FINITE ELEMENT ANALYSIS OF THERMAL FATIGUE LOADING OF NANO MATERIALS COATED TURBINE BLADE FOR CRITICAL APPLICATIONS

Kiran Ashok, Aswin C K, Ben Abraham Samuel, Prof. Akash Mohanty

1 Mechanical, Vellore Institute of Technology, Vellore, India, aswinck96@gmail.com
2 Mechanical, Vellore Institute of Technology, Vellore, India, benabraham592@gmail.com
3 Mechanical, Vellore Institute of Technology, Vellore, India, kiranashok007@gmail.com

Abstract. Thermal barrier coatings (TBC) have structures which are very complex and are employed in high temperature condition. The phenomenon of cracking is usually noticed at both the Top Coat (TC) and the interface between the bond coat and the thermally grown oxide layer under the Thermal Cyclic Fatigue (TCF) loading. In this study, the cracking behavior in Bond Coat (BC) and interface for TBC were thoroughly determined by using the commercially available ABAQUS/CAE 6.14-3 FEA software. This study also analyzed the key aspects causing the cracking behaviors in TBC. Various crack propagation path in the Bond Coat (BC) could be obtained on changing the thermal wave forms. The beginning location of TC (Top Coat) was independent of the roughness in the interface. The thermally grown oxide layer (TGO) which is thinner at the beginning could increase the service life of TBC. From the results it is evident that in order to characterize the service environment, the thermal fatigue load and the working temperatures have to be designed

1. INTRODUCTION

Failure of blade in gas turbine engines could have a harsh strike on the provision of engines and on the management of Engine soundness. Failure of blade could occur due to high rotational speed at elevated temperature. Thermal barrier coatings (TBCs) are high temperature coating material that is applied to metallic surface. These TBCs act as insulators to parts that are exposed to high and continued heat loads by the application of thermal insulators [Fig. 1.1]. Fatigue life is expressed in terms of cycles to failure. Cycles to failure can be stated as the number of loads a material can sustain until a crack starts to appear on the material. For the detailed study Finite Element Analysis (FEA) is used. FEA gives an insight of imperfections that occurred during the manufacturing process. FEA is done with the help of ABAQUS/CAE 6.14-3 software on the turbine blade and the residual stress and the interface temperatures of different coating layers were calculated. Behaviour of the surface of turbine blade was also studied by analysing the surface for crack and creep formation. In this analysis, the nanoparticle coated TBC also considered for the same purpose.
2. SCOPE OF THE WORK

Turbine blades which are under cyclic thermal load have a tendency to create thermal residual stress accumulation in the coating leading to early delamination of the multi-layered coating. So TBC coated materials came into existence in order to overcome this scenario, but even these advanced coatings have their limitations. Most of the work done so far deals with the macroscopic elements. This work deals with Nano-particle property and nanoparticle coated TBC which is a new opening, since nanoparticle has an excellent thermal property, an attempt was made to do such analysis. Stress analysis can be performed to predict the propagation of cracks. Moreover, the idea of thermal insulation of the TBC materials also studied by plotting a graph between the temperature vs. thickness.

2.1 Deliverables For Nano

Use of Nano materials in the near future is going to be high because of their high strength, good stiffness and functional properties that are better than conventional materials. The adoption of Nano materials such as YSZ opens up a promising substitute to enhance the performance and structure of a TBC because of its excellent properties which are mainly high micro-hardness, less thermal diffusivity, elastic modulus, smoother roughness etc. We will be seeing a lot of high strength composite along with the incorporation of the Nano materials due to more than satisfactory requirements it meets.

2.2 Limitation

Since we are working on Nano structured materials the calculations may deviate from the tolerance limits that are required. This problem can be solved by generating micrometer and a nanometer mesh wherever necessary. 5% is the standard for engineering tolerance used for comparison. But as we are dealing Nano structured materials in the current study, the value deviations for FEM approach can be up to 10-15% (approximately) when we are comparing the results.

3. OBJECTIVE OF THE WORK

- To calculate the residual stress of the traditional thermal barrier coating using FEA and also do the analysis of nanoparticle coated TBC.
- To find the thermal insulation of TBC material and to find out the interface temperature at each surface.
  a) Top coat-TGO interfaces
  b) TGO – Bond coat interfaces
  c) Bond coat- substrate interfaces
4. METHODOLOGY
The following flow chart which is depicted in the Figure 1 represents the workflow that is carried during the FEA analysis in ABAQUS software.

