ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology
Vol. 2, Issue 6, June 2013

RESIDUAL STRESS ANALYSIS OF HVOF COATING USING FE BASED APPROACH

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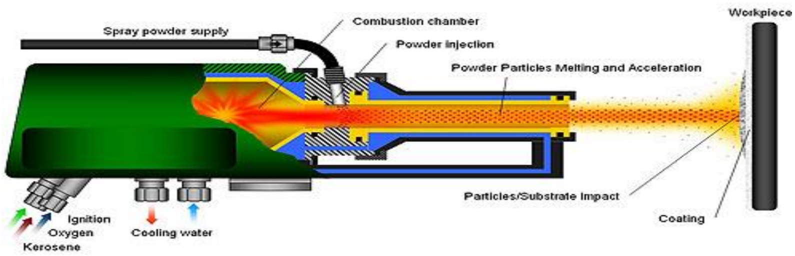
Abstract : The scope of this project is to study the effect of coating thickness on 316L stainless steel on application of thermal cycling using finite element modeling and SEM results. Due to its ability to take high thermal loads the substrate, 316L stainless steel is commonly used in high temperature applications (power plants). But, sometime it may not sustain for the given loads. WC–Co is used as a coating material and NiAl being a good bonding layer it is used as a substrate. Hence, WC–Co/NiAl coating layers were successfully deposited on 316 L stainless steel substrates by using a HVOF technique and micro structural observations were carried out using SEM analysis. The SEM analysis revealed that the oxidation between the coating layers was very low and had very good contact with the substrate, indicating a very high bonding to the substrate. This test was carried for the thermal cycling (range 373 & 873^o k) without any external load [1]. Thermal residual stresses, developed during and after thermal cycling, were determined by using FEM software package (ANSYS).It was found that the tensile stress distributions in x- direction were dominant then the compressive stresses and also the coating layer plays an important role in thermal stress

Keywords: Tungsten Carbide, Nickel Aluminum, HVOF Coating, Ansys.

I. INTRODUCTION

The serviceability and life of a component is adversely and significantly affected by the characteristics of surface in engineering materials. Hence characteristics of the surface cannot be neglected in design. Surface engineering is defined as the branch of science which deals with the methods for achieving the required surface requirements and their behaviour in engineering components service. The surface of a component can be classified on the basis of texture and colour, but more parameters are required to classify engineering components. Engineering components need to perform few functions completely and effectively, under various situations of vigorous environments.

Engineering environments are actually complex in nature, combining loading with chemical and physical degradation to the surface of the component. Surface wear damage is a major cause which affects the service life of component. An example of a component working in an aggressive environment is steam turbine blade under high temperature and pressure loads. The blades experiences high loads, high rpm and friction due to mating parts and, as a consequence, high temperatures: These factors lead to surface wear of the component. Lubrication in tribological applications reduces friction and wear, however conventional liquid lubricants fail under extreme conditions, namely low pressure, oxidative or corrosive environments, high speeds and high loads. Surface coatings can help deal with these circumstances. Improving the tool surface, not only improves the life of the tool, but also improves the surface finish of the machined part. Obviously it is important to understand the physical and chemical makeup of the applied surfaces, in order to design quality components which yield high service lives.



(a)

Fig (a) Schematic diagram of HVOF coating

Mustafa Toparli [1] et al, showed thermal stress distribution analysis of that two layers coating by FEM method with ANSYS packed program. FEM, which is one of the most powerful numerical methods, was used to predict thermal stresses. Thermo-mechanical properties such as hardness determination depending on thermal cycling, friction and wear characteristic with different load, surface roughness and microstructural investigation were carried out. Thermal stress analysis of coating system was designated for *x* and *y*-direction according to time and full length of the coating. The analysis result shows that, *x*-direction thermal stress distribution is bigger than *y*-direction for WC–Co, NiAl coatings and 316 L substrate. The maximum tensile and compressive stress distribution is obtained. Thermal stresses are calculated as compressive type both heating and cooling procedure for NiAl, but compressive characteristic thermal stresses are obtained during heating procedure for 316L substrate while tensile characteristic thermal stresses are computed for the period of cooling procedure of total thermal cycling process. The maximum values of tensile and compressive stresses are computed, respectively. Compressive stress increased at the initial node. Thermal residual stress at second Node is higher than other inter-face system in this model for *x*-direction which was located at the interface of WC–Co and NiAl coating. According to this result, WC–Co and NiAl coating interface is sensitive to thermal cycling process. Thermal analysis shows that the magnitudes of tensile stresses were calculated higher than compressive stresses. In additiond, thermal stress components for *x*-direction were found bigger than *y*-direction for time and length-dependent system solution.

