

AN INVESTIGATION INTO THE EFFECT OF CRITICAL PARAMETERS ON RESIDUAL STRESS BUILD-UP IN THERMAL BARRIER COATING

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Abstract

Thermal barrier coatings (TBCs) are widely used on different hot components of gas turbine engines such as blades and vanes. Although, several mechanisms for the failure of the TBCs have been suggested, it is largely accepted that the durability of these coatings is primarily determined by the residual stresses that are developed during the thermal cycling. In the present study, the residual stress build-up in an electron beam physical vapour deposition (EB-PVD) based TBC on a coupon during thermal cycling has been studied by varying three parameters such as cooling rate, TBC thickness and substrate thickness. A two-dimensional thermo-mechanical plane strain finite element simulations have been performed for thousand cycles. It was observed that these variations change the stress profile significantly and stress severity factor increases non-linearly. Overall, the predictions of the model agree with reported experimental as well as simulated results.

Keywords: Thermal barrier coatings, residual stress, Modeling and simulation.

1. Introduction

Thermal barrier coatings (TBCs) used on advanced gas turbine engine components increases engine efficiency and performance and thereby prolongs the life of these turbine components [1-3]. The schematic representation of a typical TBC system is shown in Fig 1.1[11]. It is now well established that Pt-modified diffusion aluminide (Pt-Al) bond coat in combination with 7% Ytria Stabilized Zirconia (7 YSZ) ceramic coat provides the best thermal barrier effect for Ni-based superalloy components of gas turbine engine [2]. The performance of TBCs is affected by several micro-structural factors [4-6], porosity in the ceramic layer [7] and stress developed in the TBC system, especially during cyclic heating and cooling (thermal cycling) in an engine environment [8-10].

Stresses in a TBC are generated through three events, namely phase transformation, rapid expansion and contractions, and mismatch of thermal expansion coefficients of the substrate and coatings. In the present study of TBC (YSZ) system, stress build-up due to the transformation of zirconia phase, from tetragonal to monoclinic phase and vice versa stress build-up has not been considered. The second contributing component to the overall residual stress is due to rapid expansion and contraction of the system because of thermal cycling. Typically for a single layer system; mathematically, the magnitude of this stress can be estimated from the following equation:

$$\sigma = \alpha (T - T_{\text{ref}}) E \quad (1)$$

where α , T , T_{ref} , E are coefficient of thermal expansion, temperature at any instant and reference of the system and Elastic modulus of the material respectively.

The third component of stresses is differential thermal contraction (DTC) also known as thermal stress, and is induced by the mismatch in CTE of the substrate and coating. And this component play a very important role in the overall failure of the ceramic layer, extensive experimental and modeling work has been carried out to understand the development of these stresses [11-19]. Considering two-dimensional stress-strain analysis, thermal stress at the interface of a two layer system [18] σ_{tb} can be estimated as:

$$\sigma_{\text{tb}} = E \Delta\alpha\Delta T (1+\nu)/(1-\nu^2) \quad (2)$$

Where E , $\Delta\alpha$, ΔT and ν are Elastic modulus of coating, CTE mismatch between bond coat and ceramic, temperature difference and Poisson's ratio of coating respectively. Both analytical and numerical methods have been adopted to model the development of thermal residual stresses in TBCs considering presence of surface undulation and plain TGO on the bond coat. Hsueh et al. [13] and Chun et al. [14] have carried out modeling with convex and concave asperities at bond coat/ceramic interface. They used analytical models where the in-plane cross-section of the TBC system was modeled as three concentric circles, namely bond coat, TGO and ceramic. Residual thermal stresses at the TGO/BC and the TGO/ceramic coat interfaces were then calculated as a function of TGO thickness. Evans et al. [11] have also used an analytical model for computing residual stresses in TBCs. Mao et al [17] have incorporated creep mechanism in their analytical model to study residual stress build-up in TBCs. Despite these attempts, analytical methods have largely failed to accurately predict the stress states in a complex system such as TBC. Therefore, numerical methods have been increasingly used in recent times. Wright et al. [12] have adopted a numerical model in which they have assumed that the material properties vary linearly with temperature. Srivathsa et al. [15] have studied development of residual stresses using finite element method considering both planar and undulated TGO. The properties of the constituents of the system are considered as temperature dependent and discussed the effect of undulations on residual stress build-up. Piotr [16] has developed a numerical model for simulating thermal stress by taking local and global approach and discussed the effect of thermal shock in stress build-up. Mao et al [17] have studied the effect of bending moment and curvature on stress variation by considering non-linear elasto-plastic deformation and thermal fatigue. Chen et al. [18] have shown that the possibility of crack initiation increases with convective coefficient which also increases the normal stress at interface of BC/TGO in their numerical simulation.