![Flowchart showing FEA method](image1)

The analysis of the Thermal Barrier Coated surface can be done using the software ABAQUS/CAE16.4-3. This is a graphical and powerful stress analysis tool and mathematical tool to solve boundary condition using Finite Element Analysis methods. An aerofoil CAD model was prepared in order to resemble the turbine blade geometry but for the analysis purpose, a simple circular cylinder was considered with TBC having same thickness dimensions. The analysis is done on a cylinder for reducing the complexity. A schematic illustration of the model is shown in Figure 2. The radius of the circular cylinder was taken to be 30 mm. The thicknesses of various layers in the coating for the 1st iteration have been mentioned in Table 4.1. The model is imported to ABAQUS platform in order to do the analysis. The file format which is imported to ABAQUS is .iges.

![Schematic representation of coating Specimen](image2)

![Thickness of different layers](image3)
Table 1. Thickness of different layers

| SL NO. | LAYERS                | THICKNESS (in μm) |
|--------|-----------------------|------------------|
| 1      | TOP COAT              | 300              |
| 2      | TGO + BOND COAT       | 5 + 145          |
|        |                       | 15 + 135         |
|        |                       | 30 + 120         |
| 3      | SUBSTRATE             | 3000             |

Multiple iterations were performed with varying thickness so as to understand how the Temperature changes with the Thermally Grown Oxide (TGO) thickness. For this purpose, the thickness was considered as 5 μm, 15 μm, and 30 μm. Study of the effect of Nano-particle reinforced material property was also analysed by changing the material property of topcoat from traditional to nanoparticle property. All the iterations were done for 20 cycles which contains a heating, dwell and cooling period. The mesh shape was chosen to be square with varying size. The cell size range was varied from 1 μm to 50 μm. The meshes were very fine at the TGO layer and the substrate layer has more coarse cells comparatively in order to reduce simulation timing. The number of nodes generated 1432154 numbers of cells 514227. Temperature varying property of each layer found experimentally was imported into the software in the form of a table. From the properties it was evident that the Top coat (Ceramic) was having the least thermal conductivity. TGO (Thermally Grown Oxide) layer is necessary for the adhesion of TC (Top Coat) and BC (Bond Coat).

Turbine blades which are under cyclic thermal load has tendency to create thermal residual stress accumulation in the coating leading to early delamination of the multi layered coating. So TBC coated materials came into existence in order to overcome this scenario, but even these advanced coating have their limitation. Most of the work done so far deals with the macroscopic elements. This work deals with Nano-particle property and nanoparticle coated TBC which is a new opening, since nanoparticle has an excellent thermal property, an attempt was made to do such analysis. Stress analysis can be performed to predict the propagation of cracks. Moreover the idea of thermal insulation of the TBC materials also studied by plotting a graph between the temperature vs. thickness.

a) Boundary Constraint

The constraints of symmetric boundary are used because of axisymmetric configuration. The different layers considered are isotropic and homogeneous. For the purpose of structural analysis fix all the edges in the bottom and sides of each face are fixed. The top boundary is set free. A maximum temperature of 1150 °C is given at the top most point of the Top Coat and a temperature of 27 °C is given at the bottom most point. The residual stress is induced during the cooling period of the thermal cycles. Phase transformation and creep mechanisms introduction which results in stress-relieving and can effect stress state in TBCs are assumed inactive during the simulation. All the boundaries are fixed since the main focus is on the TGO layer.

b) Cyclic Loading

For the setup of thermal cyclic loading the entire TBC’s (Thermal Barrier Coating) is to be kept in a constant temperature field, which varies with time in every Thermal Cycle (TC). The Finite Element (FE) calculation starts at 1150 °C which is a stress-free state followed by cooling down.
to room temperature and then heat up again up to 1150 °C. 20 thermal cycles continue the same way [11]. Each cycle is heated from 20°C to 1150 °C for 0.15 h heating period. It has a dwell period of 4 h for oxidation at 1150 °C. Each cycle is cooled down from 1150 °C to 20 °C for 0.3 h. During the idle period or the dwell period, a continuous oxidation takes place between the TC-BC interfaces, which in turn thickens the TGO layer at a decreasing rate.

The TGO thickness \( h \) is achieved at dwell time \( t \) by a parabolic equation: \( h^2 = 2kpt \), where \( kp \) is the parabolic rate constant. The creep strength of TGO layer depends on the grain size. The creep strength is affected by the cat ion impurities. The cat ions impurities are Yttrium or Zirconium. The creep strength of TC (Top Coat) depends on the procession conditions, so there is a wide range of creep parameters for both TC and TGO.