J. Stokes [2] et al, showed the analysis of residual stress generated in high-velocity oxy-fuel thermal spray tungsten carbide-cobalt deposits, both analytically and numerical modeling. Hence this technique was used as a benchmark in validating the results of the FE model. The residual stress results found using Clyne's analytical method compared well to the finite element approach introduced in this study. This approach involved combining the results of two models into a thermo-mechanical FE result. This study examined the effect of coating/substrate thickness and sample size, on residual stress in a WC-Co deposit. Increased deposit thickness was found to have the largest effect on stress when compared to initial substrate size. Deposit thickness caused the stress to change from a tensile to a compressive state, but raised the level of stress at higher thicknesses. The thermo-mechanical model introduced in this study provides an innovation method that can be used to determine stress distribution across thermally sprayed deposits, especially in complex systems such as functionally graded deposits, or coatings applied over composite materials, which are not easily analyzed using analytical techniques. The model does not however examine the effect of particle velocity and how this contributes to the stress generated during the process.

Himanshu Bhatnagar [3] et al, showed the characteristics of failure modes e.g. buckling instability and strain energy driven interfacial crack propagation at interfacial delamination in linear elastic thermal barrier coatings (TBCs) are investigated using a finite element model. The solution of a linear elastic eigen-value problem determines the onset of the buckling instability with a pre-existing delamination between bond coat and the TGO. The virtual crack extension method is employed to study strain energy release rate driven interfacial delamination at wavy interfaces. The materials and geometries in the study are chosen to be representative of TBC materials in real applications. Extensive sensitivity analyses are conducted to identify the critical design parameters affecting the onset of buckling and extension of interfacial delamination, as well as to develop parametric relations that enhance the understanding of these mechanisms. These novel parametric relations, that extend the range of applications of the functional dependence found in literature, are validated with existing relations in the literature. The paper concludes with a numerical exercise studying the competing mechanisms as the delamination extends over an undulation. It is demonstrated that the buckling instability is the leading failure mechanism at flat interfaces or near the locations of minimum cross-section in a wavy interface. However, in the vicinity of waviness, crack extension can become a dominant mode of failure. The probability of a particular mechanism taking precedence over the other depends on various geometric and material parameters and the nature of the loading. A comparative study of the predicted critical buckling stress with critical delamination stress can identify the dominant mechanism. The highlights of studies with these parametric relations are summarized below.

• The critical buckling stress relationships for two-layer TBCs has an extended range of validity and better accuracy for incipient stages of buckling instability as compared to the existing analytical solutions in the literature (Evans et al., 1997; He et al., 1998). The effect of the top coat is realized through its inclusion in the three-layer TBC model. The critical stress for this model is found to strongly dependent on the top Coat geometry and material, in addition to the relevant two layer model parameters. The effect of the top coat thickness is found to stabilize with increasing thickness.

• The parametric form for the critical stress initiating interfacial crack extension at the delamination in a three-layer TBC is vital for understanding the effect of interface morphology on the failure mechanism. Furthermore, it is helpful in quantitatively establishing criteria for dominant failure mechanisms.

• The parametric relations can be used by designers as a helpful tool in the design of reliable TBCs in thermo-mechanical applications. The life of TBCs can be prolonged through an optimal combination of geometric and material parameters that suppresses the dominant mechanism. Although the present study illustrates the competition between the failure mechanisms in detail, the validity is limited to the linear elastic TBCs. The failure modes will be further influenced by the material.