In this study, a two-dimensional (2D) finite element method based numerical model is proposed to study the thermo-mechanical behavior of the system. Simulations are carried-out on a sample subjected to a thermal cycling keeping the cycling furnace conditions in mind. Residual stress developed in TBCs during 1000 thermal cycles is calculated using ANSYS 14.0. The main objective of this particular paper is to describe the effect of three critical parameters namely substrate thickness, TBC thickness and rapidity of cooling cycle on the development of residual stresses during thermal cycling.

2. Finite Element Model

2.1 Specimen configuration

The coated specimen considered in this study is schematically shown Fig. 2.1. The specimen (substrate) has a disc shape having a diameter of 30 mm and thickness of 2 mm. CM-247LC Ni-based superalloy has been considered as the substrate material in this study. The thicknesses of the Pt-Al BC and the 7YSZ ceramic layers are 50 and 100 μm respectively. A finite element model was developed for the above TBC system using coupled field 8 noded ANSYS element plane 223 having three DOF (u_x , u_y and T) for each node. To improve the accuracy of the results, Domains are discretized with decreasing element size from substrate to bond coat/TBC interface with the smallest being of the order of 10 μm . Mesh sensitivity analysis revealed that the above mesh refinement was adequate as the error in the effective strain was less than 0.02%. The above two-dimensional plane strain model developed based on conservation principles was used for determining the stresses that develop in the TBC system during cyclic heating and cooling. The heat flux resulting from the thermal load was calculated using Fourier's heat law, which essentially relates the heat flux to the temperature gradient. The temperature gradient causes strains among the constituents of the TBC system because of the differences in their CTEs. The details of the model formulation have been provided in a previous study [15].

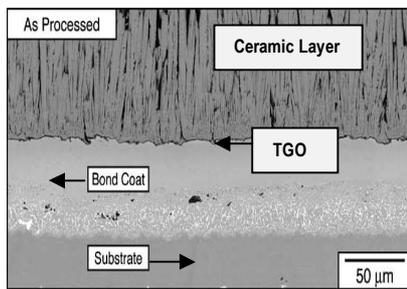


Figure 1.1 A typical TBC system showing all the constituents [11]

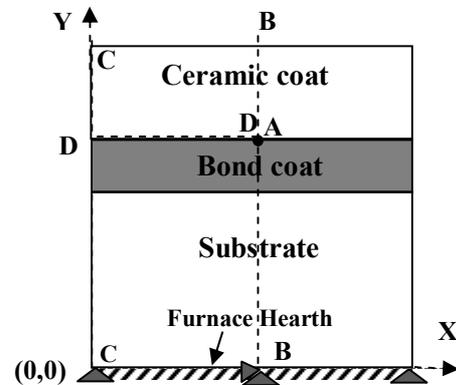


Figure 2.1. The TBC system used in the present study.

2.2. Materials Properties

The three constituents of the TBC are assumed to be homogeneous and isotropic. Thermal and elastic-plastic properties of the substrate and bond coat materials were considered to be temperature dependent. While temperature dependent thermal and elastic properties were considered for 7YSZ coating. Material properties used in the present calculations have been reported elsewhere [15, 16]. Bilinear isotropic hardening elasto-plastic behaviour has been assumed for substrate and bond coat materials. Although, the material properties such as strength, density, modulus etc., of the constituents may vary during thermal cycling [20], such variations have been neglected in this study and the properties of all constituents of TBC have also been assumed to remain unaffected during thermal cycling.

2.3. Thermal Loading

The TBC coated specimen (Fig. 2.1) was subjected to a thermal cycle consisting of a heating period inside a furnace during which, the coated specimen was exposed to the furnace temperature of 1100°C for 30 min. Subsequently, the specimen was kept outside the furnace for 30 min during which cooling of the specimen took place in ambient air. The heating and cooling period of a cycle are schematically shown in Fig. 2.2.

2.4. Boundary Conditions

As shown in Fig. 2.1 the sample is placed on the furnace hearth. It has been assumed that the heat transfer between the sample and the surrounding occurs by convection. From heat transfer point of view, while the sides and top surface of the specimen remain completely open to the atmosphere, its bottom surface remains only partially exposed. Therefore, a relatively lower convective heat transfer coefficient has been used for the bottom surface as compared to the other surfaces. Translational motion of the bottom surface of the specimen in Y direction is constrained and the mid-point of the bottom surface is constrained in x-direction. Schematically these conditions are shown in Fig 2.1.

