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# Deposition and Characterization of HVOF Thermal Sprayed Functionally Graded Coatings Deposited onto a Lightweight Material

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**There is a significant interest in lightweight materials (like aluminum, magnesium, titanium, and so on) containing a wear resistance coating, in such industries as the automotive industry, to replace heavy components with lighter parts in order to decrease vehicle weight and increase fuel efficiency. Functionally graded coatings, in which the composition, microstructure, and/or properties vary gradually from the bond coat to the top coat, may be applied to lightweight materials, not only to decrease weight, but also to enhance components mechanical properties by ensuring gradual microstructural (changes) together with lower residual stress. In the current work, aluminum/tool-steel functionally graded coatings were deposited onto lightweight aluminum substrates. The graded coatings were then characterized in terms of residual stress and hardness. Results show that residual stress increased with an increase in deposition thickness and a decrease in number of layers. However, the hardness also increased with an increase in deposition thickness and decrease in number of layers. Therefore, an engineer must compromise between the hardness and stress values while designing a functionally graded coating-substrate system.**

**Keywords** deposition and characterization, functionally graded coating, HVOF thermal spraying, lightweight materials

## 1. Introduction

Weight reduction in automobiles is of particular importance in today's market. The average vehicle weight is expected to increase, as the automobile industry continues to market new models with luxury, convenience, performance, and safe cars as demanded by their customers (Ref 1). Replacing steel or iron parts with lightweight materials is a useful way of reducing vehicle weight. Several researchers (Ref 2-4) mentioned the importance of lightweight materials like aluminum, magnesium, and titanium in the automotive industry. Aluminum sheets are used to manufacture cylindrical bores, but due to their softer nature their surface requires a wear resistance coating. Ferrous materials are currently used to coat such parts (Ref 5). However, due to thermal property mismatch between the aluminum and these ferrous materials, high residual stress is built up in the coated part during deposition. This paper proposes that aluminum/tool-steel graded coatings could be used to coat cylinder bores instead of single monolithic ferrous materials. The top tool-steel layer can provide wear resistance, while the gradual change in composition will aid the strength of the deposit by lowering residual stress.

Residual stresses are those, which are intrinsic to a component, remaining even in the absence of an externally applied load. In the HVOF thermal spraying process, individual molten or semimolten particles impinge the substrate or pre-existing molten material at a high speed. Thus despite their low mass, they incur stress fields, which depend upon the solid state of the pre-existing material. In addition to the mechanical effects of impact, temperature effects are also relevant to stress development (Ref 6). On impacting the substrate, the particles deform into lamella and cool down to their melting temperature and solidify. The rate of temperature decrease experienced by the particles is immense. Hence this leads to the formation of stress in each lamella. Once deposition ceases, cooling stresses generate due to the mismatch of coefficient of thermal expansion between the substrate and the coated layer. The generation of residual stress increases with an increase in coating thickness that results in lower bond strength of the coatings (Ref 7).

## 2. Experimental Work

### 2.1 Coating Deposition

The HVOF thermal spraying system consists of a Diamond Jet (DJ) gun, a powder feed unit a flow meter, and a gas and air supply unit. In the current research, a special powder feed device was developed to deliver two powders at desired ratios to produce different layers of graded coatings (Ref 10). The spray parameters used during coating deposition are shown in Table 1.

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**Table 1 Spray parameters used during spraying (Ref 8, 9)**

| Spray parameters | Values |
|---|---|
| Oxygen pressure, bar | 10.3 |
| Oxygen flow, slpm | 198 |
| Propylene pressure, bar | 6.9 |
| Propylene flow, slpm | 44 |
| Air pressure, bar | 5.2 |
| Air flow, slpm | 270 |
| Nitrogen carrier gas pressure, bar | 8.6 |
| Nitrogen carrier gas flow, slpm | 55 |
| Spraying distance, mm | 225 |

**Table 2 Coating deposition matrix used for stress and hardness measurement**

| Sample No | No of layers | Coating thickness, mm |
|---|---|---|
| A1 | 5 | 0.50 |
| A2 | 5 | 0.30 |
| A3 | 5 | 0.20 |
| A4 | 5 | 0.10 |
| A5 | 3 | 0.50 |
| A6 | 2 | 0.50 |
| A7 | 1 (Tool-Steel) | 0.50 |

### *2.2 Measurement of Residual Stress*

Clyne's analytical method (Ref 11) is a quick and nondestructive method of measuring residual stress compared to other techniques such as the x-ray diffraction and Hole drilling method. It also considers misfit strains (Δε), that is, relative difference between the stress-free dimensions of different layers and substrate in determining its stress results. Stresses at the midpoint of each layer of the deposit and at the top and bottom of the substrate can be found for each case using the equations derived by Tsui and Clyne (Ref 11).

