Stress evaluation of CSZ and SiAlON under Thermo-Mechanical loading condition

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Abstract—This work deals with the Thermo-mechanical analysis of Thermal barrier coating over Aluminum 2026 alloy through Finite Element Method in ANSYS 15.0R software. The coating material is Nano composite (metal matrix). It consists of double ceramic layer (TC1, TC2) with a layer of bond coat (BC) between the substrate (SUB) and the ceramic layers. The top Ceramic layer is of a new kind of refractory material with better oxidation resistant and corrosion resistant above 1000°C. The inside ceramic layer is well known for thermal resistant. In order to give a better bonding strength, the grain size of the coating powder is maintained at Nano scale. A Finite Element model has been developed to identify the intermittent temperature of the coatings under thermal loading conditions. From this FEA result the model was subjected to thermo-mechanical stress analysis to find out the stress distribution over the coatings and the substrate. We analyzed with three different temperatures in the same model. The result shows that the double ceramic layer will reduce the Substrate temperature effectively. The interfacing area and the edges of the coating experience more stresses when compared to other area. The paper reveals that the coated material’s stress concentration is very less when compared to the uncoated material.

Keywords—Thermal barrier coating, Finite Element Method, Nano composites, Double ceramic layer, Thermo-Mechanical loadings.

I. INTRODUCTION

The resources like fossil fuels are depleting faster rate recently. This demands improving the efficiency of high temperature components which is used in the application of automobiles, aerospace and power industries. When a material is subjected to a challenging thermal environment it must have good material properties. The increasing temperature in these environments will increase the efficiency and at the same time the life time of the material is reduce [6]. The applications such as automobile engines, Gas turbines are operating in a high temperature environment facing such problems [1]. In order to sustain the materials in such conditions Thermal Barrier coatings is provided to those materials. Though ceramic materials having good thermal resistant properties we are going that material for coating [2]. Thermal barrier coating applied to the combustion chamber reduces the fuel consumptions as well as pollution and also improve the fatigue life of the component. [9] The factors influencing the life time of the coating are formation of oxides, corrosion, and thermal mismatches etc. [1]. One single coating cannot able to solve such problems, so we are going for a Double layer.

Thermal barrier coatings are normally made of a top coat with zirconium oxide and a metallic bond coat. In this paper the top coat is of two layers. The first layer (TC1) is made of synthesized SiAlON a new kind of refractory material, the second layer (TC2) is of CSZ (ZrO2 7-8 Wt. % CeO2 and that of bond coat is NiCrAlY. Double ceramic layer will effectively protect the substrate material. Research
show that the total of 450nm thickness of coating including bond coat gives a better results [5]. Coating can be applied by mainly two process. They are diffusion process and overlay process. However the plasma spraying process is comes under the overlay process which gives a better results in ceramic coatings [1]. During thermal spray deposition processes a high amount of heat is transferred to the substrate material and the coatings. This can lead to a distribution of residual stress in these area [11]. The coating sintering temperature also plays a role in the property of the coating material, it shows that coating sintering temperature makes more contribution to the thermal conductivity of the Nano structured coating material. [12].

II. EXPERIMENTAL PROCEDURE

In this model first we investigated the temperature distribution in the coating with three different temperatures. From this result we switch over to thermo-mechanical stress analysis and the inputs are from the previous thermal analysis. Doing this we calculated the stresses present in each layer. A finite element numerical model was created and analyzed with one side is maintained at room temperature and the other side is exposed to three different temperature.

III. SIMULATION PARAMETERS

There are so many ways to analyze the temperature distribution of thermal barrier coatings by numerical method. For the simplification of our problem consider the 3D model as a 2D-plane model. In this the Heat transfer is occurred along the thickness direction of the coating. For simulation the element type used in ANSYS 15.0 is, for thermal analysis SOLID Q 4 node 55 and for structural analysis SOLID Q 4 node 182 are used.

a) Physical Model

The Fig.1. Shows the physical model of the TBC coated Aluminum 2026 substrate. In this heat conduction and heat convection mechanisms are considered. From the surrounding to the first layer (TC1) convection takes place and heat conduction takes place at the intermittent layers.

![Fig.1](image)

b) Finite Element Model And Boundary Conditions

The finite element model was shown in Fig.2. it consist of four layer, Top ceramic layer(TC1), inside ceramic layer (TC2), bond coat layer(BC) and a substrate layer(SUB). The thickness of the coatings is taken from previous literature. In this model the heat transfer is occur in the thickness direction. For analyzing this model in ANSYS the following assumptions are made.

i. All layers are Homogenous and isotropic.

ii. The top and bottom of this model is considered as adiabatic condition.
Three different temperature of 500°C, 700°C, 1000°C are taken into consideration. The convective heat transfer Co-efficient in the hot side is 3000 W/m²·k and the other side is maintained at 30°C and the respective heat transfer co-efficient is 2500 W/m²·k.

c) Material Properties

The thermal conductivity of the top layers TC1 and TC2 are calculated by using the formula $K = K_0 (1 - \epsilon)$, which is presented in the literature [5].