2.5. Parametric considerations

In the present study, three different parameters have been considered in terms of their effect on temperature and stress distribution in the TBC. These parameters are: (a) substrate thickness, (b) ceramic (7YSZ) layer thickness, and (c) rapidity of cooling during the cooling period. Rapidity of cooling has been varied by altering the convection coefficient. In the present study, one parameter at a time has been changed while assessing the effects of these parameters. All combinations of these parameters for which computations were made are listed in Table 2.1 along with their values. Structural boundary conditions have been kept same in all the cases.

Table 2.1 The various combinations of parameters considered for simulations in this study. The BC thickness has been kept constant at 50 μm in all the cases.

Condition	Substrate thickness (mm)	Ceramic layer thickness (μm)	Heating period	Cooling period	Type of air cooling used (η in $\text{W}/\text{m}^2 \cdot \text{K}^{-1}$)
Variation of rapidity in cooling					
1	2	100	30 min.	30 min.	Natural cooling ($\eta = 5$)
2					Natural cooling ($\eta = 10$)
3	2	100			Natural cooling ($\eta = 25$)
Variation of 7YSZ thickness					
4	2	50	30 min.	30 min.	Natural cooling ($\eta = 5$)
5		300			
6'		50			Natural cooling ($\eta = 25$)
6''		300			
Variation of substrate thickness					
7	0.5	100	30 min.	30 min.	Natural cooling ($\eta = 5$)
8	5				

2.6. Simulation Details

Two-dimensional plane strain finite element simulations have been performed using ANSYS 14.0. A transient thermo-mechanical coupled analysis has been employed for carrying-out the simulation. Analysis is carried out for a stepped loading condition. High performance computing features using a distributed Sparse equation solver on a single machine with

distributed memory option has been used to reduce the computational time. Newmark backward difference scheme is used as time integration algorithm. This approach helped increasing computational speed without compromising on convergence in both force and displacement under L2 norm.

3. Results and Discussion

Residual stresses computed from the present finite element study are mainly due to differential thermal contraction and also due to rapid expansion and contraction during the thermal cycling. Specimen has been subjected to 1000 thermal cycles and stress distributions are calculated for the entire TBC system. Three stress components namely: (i) radial stress (σ_x or in-plane stress) component that refers to the stress parallel to the interface; (ii) normal stress (σ_y or out-of-plane) component corresponding to stress profile through the thickness of the coatings or perpendicular to the interface; and (iii) shear stress (σ_{xy}) in xy-plane have been considered as these are mainly responsible for TBC failure.

It can be appreciated that the rate of change of stress, i.e. stress change (build-up or relaxation) at a given location and any instance during cooling cycling is going to be a critical factor from the stand point of TBC failure. A higher rate of change of stress would likely cause a faster TBC failure. To examine this aspect, the maximum value in the plot $d\sigma_x/dt$ vs time plots, i.e. $(d\sigma_x/dt)_{max}$, has been used to indicate the severity in stress change at the interfaces. The above factor, i.e. $(d\sigma_x/dt)_{max}$ has been referred as stress severity factor (SSF) in this paper.

3.1 Verification of the model

The accuracy of finite element model was verified by comparing the computational result of residual stress in a two-layer system, considering the bond coat and ceramic coat, with the analytical solution of stress (σ_x) at coating surface using Eq. (2). Comparison of residual stress at the substrate/bond coat interface is shown in Fig 3.1. It can be seen from Fig. 3.1 that the calculated residual stress (-255 MPa) at the interface of bond coat/ceramic coat having 100 μm coating thickness agrees well with the analytical value obtained from Eq. (2). As expected, an increase in coating thickness, e.g. 300 μm coating would lead to a greater deviation of FE result from the analytical solution. As the validity of FE model has been verified, the analyses were extended to include substrate making it as functionally gradient TBC system.

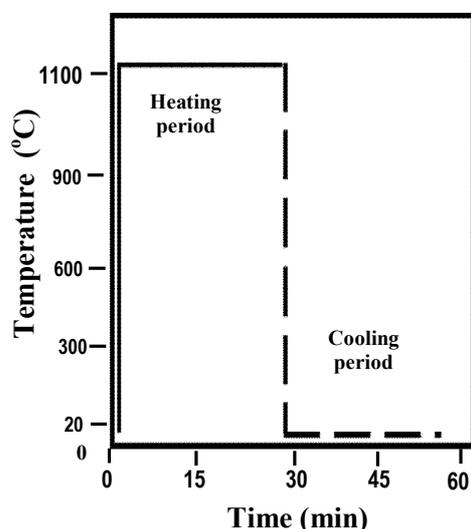


Figure 2.2. Thermal cycle used for simulation studies.

