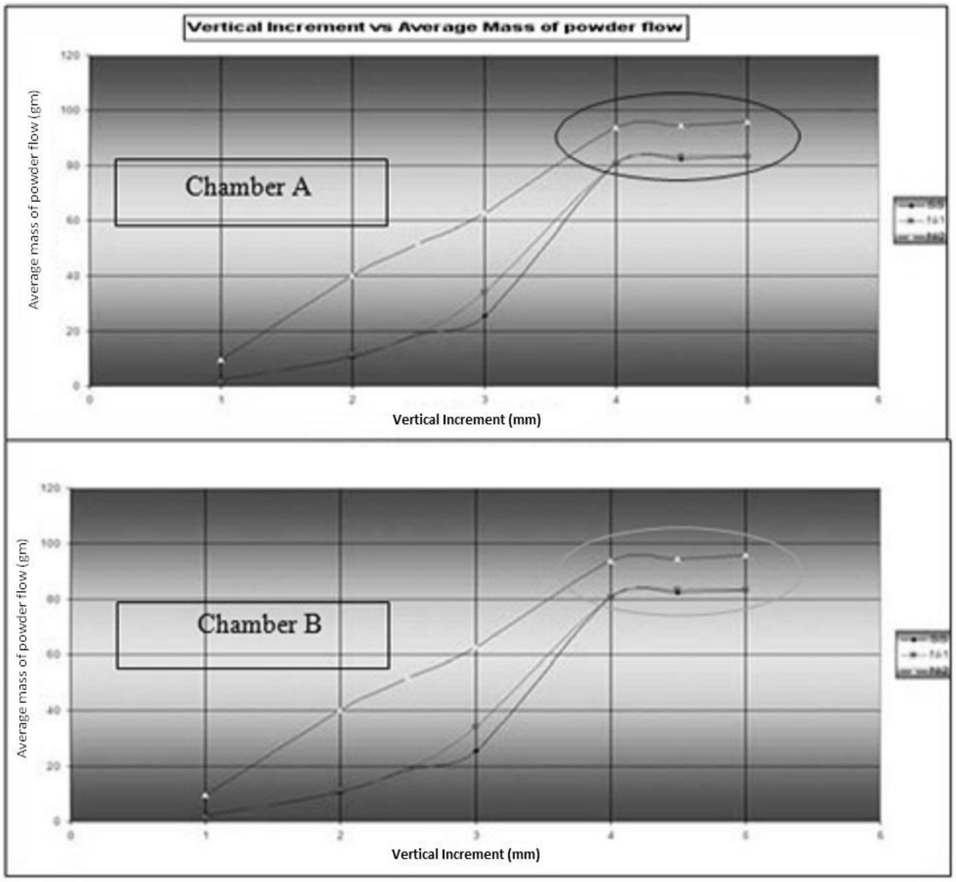

Figure 5. Comparison of average mass of Diamalloy 1003, Diamalloy 1005 and Diamalloy 2001 powder flow between Chamber A and Chamber B.

Table 2. Vertical increment or decrement composition of needle shaped bolt with different powders, the chemical composition of starting powders.

Percentage of powder composition	Diamalloy 1003 (Base powder material)		Diamalloy 1005		Diamalloy 2001	
Needle shape bolt either 'A' or 'B' (%) [Initial position is	Increment or Decrement (mm)	Approximated mass of powder (gm), Time delay, T=10 sec (Data from Figure 5)	Decrement (mm)	Approximated mass of powder (gm), Time delay, T=10 sec (Data from Figure 5)	Decrement (mm)	Approximated mass of powder (gm), Time delay, T=10 sec (Data from Figure 5)
100	4.00	80	4.00	80	3.50	90
75	3.50	60	3.50	60	3.10	68
50	3.00	40	3.00	40	2.20	46
25	2.50	20	2.50	20	1.30	24
0	0	0	0	0	0	0
Chemical Composition (wt%)	Cr 17, Ni 12, Mo 2.5, Si 1, C 0.1, Fe (Bal). (Bond Coat)		Cr 21.5, Mo 9, Nb 3.6, Ti<0.4, Al<0.4, Fe<0.5, Ni (Bal)		Cr 17, Fe 4, Si 4, B 3.5, C 1, Ni (Bal). (Top Coat)	

4.4 Analysis

It can be seen in Table 3 that chromium (Cr) 17% is common for both FGM powders; boron (B) was not detected by the EDS technique during analysis. Hence iron (Fe), molybdenum (Mo) and silicon (Si) were used to validate the design from Bond coating to Top coating. The Fe desired amount should tend towards 67.4% (Bal.) in the Bond coating and 4% in the Top coating according to Table 2. The FGM coating obtained values of Iron 69.37% in the Bond coat, 66.55 % in the middle of the coating and 38.50% in the Top coat. For Mo the desired amount was 2.50% in the Bond coat and 0% in the Top coat and again 0.36% was obtained in the Bond coat, 0.13% in the middle of the coating and 0.21% in the Top of the coating. Although there is difference between the desired values and measured values for these two elements (Fe and Mo), but this analysis shows that their chemical composition (wt %) varied (decreased) from the Bond coat to the Top coat which was desired. The Si desired amount should tend towards 1.00% (Bal.) in the Bond coating and 4% in the Top coating according to Table 2. The FGM coating obtained values of Si 0.28% in the Bond coat, 0.39 % in the middle of the coating and 0.79% in the Top coat. However it's of chemical composition (wt %) varied (increased) from the Bond coat to the Top coat which was also desired. For nickel (Ni) the desired values and obtained values was not match significantly in this current research. Few possible reasons are detailed in the end of this results discussion.