W.G. Mao [4] et al, showed that the functionality and reliability of coated devices are strongly related to the variation of thermal residual stress distribution. On the basis of the prior investigations, they considered the influence of creep deformation in the ceramic coating on residual stress in constitutive equation. Finally, they have obtained a new two-dimensional analytical solution under the condition of coupled effects of temperature gradient, thermal fatigue, elasto-plasticity deformation and high-temperature creep deformation. The main conclusions of this investigation are summarized as follows.

- The evolution rules of residual stress distributions in TBCs with respect to thermal cycling have been obtained. The variation of residual stress in the TGO is in good agreement with the prior experimental results. They found that the residual stress of TGO was obviously larger than that of the other layers. It is believed that the stress singularity characteristic in TGO will play an important role during the process of spalling/bucking failure of the ceramic coating.
- It is found that the creep deformation of ceramic coating has a strong influence on thermal residual stress distribution in the ceramic coating, which mainly results in the stress relaxation in TBCs system. In addition, the stress variations in the substrate are so small that they never attain the temperature-dependent corresponding yield strength.
- Finally, the relationship of uniform strain increment and thermal cycling had been obtained and discussed. Due to the influence of elasto-plasticity deformation and high-temperature creep deformation, the residual uniform strain of the TBCs system develops tardily with thermal cycling.

Sofiane Guessasma [5] et al, published the paper and showed that their study aims at gaining a better understanding of the microstructural features that control the mechanical and the tribological performances of WC–12 wt.% Co coatings under High Velocity Oxygen Fuel (HVOF) spraying conditions. Their paper looks at the influences of the HVOF process parameters for WC–12Co material on the microstructural and the tribological behaviours of the coatings. The correlation between the coating microstructure and the wear behaviour is investigated by observing and analysing the microstructure and by studying the friction moment using enhanced statistical tool based on neural computations. According to the experimental and the numerical results, it has been shown that the spray parameters affect the phase composition, hardness and porosity of HVOF sprayed WC–12Co coatings and the correlations with HVOF process parameters are fully predictable in the steady-state regime.

O. Culha [6] et al, published paper that concerns the determination of mechanical properties such as hardness, elastic modulus and yield strength of WC-based cermet coatings for a roller cylinder. With this regard, Co and Ni containing WC-based coatings were sprayed on Ni–Al deposited 316 L stainless steel substrates by using High Velocity Oxygen Fuel (HVOF) technique. These HVOF sprayed coatings were analyzed by Scanning Electron Microscopy (SEM) with an Energy Dispersive Spectroscopy (EDS) system attachment. Mechanical properties of the coatings were examined by Shimadzu Dynamic Ultra-micro hardness test machine in order to determine the Young's modulus through load–unload sensing analysis. In addition to mechanical investigation, hardness–depth and hardness–force curves of WC-based coatings were investigated. It was found that both of these characteristics exhibit significant peak load dependency. Experimental indentation studies were carried out to determine load–unload curves of WC-Co and WC-Ni based coatings under 300 mN, 350 mN, 400 mN and 450 mN applied peak loads. Hardness and Young's modulus of WC-based coatings were calculated from experimental indentation test data of samples. It has been observed that the hardness and Young's modulus of the coating depends on the contact area and indentation size. The originality of this study is to determine the indentation size effect and contact area variations on mechanical properties of HVOF sprayed WC-based coatings.

Onur Sayman [8] et al, performed thermal stress analysis in WC–Co/Cr–Ni multilayer coatings deposited on 316L steel substrate during the cooling process from high temperature to room temperature. Firstly, the cooling curve of this coating system was measured by a thermocouple, experimentally. Then, this curve was considered for numerical analysis. With this regard, a transient thermal analysis was carried out using finite element method (FEM) utilizing ANSYS software. Thermal residual stresses were calculated for all system and were compared for different nodes selected in terms of concentrated stress areas on the model. The compressive and tensile stresses occurred in WC–Co/Cr–Ni coatings and 316L substrate owing to the different thermal expansion coefficients in each material, respectively. Additionally, the cooling curves determined from experimental and numerical studies are very similar to each other.