5. RESULT AND DISCUSSION

The materials with traditional and Nano material property was successfully simulated and the graphs shows that the proposed material that is the Nano coated material has a higher efficiency in insulating the temperature, at high temperature working conditions. Stress analysis is presented as a prerequisite for crack behaviour. The results show the effect of TGO when the TBC coated material is subjected to Thermal Cyclic Loading (TCL). Maximum shear stress is used to determine the variation of residual stress at various cycles and is depicted below. Each cycle there was a decrease in maximum principal stress in the TGO layer and Top Coat. The graph below shows the temperature vs. thickness in the case of 5μm. The graph shows that the insulation property of the top coat is larger compared to the TGO and bond coat.

5.1 Temperature flow along the TBC

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5.2 Comparison of temperature variation along the TBC interface of different TGO thickness

Figure 7 shows the Temperature vs. Thickness variation for 5μm. The top coat which is ceramic coating made up of Yttrium stabilised Zirconia insulates the major temperature from entering to the substrate and this is the main reason for the protection of the substrate from degrading at a faster rate. From the graph a comparison was done between the Nano YSZ and the traditional YSZ top coat with the same thickness of TGO layer of 5 μm. It was observed that the insulation property of the Nano coated YSZ top coat has more efficient insulating property than the traditional YSZ topcoat and naturally there was a larger temperature drop in the Nano coated, top coat and the drop was almost 25 °C. The temperature that was obtained from the graph at various interfaces for the traditional top coated YSZ for 5μm are as follows 398 °C for TC/TGO, 395 °C for TGO/BC, 302 °C for BC/substrate. In the case of nanomaterial top coated YSZ for 5μm are as follows 374 °C for TC/TGO, 36 °C for TGO/BC, 283 °C for BC/substrate coat.

![Figure 7](image_url)

**Figure. 7 Temperature vs. Thickness 5μm**

Figure 8 shows the temperature vs. thickness variation. There was no change in the thickness of the ceramic coating made up of Yttrium stabilised Zirconia remain the same but there was an increase in the TGO thickness to 15μm and this also lead to the decrease in the bond coat-135μm as the total thickness of bond coat plus TGO layer should remain 150μm. The TGO layer is formed by the corrosion of the bond coat and the aluminium present in the bond coat gets oxidised more quickly increasing the TGO layer. Again a comparison was made between Nano YSZ and the traditional YSZ top coat but in this case we have considered a different thickness of TGO which is 15μm. A larger temperature drop in the Nano coated top coat and the drop was almost 25 °C. The temperature that was obtained from the graph at various interfaces for the traditional top coated YSZ for 15μm are as follows- 399.5 °C for TC/TGO, 381 °C for TGO/BC, 315 °C for BC/substrate. In the case of nanomaterial top coated YSZ for 15μm are as follows 374 °C for TC/TGO, 368 °C for TGO/BC, 298 °C for BC/substrate coat. The temperature drop at the bond coat was comparatively reduced in comparison with the 5μm thick TGO layer, from this it can be seen that the temperature drop that was created got reduced with increase in TGO thickness.
Figure 10 represents the temperature variation with thickness. In the case of 30μm thick TGO layer. There was no change in the thickness of the ceramic-top coat and only the material property was varied, that was traditional and Nano particle properties are used for this purpose of analysis. There was an increase in the TGO thickness to 30μm and this also leads to the decrease in the bond coat thickness to 120μm as the total thickness of bond coat plus TGO layer should remain 150μm. Temperature drops in TBC material when it moves from top most point of the topcoat to the TGO Topcoat interface. The temperature that was obtained from the graph at various interfaces for the traditional top coated YSZ for 15μm are as follows 402°C for TC/TGO, 382°C for TGO/BC, 341°C for BC/substrate. In the case of nanomaterial top coated YSZ for 15μm are as follows 375°C for TC/TGO, 361°C for TGO/BC, 311°C for BC/substrate coat. The temperature drop at the bond coat was comparatively reduced in comparison with the 5μm and 15μm thick TGO layers, from this it can be seen that the temperature drop that was created got reduced with increase in TGO thickness.