Again one can see (Table 3) that although Cr, Ni and Mo are common; for both FGM powders, combining these materials will increase by their wt% from the Bond coat to the Top coat. Experimental results show that the wt% of the Cr, Ni and Mo values increased from the Bond coat (Cr-14.35, Ni-7.42 and Mo-0.63) to Top coat (Cr-16.27, Ni-3.92 and Mo-0.82) and the values obtained in the middle of the coating were; Cr-13.22, Ni-7.33 and Mo-0.74. Except the Ni the other two elements (Cr and Mo) composition varied (increased) according to the desired values from the Bond coat to the Top coat. However there was little difference between desired and obtained values considering at each point which is negligible as the wt % of each element is depending on the other elements which are present in the same point. Another two elements noibium (Nb) and titanium (Ti) was used to validate the design from Bond coat to Top Coat. The desired amount of Nb should range from 0% in the Bond coat to 3.6% in the Top coat; hence an increase of this element by wt% from the Bond coat to the Top coat. The FGM coating obtained values of 0% in the Bond coat, 0.60% in the middle of the coating and 0.08% in the Top coat for the element of Nb wt %. The desired amount of Ti should range from 0% in the Bond coat to <0.40% in the Top coat; hence an increase of this element by wt% from the Bond coat to the Top coat. The FGM coating obtained values of 0% in the Bond coat, 0.09% in the middle of the coating and 0.42% in the Top coat for the element of Ti wt %. The Fe desired amount should tend towards 67.40% (Bal.) in the Bond coating and

Table 3. Range of Chemical composition compared for FGM coatings (*13 out of 16 Elements showed the same trend in composition FGM coating change as that of bulk powder materials).*

Sample No. 1	Desired-Measured and Trend (↑[1]↓[2])	Bond Layer wt%	Middle Layer wt%	Top Layer wt%
Fe-Iron	Desired ↓ Measured ↓	67.40 (Bal.) 69.37	-[3] 66.55	4.00 38.50
B-Boron	Desired - Measured -	0 0	- -	3.5 -
Si-Silicon	Desired ↑ Measured ↑	1.00 0.28	- 0.39	4.00 0.79
Ni-Nickel	Desired ↑ Measured ↓	12.00 8.10	- 7.30	70.50 (Bal.) 2.69
Cr-Chromium	Desired - Measured ↑	17.00 16.86	- 15.92	17.00 10.49
Mo-Molybdenum	Desired ↓ Measured ↓	2.50 0.36	- 0.13	0 0.21
C-Carbon	Desired ↑ Measured ↑	0.10 4.65	- 6.20	1.00 29.99
Sample No. 2				
Ni-Nickel	Desired ↑ Measured ↓	12.00 7.42	- 7.33	64.60 (Bal.) 3.92
Cr-Chromium	Desired ↑ Measured ↑	17.00 14.35	- 13.22	21.50 16.27
Mo-Molybdenum	Desired ↑ Measured ↑	2.50 0.63	- 0.74	9.00 0.82
Nb-Noibium	Desired ↑ Measured ↑	0 0	- 0.06	3.60 0.08
Fe-Iron	Desired ↓ Measured ↓	67.40 (Bal.) 63.33	- 63.86	<0.50 62.61
Si-Silicon	Desired ↓ Measured ↓↑	1.00 0.33	- 0.22	0 0.47
C-Carbon	Desired ↓ Measured ↓	0.10 9.74	- 9.86	0 6.34
Ti-Titanium	Desired ↑ Measured ↑	0 0	- 0.09	<0.40 0.42
Al-Aluminium	Desired - Measured -	0 -	- -	<0.40 -

[1] (↑) Increased [2] (↓) Decreased [3] (-) Not detected

<0.50% in the Top coating according to Table 3. The FGM coating obtained values of iron 63.33% in the Bond coat, 63.86% in the middle of the coating and 62.61% in the Top coat. For Si the desired amount was 1.00% in the Bond coat and 0% in the Top coat and again 0.33% was obtained in the Bond values and measured values for these two elements (Fe and Si), but this analysis shows that their chemical composition (wt %) varied (decreased) from the Bond coat to the Top coat which was desired. Aluminum (Al) was not detected during the analysis using EDS technique in this current research.

Carbon (C), oxygen (O), calcium (Ca) and magnesium (Mg); these four elements were found during this EDS analysis. Comparatively presence of high carbon and oxygen could be contamination from the mounting powder (Phenolic resin). It was also observed using a point analysis on the mounting element surface during EDS analysis that contains higher percentage of C compared to the sample (both case). However the trend of varying composition of C (from the Bond coat to Top coat measured value) is according to the desired value (for the sample 1; increased and for sample 2; decreased). Ca and Mg could be contaminated from the hand or oxidation on the surface of the Samples. When two X-Rays from the same element hits the detector at the same time, these produced an artefact peak called sum peak. This energy values are added together. Such as K 1 line for Ni = 7477 ev X 2 = 14954 ev and For Al = 14870 ev (Which are almost same value and this values were found during EDS analysis). Therefore some Ni X-Ray can be misinterpreted as Al. This could be the possible reason for not detecting Al and B. For qualitative analysis EDS system is reliable. Azizpour *et al*. (2013); Stokes (2008) reported that; for quantitative analysis EDS is preferable to analysis with a standard, where by that sample is compared to a standard of known composition. Otherwise many correction factors are used by the system during the analysis. EDS system is focused on very small volume.

5. Conclusion

In this current research, semi-automated dual feed of the HVOF thermal spray process was designed to produce functionally graded coatings. This included design, FEA analysis, calibration and validation of a co-injection semi-automated system used to deposit stainless steel/nickel base alloy FGM coatings simultaneously on stainless steel substrate.

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