II. EXPERIMENTAL ANALYSIS OF COATING LAYERS

The WC-Co & NiAl coated specimen of dimension 100X100X2 is cut into small bits of dimension 10X10X2 using wire cut technique for mounting the specimen in SEM machine. The figure (a) shows the 10X10X2 SEM specimen. The observation of Cross-section is most important factor for manufacturing and determination of adhesion properties of coatings. However, perfect mechanical sample preparation often damages the interface layers and makes such observations somewhat ambiguous. Hence a cross section polishing machine is used for preparing the specimen. the sample was cut into small sectioned using diamond saw and the small sections are mounted in cross section polishing

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology
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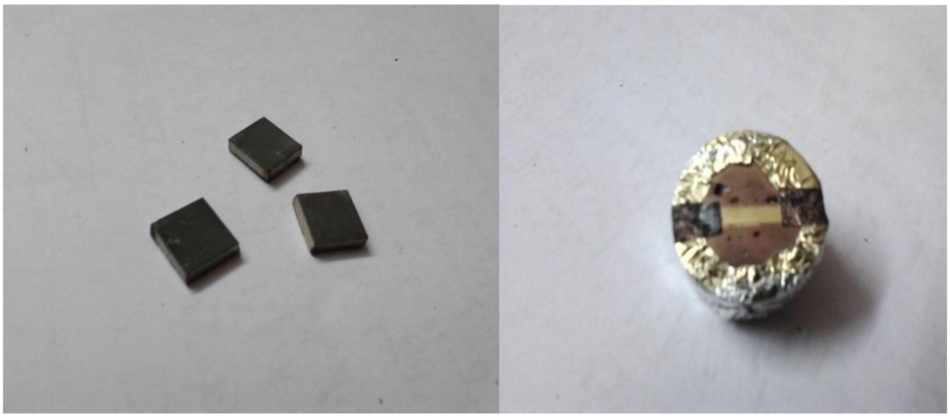
instrument and finely polished with Ar ion beam. The below figure (b) shows the finely polished specimen mounted in metal base in order to obtain the SEM images for coating thickness. This specimen helps in checking the layers of the coating and their thickness.

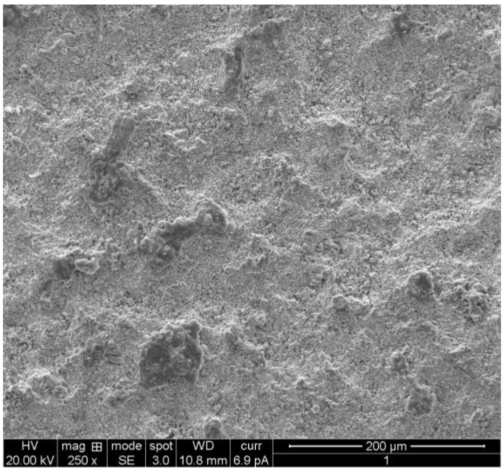


(b) (c)

Fig(b) specimen sample for SEM, Fig (c) SEM specimen for coating thickness.

III. FE ANALYSIS RESULTS AND DISCUSSION

The cleaned and polished specimen was used for SEM and EDX testing. The SEM micrographs were taken at different magnifications and are shown in the figure (b) & (e).



(d)

Fig (d): SEM of WC-Co coating surface at 250 &500 X zoom

The coating consisted of columnar grains with grain boundaries that extended completely across the coating. No pores were observed within the cross-section as shown in figure (e), the image of taken during analysis are evident of no pores or coating defects. The cross-section morphology of the WC-Co and NiAl bond coating deposited is show in image.