Figure 9 Temperatures vs. Thickness 15μm

5.3 Temperature vs. TGO thickness

Figure 11 represents the Temperature vs. TGO thickness at the Topcoat/ TGO interface. The graph represents that the temperature ranges from 398°C to 402°C. From these graphs the first inference that was obtained is that the thermal insulation doesn’t very much in topcoat with change in TGO layer thickness. The major change that was made during the analysis is change in material property of the top coat. The Nano material top coat when compared with the traditional material property put out a very positive result by dropping the temperature difference at the interface of the layers by 250°C. This way the insulating property of topcoat is enhanced when compared with the earlier used traditional top coat materials.
Figure 10 shows the temperature variation with thickness, in the case of 15μm thick TGO layer. There was no change in the thickness of the ceramic coating made up of Yttrium stabilised Zirconia remain the same but there was an increase in the TGO thickness to 15μm and this also lead to the decrease in the bond coat-135μm as the total thickness of bond coat plus TGO layer should remain 150μm. The TGO layer is formed by the corrosion of the bond coat and the aluminium present in the bond coat gets oxidised more quickly increasing the TGO layer. Again a comparison was made between Nano YSZ and the traditional YSZ top coat but in this case we have considered a different thickness of TGO which is 15μm. A large temperature drop in the Nano coated top coat and the drop was almost 25°C. The temperature that was obtained from the graph at various interfaces for the traditional top coated YSZ for 15μm are as follows 399.5°C for TC/TGO, 381°C for TGO/BC, 315°C for BC/substrate. In the case of nanomaterial top coated YSZ for 15μm are as follows 374°C for TC/TGO, 368°C for TGO/BC, 298°C for BC/substrate coat. The temperature drop at the bond coat was comparatively reduced in comparison with the 5μm thick TGO layer, from this it can be seen that the temperature drop that was created got reduced with increase in TGO thickness.

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5.4 Maximum principal Stress vs. Time

Figure 14 shows the plots of Maximum principal stress vs. time. In the graph which is shown a superimposition of 4 graphs all of them showing the maximum principal stress at various layers in 5μm thick TGO layer. The plot shows the variations in maximum principal stress when passing through the time and has to cross through the heating, dwell and cooling condition. The red and the green line show the variation of the 5μm thick TGO layer maximum principal stress. From the plot the Nano particle coated TGO has lesser stress compared to the traditional coating. In the case maximum principal stress varies from 215.42 MPa to 143.57 MPa and the residual stress varies from 130.43 to 70.49 at end of 20 cycles in the case of TGO for traditional coating. In the case of Nano particle coated TBC the stress variation is comparatively lower and the variation of maximum principal stress varies from 201.42 to 129.57. The variation in the case of residual stress is as follows 116.44 to 56.19. The dark blue and line and the light blue line shows the variation of the 5μm thick Top Coat layer maximum principal stress and residual stress. From the plot the Nano particle coated Top coat has lesser stress compared to the traditional coating. In the case maximum principal stress varies from 293.42 MPa to 233.57 MPa and the residual stress varies from 210.77 to 135.49 at the end of 20 cycles in the case of TGO for traditional coating. In the case of Nano particle coated TBC the stress variation is comparatively lower and the variation of maximum principal stress varies from 275.99 to 203.57. The variation in the case of residual stress is as follows 190.41 to 130.19. From the plot the Nano particle coated TGO has lesser stress compared to the traditional coating.

![Figure 13 Maximum principal stress vs. Time (5 μm)](image-url)
233.57MPa and the residual stress varies from 210.77 to 135.49 at the end of 20 cycles in the case of TGO for traditional coating. In the case of Nano particle coated TBC the stress variation is comparatively lower and the variation of maximum principal stress varies from 275.99 to 203.57. The variation in the case of residual stress is as follows 190.41 to 130.19. From the plot the Nano particle coated TGO has lesser stress compared to the traditional coating.

Figure 14 plots the Maximum principal stress vs. time. In the graph which is shown a superimposition of 4 graphs all of them showing the maximum principal stress at various layers in 30µm thick TGO layer. The plot shows the variations in maximum principal stress when passing through the time and has to cross through the heating, dwell and cooling condition. The red and the green line show the variation of the 30µm thick TGO layer maximum principal stress. From the plot the Nano particle coated TGO has lesser stress compared to the traditional coating. In the case maximum principal stress varies from 250.49 to 178.49 and the residual stress varies from 165.49 to 106.34 at end of 20 cycles in the case of TGO for traditional coating. In the case of Nano particle coated TBC the stress variation is comparatively lower and the variation of maximum principal stress varies from 245.42 to 174.57. The variation in the case of residual stress is as follows 116.44 to 111.19. The dark blue and line and the light blue line shows the variation of the 5µm thick Top Coat layer maximum principal stress and residual stress. From the plot the Nano particle coated top coat has lesser stress compared to the traditional coating. In the case maximum principal stress varies from 349.9 to 279.57 and the residual stress varies from 266.47 to 206.97 at the end of 20 cycles in the case of TGO for traditional coating. In the case of Nano particle coated TBC the stress variation is comparatively lower and the variation of maximum principal stress varies from 289.99 to 213.57. The variation in the case of residual stress is as follows 206.41 to 147.19. From the plot the Nano particle coated TGO has lesser stress compared to the traditional coating.