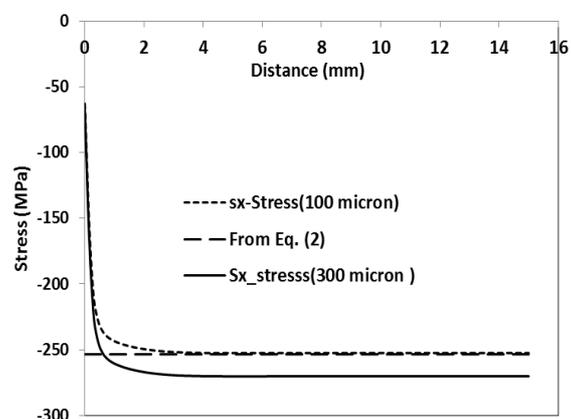


Figure 3.1. Stress distribution at substrate/BC interface in the axial direction during hold time plotted as a function of radial distance from the edge to the center of the specimen.

3.2 Typical Temperature and stress distribution during a thermal cycle

As previously mentioned, simulations were carried-out on the 2 D specimen shown in Fig. 2.1 for the conditions mentioned in Table 1. The temperature change at the midpoint of 7YSZ/BC interface (Point A fig. 2.1) with time during the first thermal cycle is as shown in Fig. 3.2. The temperature at this point attain the furnace temperature of 1100 °C in about 6 min. after which it remains constant at this value for the remaining duration of heating period. During cooling period, the temperature drops under natural cooling quickly from 1100 °C to 120 °C in about 10 min. Subsequently, the temperature drops fairly slowly as evident from Fig. 3.2. Similar trend is observed during subsequent thermal cycles (up to 1000 cycles). The stress (σ_x) build-up at point A corresponding to the above temperature change has also been plotted in Fig. 3.2. It is evident from this figure that the stress at interface remaining compressive and reaches a maximum of 255 MPa during heating period and these compressive stresses were released during cooling cycle. At the end of cooling cycle, the stress becomes near zero. Stress (σ_x) distribution through center across the thickness of the specimen (along the line B-B in fig. 2.1) has been plotted as shown in Fig 3.3. From this figure it is clear that during heating and cooling cycle, interfaces are the only stress concentration regions across the thickness of the specimen. Compressive stresses (255 MPa) developed at the interface are relaxed to 120 MPa during the cooling cycle. Also, stress gradients are very high at 7YSZ/ bond coat interface during heating and cooling cycle. And a clear stress reversal can be noticed across the interfaces. While the substrate and top coat remain under tension during thermal cycle, bond coat remains in compression.

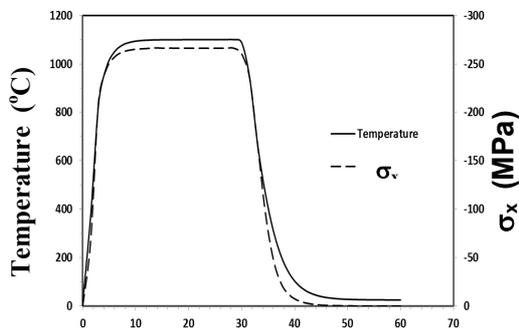


Figure 3.2 Temperature and stress (σ_x) distribution at point A (Fig. 2.1) during the first thermal cycling.

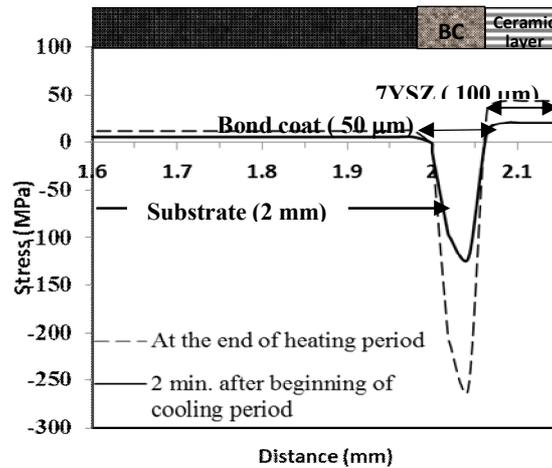


Figure 3.3 Stress (σ_x) distribution along line B-B shown in Fig. 2.1

In Fig 3.4, stresses (σ_y) are plotted along the line B-B (Fig. 2.1) of the specimen during the first thermal cycle. It can be noticed that during the heating cycle, the specimen is subjected to tensile stress and the maximum stress is noticed at the 7YSZ/bond coat interface with high stress gradients. While experimentally measured maximum stress at the 7YSZ/BC interface is around 70 MPa [21] which is in good agreement with the present FEA results; although, simulated stresses are slightly lower than the measured values. This could be attributed to the effect of interface roughness of specimen, FEA performed in this study assumed flat interfaces between dissimilar materials. On the contrary, it has been shown that surface roughness generates higher stresses (σ_y) [22]. The surface of the top coat retained a very small tensile stress (0.0052 MPa) at the end of the first thermal cycle. With thermal cycling this tensile stress has slowly become compressive and the effect this will be discussed later. Further, stress (σ_y) distribution along the line C-C (Fig. 2.1) of the specimen has been plotted