In order to measure residual stress, (80 mm * 10 mm * 0.9 mm) aluminum strips were coated with aluminum/tool-steel functionally graded coatings to a desired thickness having a desired number of layers. Following deposition, the distributed stresses were deducted by measuring the resulting deflection of the samples using the analytical equations (Ref 11). The coating deposition matrix used for stress and hardness measurement is shown in Table 2 (Ref 12).

### *2.3 Stress and Hardness Measurement*

Some of the samples used in Clyne's analytical method were also used to measure residual stress using the RS-200 Milling Hole drilling method to compare between the two techniques of stress measurement. The residual stress values were subsequently calculated using the equations derived in ASTM E837-95 (Ref 13). Hardness of different types of aluminum/tool-steel functionally graded coatings was measured by Vickers hardness testing method using the Leitz Miniload hardness tester. For each deposit thickness and each number of layers five readings were taken, and the minimum, average, and maximum values are shown in the results section. However, the line is drawn using the average hardness values.

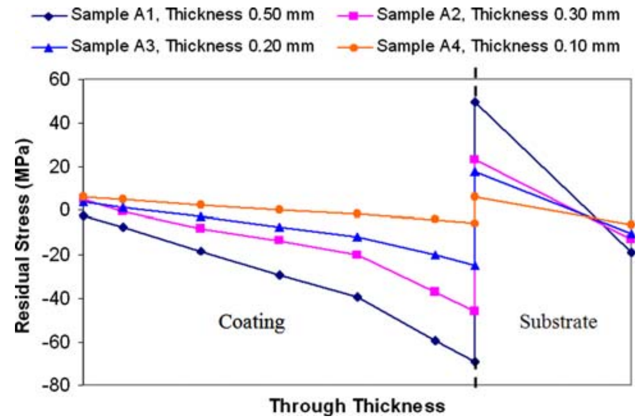


**Fig. 1** Distribution of residual stress through the coating and the substrate for different deposit thickness

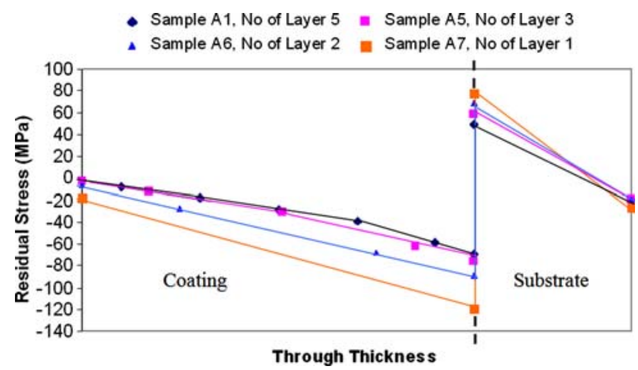


**Fig. 2** Distribution of residual stress through the coating and the substrate for different number of layers

## 3. Results and Discussion

### *3.1 Residual Stress Measurement*

The variation of through thickness residual stress with deposition thickness and number of layers are shown in Fig. 1 and 2, respectively. Figure 1 shows that the residual stress found at the top of the coatings (extrapolated values) were −2, 5, 4, and 6 MPa for samples A1, A2, A3, and A4, respectively. Thus, there was a transition of surface stress from compressive to tensile with a decrease in deposition thickness, which supports results found for WC-Co deposits by Stokes (Ref 6), where at a certain thickness the stress at the top of the deposit changed from a tensile state to a compressive state. The stress change across the interface reduced as the deposit thickness decreased. The decrease of residual stress with a decrease in the coating thickness was also found by other researchers (Ref 14-16). Again the results showed the stress at the interface changed from a compressive to a tensile value from the deposit interface to the substrate interface (due to what is known as misfit strain Ref 11), while the stress changed from tensile to compressive from the top to the bottom of the substrate in each case.