Figure 13 Maximum principal stress vs. Time (15µm) Figure 14. Maximum principal stress vs. Time (30µm)

5 CONCLUSION
The interface temperature for the TBC material was calculated with varying temperature and the graphs were plotted. The residual stress graph with time was plotted. A comparative study of Nano particle and traditional coated material in terms of the insulation property and the residual stress variation in both the cases. From these results the proposed material which is the Nano coated YSZ can be utilized for the critical applications of the turbine blade as it has higher thermal insulating properties compared to the traditional. So the use of Nano-coated YSZ can increase the life of the turbine blade and hence be economical.
**Reference**

[1] Biao Li, Xueling Fan, Tiejun Wang and Kun Zhou 2015 Interfacial fracture behaviour of double-ceramic-layer thermal barrier coating system with segmented structure J. of Engg Fracture Mechanics

[2] Cen, W Y Qin and Yu Q M 2014 Analysis of interface delamination in thermal barrier coating system with axisymmetric structure based on corresponding normal and Tangential stresses J. of Surface and Coatings Tech.

[3] Jianan Song, Shaolin Li, Xiaoguang Yang, Duoqi Shi and Hongyu Qi 2016 Numerical study on the competitive cracking behavior in TC and interface for thermal barrier coatings under thermal cycle fatigue loading, J. of Surface aCoatings Tech.

[4] Jiang B S, Xu H D, Wanga and Lu Y U 2017 Modelling functionally graded materials in heat transfer and thermal stress analysis by means of graded finite elements J. of Applied Mathematical Modelling

[5] Jishen Jiang, Lingxin Jiang, Zhenwei Cai, Weizhe Wang, Xiaofeng Zhao, Yingzheng Liu and Zhaomin Cao 2016 Numerical stress analysis of the TBC-film cooling system under operating conditions considering the effects of thermal gradient and TGO growth J.of Surface and Coatings Technology

[6] Jishen Jiang, Weizhe Wang, Xiaofeng Zhao, Yingzheng Liu, Zhaomin Cao and Ping Xiao 2018 Numerical analyses of the residual stress and top coat cracking behavior in thermal barrier coatings under cyclic thermal loading J. of Engg fracture mechanics

[7] Marcin, Bia Las 2008 Finite element analysis of stress distribution in thermal barrier coatings J. of Surface & Coatings Tech.

[8] Moridi, Azadi M and Farrahi G H 2012 Thermo-mechanical stress analysis of thermal barrier coating system considering thickness and roughness effects J. of Surface and Coatings

[9] Nayebpashaee, Seyedein S H, Aboutalebi M R, Sarpoolaky H and Hadavi S M M 2015 Finite element simulation of residual stress and failure mechanism in plasma sprayed thermal barrier coatings using actual microstructure as the representative volume J. of Surface and coatings tech.

[10] Valente C Bartuli M Sebastiani and Casadei F 2004 Finite element analysis of residual stress in plasma-sprayed ceramic coatings J. of SAGE

[11] Abbas, Guo H and Ramzan M 2018 Comparative study on effect of oxide thickness on stress distribution of traditional and Nano structural zirconia coating systems J. of Ceramics

[12] Wang, Wanga Y, Zhang W Q, Suna X G, Hea J Q, Pana Z Y and Wanga C H 2011 Finite element simulation of stress distribution and development in 8YSZ and double-ceramic-layer La2Zr2O7/8YSZ thermal barrier coatings during thermal shock J. of Applied Surface Science

[13] Youho Lee, Jeong Ik Lee and Hee Cheon NO 2010 Mechanical analysis of surface-coated zircaloy cladding J. of Surface & Coatings Tech.

[14] Abbas, Guo H and Ramzan M 2018 Comparative study on effect of oxide thickness on stress distribution of traditional and Nano structural zirconia coating systems J. of Ceramics

[15] Yu, Cen L and Wang Y 2017 Numerical study of residual stress and crack nucleation in thermal barrier coating system with plane model J. of Ceramics International

[16] Yu, Zhou H L and Wang L B 2015 Influences of interface morphology and thermally grown oxide thickness on residual stress distribution in thermal barrier coating system J. of Ceramics Int.