$K_0 = 3$

K is the effective thermal conductivity; $K_0$ is the thermal conductivity of dense body and $\epsilon$ is the porosity. The remaining are taken from others work [6].

| Properties       | TC1 | TC2 | BC  | SUB |
|------------------|-----|-----|-----|-----|
| Conductivity w/mk| 11  | 0.2 | 32.1| 190 |
| Density gm/m³    | 3.24| 6.2 | 8.21| 2.77|
| Expansion coeff. x 10⁻⁶/°C | 3   | 10  | 13.8| 22.9|
| Elastic modulus GPa | 250 | 200 | 190 | 72.4|
| Poisson ratio    | 0.28| 0.27| 0.3 | 0.33|

IV. RESULT AND DISCUSSION.

a) Thermo mechanical analysis at 500°C

Left side of the model is subjected to 500°C and the other side is at room temperature. There is no heat transfer takes place at the upper and the lower side of the model. The Fig.3. Shows the temperature distribution and their respective stress present in the model at 500°C.
There is no micro cracks formed in this stress concentration. Almost the base body’s temperature is room temperature only. Presence of coating at this temperature effectively reduces the stress intensity factor in the substrate. The stress formed in the interface is mainly due to the result of different in the value of co-efficient of thermal expansion of the materials.
Table II. Temperature Distribution

| Variable | TC1  | TC2  | BC   | SUB |
|----------|------|------|------|-----|
| Temp °C  | 381  | 289  | 227  | 166 |

b) Thermo-mechanical analysis at 700°C

Fig. 4. shows the temperature distribution and their respective stresses present at the temperature of 700 °C.

Fig. 4(a). Temperature Distribution at 700°C

Fig. 4(b) stress in axial

Fig. 4(c) vonmisses stress
Table III. Temperature Distribution

| Variable | TC1 | TC2 | BC  | SUB |
|----------|-----|-----|-----|-----|
| Temp oC  | 530 | 399 | 312 | 224 |

The interface temperature between the BC/SUB and BC/TC has random in nature. The idealized result of the single simulation may not give the real behavior of the coating. It is observed that the failure will come in the interfaces between the SUB and the BC during high temperatures. The interfaces stress between the SUB and the BC experiences less amount. This range will not affect the base material to fail.

c) Thermo mechanical analysis at 1200oC

A transient coupled temperature-displacement is carried out in this model. A finer mesh is applied in the intermittent layer where the stress is maximum. For this temperature range, considering the absence of the crack propagation because results show that above 1200oC only crack will propagate in coating. The influence of the thermal distribution cycle of the thermal barrier coating also not important so we are considering a single load cycle. In the first stage of the temperature analysis is the actual working condition of the IC engine outlet port, because the outlet temperature is below 500oC. Temperature at 1000oC we are considering only temperature and stress distribution without considering oxidation, up to this range no oxides forms in the coating. Fig.5. shows that the temperature distribution and their respective stresses present at the temperature of 1000 oC.
To ensure the model is working properly, a comparison between with coating and without coating also analyzed under the same thermo-mechanical loading condition. In the first stage we identified the critical stress area. In the second stage the size of mesh in the interface area is increased.

Table IV. Temperature Distribution

| Variable | TC1 | TC2 | BC  | SUB |
|----------|-----|-----|-----|-----|
| Temp °C  | 754 | 564 | 438 | 311 |

Fig. 5(c) Vonmises stress

Fig. 6(a) Temperature distribution in SUB

Fig. 6(b) Vonmises stress in SUB
Table V. Maximum and Minimum Vonmises stress

| Temp °C   | Max Stress(GPa) | Min Stress(GPa) |
|-----------|----------------|-----------------|
| 500       | 1.08           | 0.000123716     |
| 700       | 1.51           | 0.000167693     |
| 1000      | 2.15           | 0.000235813     |
| 1000 (Only SUB) | 10.6       | 0.632000000     |

Fig.7. shows the Temperature vs Stress graph at 500°C, 700°C, 1000°C. It is noted that the temperature range increases the stress experience by the material also increases.