as shown in Fig. 3.5. During the heating cycle stresses at the free edge are practically zero, because expansions during heating were not restrained. Although, it is true even during cooling cycle, but due to CTE mismatch, stresses build-up significantly in the TBC system. While compressive stresses are observed within the substrate, the maximum tensile stresses have been noticed at BC/7YSZ interface. It can be seen that the stress gradients are very high at BC/7YSZ interface. These gradients may lead to opening-up the top coat from the edge of the specimen. This opened edge of coating or delamination of coating may be further assisted by stress (σ_y) distribution from the edge to the center along the 7YSZ/bond coat interface (line D-D in Fig. 2.1). This stress (σ_y) distribution is as shown in Fig. 3.6. A maximum stress of 230 MPa was found near free edge of the specimen and this value is decreased with distance from edge to the centre. Also it has been observed that the shear stress showed a considerable stress concentration at the BC/7YSZ interface near the free edge. Hence, this tensile stress (σ_y) may cause spallation of the coating, initiated at the free edge, propagates radially towards the center region of the specimen causing a progressive delamination [23, 24] with thermal cycling. The magnitudes of the stress at the 7 YSZ/BC interface and stress states during the thermal cycle are in good agreement with the earlier reported/measured values [23, 25]. Further the results of these simulation studies have been analyzed by considering only σ_x stresses as these are more critical from failure point of view.

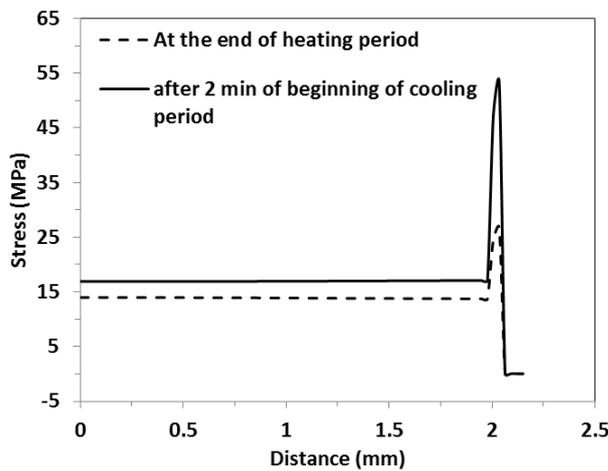


Figure 3.4. Stress (σ_y) distribution along the line B-B (Fig. 3.1).

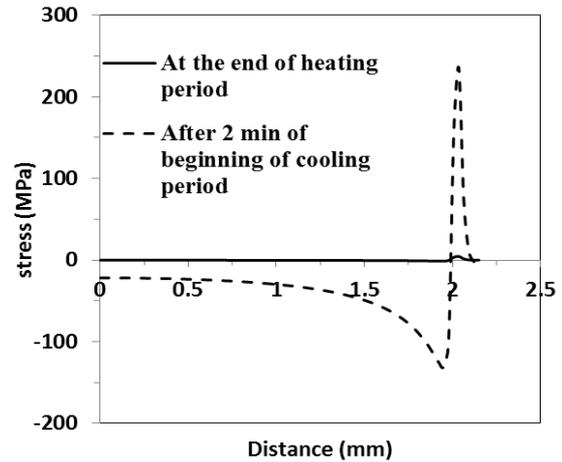


Figure 3.5. Stress (σ_y) distribution along the line C-C (Fig. 3.1).

3.3 Effect of cooling rate

In actual gas turbine environments, TBC components undergo cooling with various rapidity during thermal cycling. Rapidity in cooling (or the rate of heat extraction during cooling period) can affect the life of TBCs. In fact, reduced life of TBCs under forced cooling as compared to that under natural cooling has been reported [24-29]. As mentioned previously, the effect of rapidity in cooling during cooling period has been examined by considering three different convective heat transfer coefficients during cooling period and the heat transfer coefficient during heating period has been kept at constant in all the three above conditions. The variation of temperature and stress with time at location A (Fig. 2.1) during the first thermal cycle is shown in Fig. 3.7 (a) and (b) respectively. As expected, the temperature variation in all the three constituents (7YSZ, BC and substrate) is identical during the heating period as the same convective coefficient has been considered during this period. During cooling period, however, the effect of rapidity in cooling is clearly visible, as shown in Fig 3.7 (a). Rate of temperature drop for higher coefficient is much higher than that for lower