Figure 2 shows the variation of through thickness residual stress with number of layers. The residual stress decreased with an increase in number of layers, a result supported by Khor et al. (Ref 17) for graded coatings. The residual stresses at the top of the coatings were all compressive. Again, the results

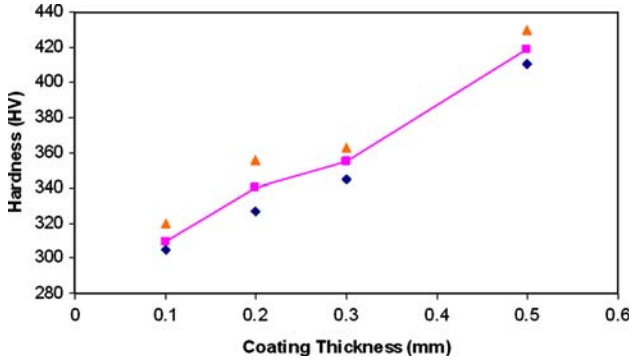


**Fig. 3** Variation of hardness with deposit thickness

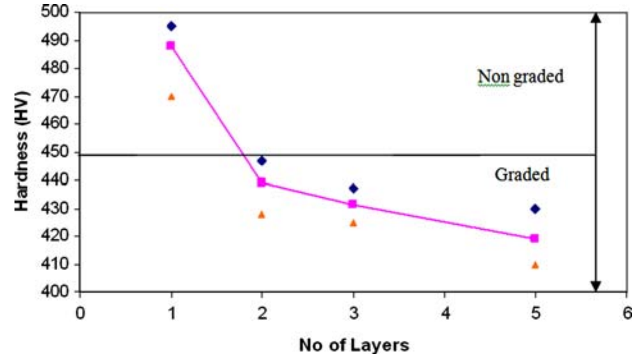


**Fig. 4** Variation of hardness with number of layers

showed a similar profile to that found in Fig. 1. The single layer's (A7, a traditionally coated substrate) stress distribution is much higher than that of the FGM layers (A1, A5, and A6). It can also be observed that an increase in the number of graded layers caused a decrease in residual stress built up in the deposits. The results indicate that increasing the number of layers to 2, 3, 5, or more has more an effect on the stress change across the deposit rather than on the stress at the top of the deposit, which can be attributed to the mismatch of properties. This is especially true as previous research found that the Young's modulus and coefficient of thermal expansion (CTE) between the layers decreased (Ref 18, 19), and therefore increasing the number of layers is a useful way of reducing the residual stress in graded coatings.

The relationship between the residual stress measured using Clyne's analytical method and results found using the experimental Hole drilling method were conducted. While there were minor differences between the two measurement methods, correlation between them was reasonable.

### 3.2 Hardness Measurement

The variation of hardness with deposit thickness (all having 5 layers) is shown in Fig. 3. The maximum difference (found between the minimum or maximum to average hardness values) for a particular deposit thickness was 4.7%. Figure 4 shows that the hardness increased with an increase in the deposit thickness, a result supported by other researchers (Ref 20-22). The reason may be attributed to the fact that an increase in the deposition thickness allowed (caused) an increase in residual stress, which in turn increased the hardness (Ref 23, 24). With an increase in residual stress, the number of defects in the coating increases. These defects act as obstacles for dislocation motion, which in turn increases the hardness (Ref 25, 26). The average hardness value of a 0.50 mm deposit was 419 HV, which was 35% higher than that of 310 HV found for a deposit of 0.10 mm thickness.