V. CONCLUSION

In this study we investigated the double ceramic layer coating applied to the aluminum substrate. Thermo-Mechanical stress analysis in x-direction and y-direction are taken into account. It is found that stress in x-direction is a tensile stress and the stress in y-direction is a compressive stress. The compressive stress role is very less so it is neglected. From the above figure it is identified that the stress in the Bond coat is more when compared to the Top coat layer. From the results we came to know that CSZ having better thermal resistant and it gives a better result even in 1000°C also. The first layer SiAlON effectively reduce the stress due to the effect of this temperature. We conclude that the Double ceramic layer of CSZ and SiAlON will give it optimum performance above 1000°C also. However the maximum stress obtained by this model is less and these stresses will not affect the working condition of the base material.

VI. FUTURE WORK

The same model presented in this paper is fabricate, and this will be analyzed to find the thermal resistant, oxidation resistant and corrosion resistant of the coatings experimentally.
APPENDIX

TBC-Thermal Barrier Coating.
TC- Top Coat
BC- Bond Coat
SUB- Substrate
CSZ- Ceria Stabilized Zirconia.

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REFERENCES

[1] R. Rajendran (2012) “Gas Turbine Coatings-An overview” in Engineering Failure Analysis, pp.355- 369.
[2] S.C. Sharma, N.M. Gokhale, Rajiv Dayal, Ramji Lal (2002) “Synthesis microstructure and mechanical properties of Ceria stabilized tetragonal Zirconia prepared by spray drying technique” in Material Science vol 25, No.1, pp. 15-20.
[3] Meng Han, Guodong Zhou, Jihua Huang, Shuhai Chen, (2013), “ A Parametric study of double-ceramic layer thermal barrier coatings”, in Surface and Coating Technologies, 236, pp.500-509.
[4] C. Zhang, K. Komeya, J. Tatami, T. Meguro, Y. B. Cheng (2000), “Synthesis of Mg-α SiAlON powders from talc and halloysite clay minerals”, in Journal of European ceramic society 20, pp.1809-1814.
[5] L. Wang, X. H. Zhong, Y. X. Zhao, S. Y. Tao, W. Zhang, Y. Wang, X. G. Sun, (2014), “Design and optimization of coating structure of the thermal barrier coating fabricated by atmospheric plasma spraying via Finite element method” in Journal of Asian Ceramic Society, vol 2, pp.102-116.
[6] M. Rezvani Rad, G. H. Ferrahi, M. Azhadi, M. Ghodrati, (2015), “Stress analysis of thermal barrier coating system subjected to out of phase of thermo-mechanical loadings considering roughness and porosity effects”, in Surface and coating technology 262, pp. 77-86.
[7] A. K. Saini, (2013),”Simulated thermal analysis of 8Y- PSZ/NiCrAlY coating over ALSI alloy”, in International Journal of Advanced research in Engineering and Applied Sciences, vol.2. No.8.
[8] Natalja Zilinska, Ilnars Zaltes, Janis Krastins, (2012),”Investigation of production of fine grained SiAION ceramic from nano powders”, in Material science vol.18, No.3.
[9] O. Kovaric, P. Hausild, J. Siejl, Z. Pala, J. Matejicek, V. Davidov, (2014), “The influence of plasma sprayed multilayer of Cr2O3 and Ni10Wt.%Al on fatigue resistant”, in Surface and coating technology 251, pp.143-150.
[10] Irina Bamimkova, Sergey uvarov, Marina Davidova, Oleg Naimark, (2014),”Study of ceramic tube fragmentation under shock wave loading”, in Procedia Material Science vol.3, pp.592-597.
[11] Ming Song, Yue Ma, Sheng Kai Gong, (2011),”Analysis of residual stress distribution along interface asperity of thermal barrier coating system on macro curved surface”, in Progress in natural sciences: Materials international, vol 21, PP.262-267.
[12] Wang Kai, Peng Hui, GUO Hongbo, Gong Shengkai, (2012),”Effect of sintering on thermal conductivity and thermal barrier effects of thermal barrier coatings”, in Chinese journal of aeronautics 25, Pp.811-816.
[13] Hasan Koruk a, Jason T. Dreyer, Rajendra Singh a (2013) on “modal analysis of thin cylindrical shells with cardboard liners and estimation of los factor”, mechanical systems and signal processing
[14] T. Subramani, Athulya Sugathan (2012) on “Finite Element Analysis of Thin Walled- Shell Structures by ANSIYS and LS- DYNA”, Volume Issue.4, July-Aug. 2012 Pages 1576-1587
[15] Matin Latifi, Fatemeh Farhatnia, Mahmoud Kadkhodaei (2013) on “Buckling analysis of rectangular functionally graded plates under various edge conditions using Fourier series expansion”, Volume 41, September–October 2013, Pages 16–27