one. A similar trend is also evident in terms of stress variation with time as shown in Fig. 3.7 (b). The effect of rapidity in cooling becomes more evident by plotting rate of stress change ($d\sigma_x/dt$) vs. time, as shown in Fig. 3.8. The value of stress change $(d\sigma_x/dt)_{\max}$ or SSF for $\eta = 25 \text{ W.m}^{-2}.\text{K}^{-1}$ is around 90 MPa.s^{-1} which is nearly twice the value of 45 MPa.s^{-1} corresponding to $\eta = 5 \text{ W.m}^{-2}.\text{K}^{-1}$. Thus, it is apparent that the severity of stress change at BC/7YSZ interface during the cooling period of any given cycle increases significantly by increasing the rapidity in cooling, i.e. increasing the value of η .

Due to this, the chances of 7 YSZ/bond coat interface failure are high. More heat will be dissipated to the air with a higher convection coefficient due this less heat being transferred by conduction to the adjacent layer(s). Therefore, the underlying substrate would be at a lower temperature, resulting in induced thermal stress component is lower. These results are in good agreement with those given by Bialas [21]. If no temperature gradient is considered during the cooling, the stress would remain in compression [30]. Therefore, the cooling rate rather than the temperature difference of the thermal cycle is crucial for crack formation at the interface [30, 32].

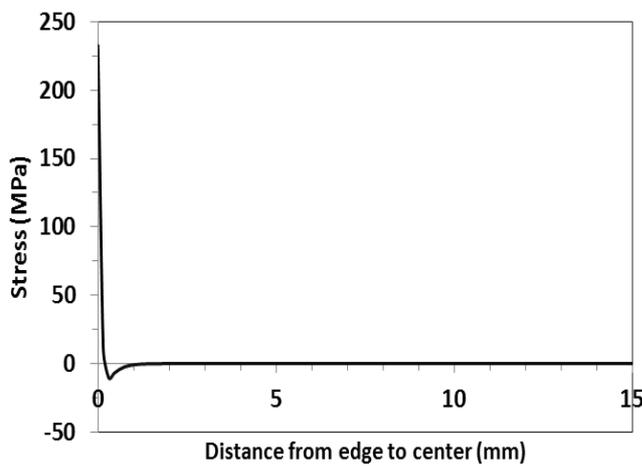


Figure 3.6. Stress (σ_y) distribution along the line D-D (Fig. 3.1).