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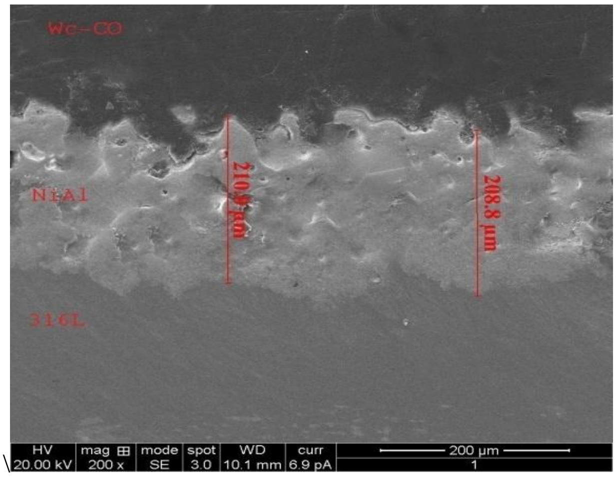
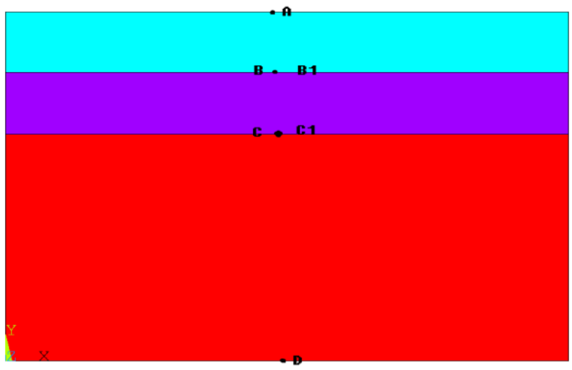


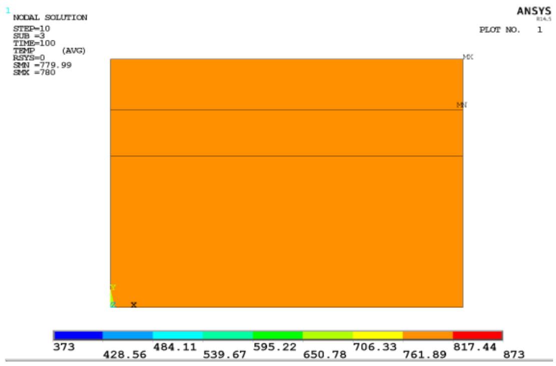
(e)

Fig (e) : SEM micrograph of WC–Co and NiAl coating cross-section.

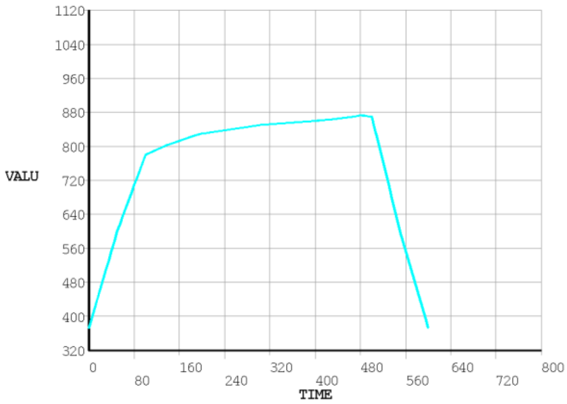
The fig (f) represents Cross section of coating showing nodes for interpreting results. Ansys tool is used for carrying out the residual stress analysis. Node A is located at top of WC-Co layer, Node B and B1 is located at the interface of WC-Co and NiAl, Node C and C1 is located at the interface of NiAl and 316L steel, Node D is located at the end of 316L steel layer. The top layer represents WC-Co coating with thickness of 250µm, the middle layer with thickness of 205µmand the substrate with thickness 750 µm respectively.



(f)



(g)



(h)

Fig (f) : Selected nodes on Cross section, Fig (g) Temperature contour, Fig (h) Temperature curve (location-A)

The iteration 4 is carried out by changing the WC-CO coating thickness from 250µm to300µm using same symmetric boundary conditions and material properties. The top layer represents WC-Co coating with thickness of 300µm, the