Figure 4 shows the variation of hardness with number of layers. The hardness increased with a decrease in number of layers, possibly due to the increase of residual stress with a decrease in number of layers. The average hardness value of a single-layer deposit was 488 HV, which was 16% higher than that of 419 HV for a five-layer deposit of same thickness. Again, hardness values increased linearly from a 5-layer graded coating to a 2-layer one. However, there was a higher increase from the 2-layer coating to the single-layer coating (normal monolithic coating). This single-layer coating was not a

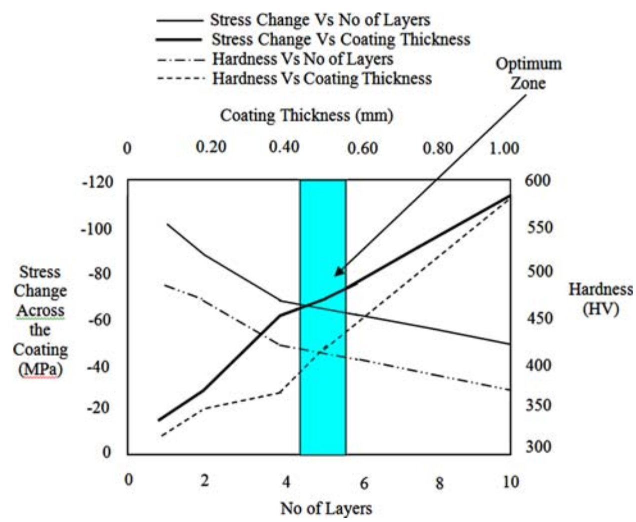


**Fig. 5** Prediction of stress change and hardness against coating thickness and number of layers

functionally graded coating, rather an aluminum substrate coated with the tool-steel to a thickness of 0.50 mm. As a result, it yielded much higher hardness values compared to the graded coatings.

The variation of residual stress change across the coating and hardness with increasing thickness (up to 1 mm) and number of layers (up to 10 layers) is predicted in Fig. 5 (extrapolation of results found in Fig. 1 through 4). This figure shows that residual stress change increased with an increase in coating thickness; however, increasing the number of graded layers decreased the stress change. According to Fig. 5, a graded coating with a thickness of 0.50 mm having five graded layers gave the optimum residual stress change across the deposit. If the coating thickness was decreased, it could have given lower stress change; however, the decrease in coating thickness would have resulted in decrease in number of layers (if the thickness of each layer had to be fixed) and increase in stress change across the deposit. Again, if the number of layers was increased, it would have given lower stress change; however, the increase in number of layers would have resulted in increase in coating thickness (same reason) and increase in stress change across the deposit. Figure 5 also shows that the hardness increased with an increase in coating thickness;

however, increasing the number of graded layers decreased hardness. Like residual stress, a graded coating with a thickness of 0.50 mm having five graded layers had the optimum hardness value (Fig. 5). If the number of layers was decreased, it would have given higher hardness, however the decrease in number of layers would have resulted in decrease in coating thickness (if the thickness of each layer had to be the same) and decrease in hardness values. Again, if the coating thickness was increased, it would have given higher hardness; however, increase in coating thickness would have resulted in increase in number of layers (same reason) and decrease in hardness values. Thus, the current research suggests that a five-layer aluminum/tool-steel graded coating having a thickness of 0.50 mm will yield the optimum between low residual stress and high hardness for the system. This is useful for engineers designing functionally graded coating/substrate systems for a wide range of material combinations in future.

## 4. Conclusions

The current research sets out to identify the effect of coating thickness and number of layers on residual stress and hardness. Results found in the research show that the residual stress decreased with a decrease in thickness and an increase in number of layers, whereas the hardness values increased with a decrease in number of layers and an increase in thickness. This paper predicted that if 5 layers of graded material are sprayed, then the residual stress compared to that of a traditional single layer (of the same thickness) will be reduced by approximately 49% (from −101 to −51 MPa). However, this benefit is mitigated somewhat by the fact that applying these multilayers reduces the hardness by approximately 14% (from 488 to 419 HV) compared to the traditional single-layered deposit. A five-layer aluminum/tool-steel graded coating having a thickness of 0.50 mm was found to have the optimum between low residual stress and high hardness. If the coating thickness was decreased from 0.50 mm to a lower value, it would have decreased the residual stress; however, the hardness values would have decreased as well. Again, if the number of layers was decreased from 5 to a lower value, it would have increased hardness; however, the residual stress values would have also increased. Thus, the results support the suggestion of a five-layer aluminum/tool-steel graded coating having a thickness of 0.50 mm to yield the optimum between low residual stress and high hardness values.

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