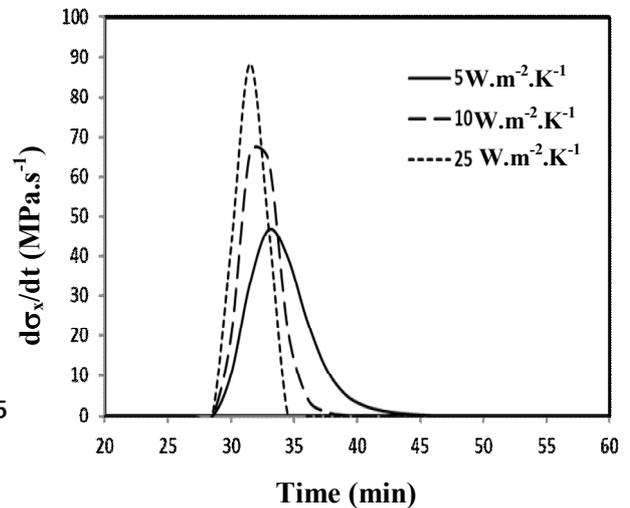


Figure 3.8. Stress gradients at 7YSZ/BC interface

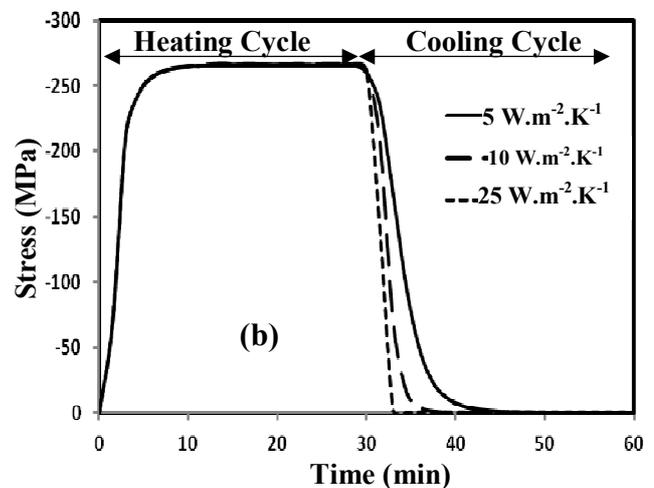
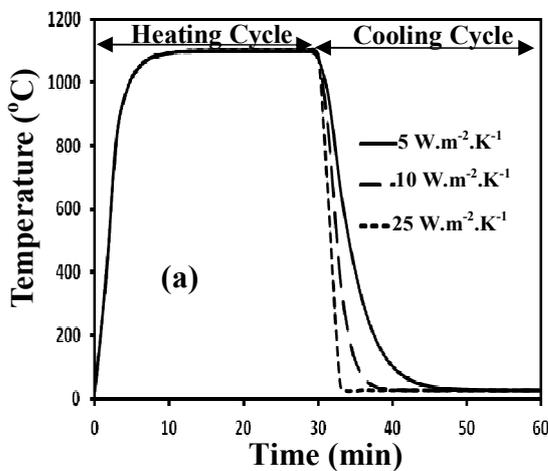


Figure 3.7. Effect of rapidity in cooling at a point A (Fig. 2.1) in terms of (a) temperature and (b) stress

3.4. Effect of thermal barrier coating thickness

One way to have a higher operating temperature in the gas turbine engine would be to use a thicker 7YSZ ceramic coat. This would produce a higher temperature gradient across the ceramic layer and, therefore, keep the metallic bond coated substrate at a comparatively lower temperature. Simulations have been carried out using three different ceramic layer thicknesses to examine the effect of thickness on the stress developed at ceramic/bond coat interface. Stress analysis has been carried out with 7YSZ layer of thickness of 50, 100 and 300 μm . The other parameters used for simulation were kept same as listed under Conditions 1, 10 and 11 in Table 2.1. The variations of temperature and stress at point A (Fig. 2.1) with time during the first thermal cycle are plotted in Fig. 3.9 for the above three ceramic layer thicknesses. It is evident that the variation in temperature and, hence the stress, at point A remains virtually the same during both heating and cooling periods of all three ceramic layer thicknesses. In other words, the ceramic layer thickness has no appreciable effect on the stress (σ_x) change at the ceramic/BC interface during the first cycle. This is also evident in terms of the variation in $d\sigma_x/dt$ with time during cooling period as shown in Fig. 3.10. It is important to point out here that the bottom surface of the coated specimen in the present configuration (Fig.2.1) is resting on the furnace base and not directly exposed to the environment. Therefore, a lower convection coefficient has been considered for this surface. In actual application of TBC coated hollow components, however, this surface will be internally cooled by passing air. In such case, the convection coefficient for this surface would be much higher than the value as considered in this study. To examine this aspect, a hypothetical situation was considered where the convection coefficient for the bottom surface of the sample is much higher. The other conditions are kept constant as mentioned before (see conditions 6' and 6'' in Table 2.1). Comparison of σ_x and temperature for this hypothetical situation was carried out for ceramic layer thicknesses of 50 and 300 μm . Figure 3.11 shows the $(d\sigma_x/dt)$ vs. time plot for the first cycle for the convection coefficient of $25 \text{ W.m}^{-2}.\text{K}^{-1}$ for two ceramic thicknesses, namely 50 and 300 μm . It is clear that $(d\sigma_x/dt)_{\text{max}}$ or SSF for the higher ceramic thickness (300 μm) at 52 MPa.s^{-1} is nearly 20% lower than the value of 65 MPa.s^{-1} obtained for the lower thickness of the ceramic coating (50 μm). From the above results, it can be expected that in actual application, the ceramic layer thickness would have much more significant effect as compared to that observed in this study.

However, the effect of TBC thickness can be seen across the thickness of the specimen as shown in Fig. 3.12. From this figure, it is clear that increase in coating thickness resulted in reducing stresses in substrate but increases the tensile stresses of the top coat. Whereas, bond coat and substrate/BC interface has become more compressive. This is because of the greater thermal gradients, which leads to higher thermal stresses that occur within the top coat. In addition, the increased thickness of the coating will increase the stored elastic strain energy which increases the energy release rate for crack propagation. Increased top coat thickness also increases the shear stresses near the free edge, because of this increase in coating thickness may decrease the life these coatings. Therefore, one can notice that there is an optimum topcoat thickness between extremely thick and thin top coatings. In addition, these layers are desired to be thin and low density to limit the centrifugal load on rotating engine components and have good thermal and mechanical compatibility.