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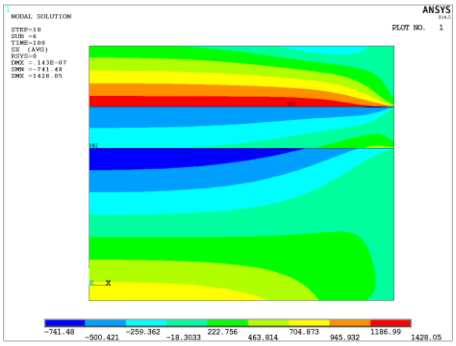
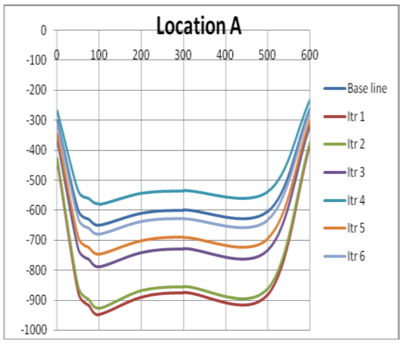
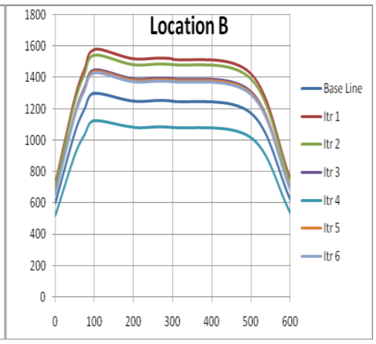
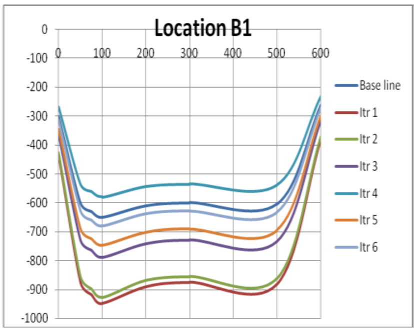
middle layer with thickness of 205µm and the substrate with thickness 750 µm respectively. The thickness of the coating is in microns the material is getting heated rapidly[1], refer fig (f) and the temperature curve at node location-A over time is as shown in the fig (h) .The stress contours are shown in Fig (l) . plots from (m) to (r) represent stress plots with one on one comparision of iterations at diffferent node locations.

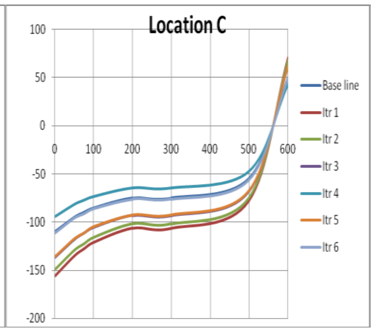


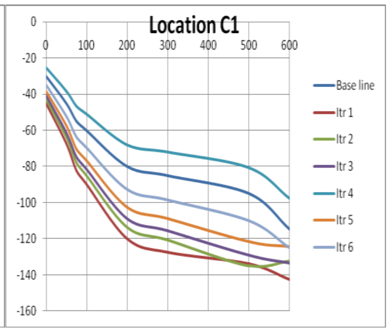




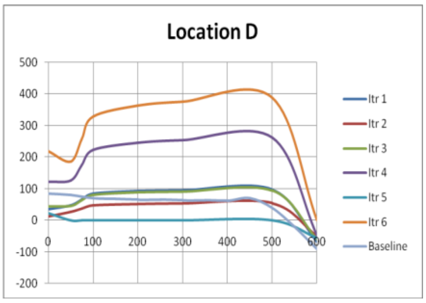
(l) (m) (n)







(o) (p) (q)



(r)

Fig (l) X-directional stress contour at 100s, Fig (m) comparison of stress plots of different iteration at lacation A, Fig (n) comparison of stress plots of different iteration at lacation B, Fig (o) comparison of stress plots of different iteration at lacation B1, Fig (p) comparison of stress plots of different iteration at lacation C, Fig (q) comparison of stress plots of different iteration at lacation C1, Fig (r) comparison of stress plots of different iteration at lacation D.

IV. CONCLUSION

ISSN: 2319-8753

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It is clear that residual stress play an important role when the components are loaded thermally (heating). From the analysis, it is evident that the substrate behaves elasto-plastically and hence, this layer becomes soft. Henceforth, inducing compressive stresses at the layer interference and we can conclude as fallows.

- Coating of the components will store compressive stresses when it is heated and this helps in resisting crack initiation.
- The coating substrate, Ni-Al is a good binder.
- By increasing the Ni-Al with thickness as compared to WC-Co will yield better results.
- For a small change in coating thickness, there is a comparative change in residual stresses.

From the SEM results, it is clear that using Ni-Al will reduce oxidation. Hence, porous formation will be less.

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