For these reasons, thick topcoats fail because of spalling, cracking, and chipping within the topcoat layer. Whereas thinner coatings are less susceptible to these types of failures and are

affected more so by thermal expansion mismatch between the various layers and by oxide formation at the bond coat/ topcoat interface.

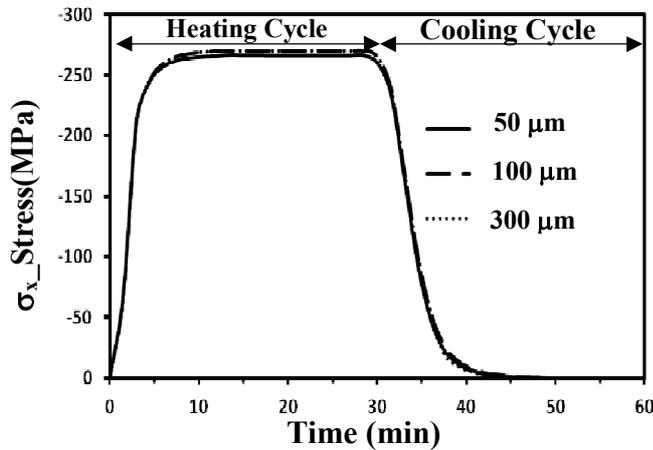


Figure 3.9. Effect of 7YSZ layer thickness at point A (Fig. 2.1) during first thermal cycle

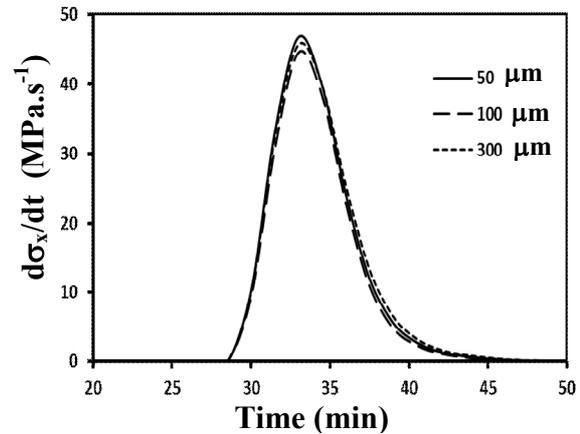


Figure 3.10. Effect of 7YSZ layer thickness on rate of stress change at point A during first thermal cycle

3.5. Effect of substrate thickness

Turbine components such as blades and vanes have varying section thickness with minimum thickness as low as 0.5 mm and maximum thickness up to 5 mm. Such variation in substrate thickness can potentially cause significant stress variations among various locations of the component during thermal cycling [33-36]. The effect of substrate thickness on stress build-up in TBC has been simulated by considering substrates of three different thicknesses, namely 0.5, 2 and 5 mm. The other parameters used for simulation have been kept constant, as mentioned under conditions 1, 12 and 13 in Table 2.1. From Fig. 3.13, it is apparent that the temperature and the corresponding stress distribution for different substrate thicknesses are very different. For example, the temperature rise at the interface (at point A in Fig. 2.1) during heating period and temperature fall during cooling period occur at a much faster rate as the substrate thickness decreases from 5 mm to 0.5 mm. The temperature at BC/ceramic layer interface drops from 1100°C at the beginning of cooling period to close to RT in 3 min for substrate thickness of 0.5 mm. The corresponding duration over which such a temperature drop occurs in case of 5 mm thick substrate is much higher at 30 min. This differential rate of cooling caused by the variation in the thickness of substrate affects the rate of stress change at the BC/7YSZ interface during the cooling period, as evident from Fig. 3.14. From the $d\sigma_x/dt$ vs. time plot for the first thermal cycle for the above three substrate thicknesses it is apparent that the $(d\sigma_x/dt)_{max}$ or SSF corresponding to 0.5 mm thick substrate at 75 MPa.s^{-1} is nearly 4 times higher than that for 5 mm thick substrate. The SSF for 2 mm thick substrate is about 2 times lower than that for 0.5 mm thick substrate. Thus, it is clear that the variation in the thickness of the substrate (for a given bond coat and 7 YSZ thicknesses) would have a major effect on the life of the TBC. This aspect is important in the context of turbine engine components (blades and vanes) where TBC on the thinner sections of the component would be more vulnerable to failure.

3.6. Stress variation over 1000 thermal cycles

The results pertaining to the effect of various factors such as cooling rate, substrate thickness etc. on the stress change at BC/ceramic layer interface, as presented in the preceding sections,

have been obtained in the first thermal cycle. However, coated components in the actual use undergo several thermal cycles before the ceramic layer fails. To examine the stress build-up in such a situation, simulations were carried-out up to 1000 thermal cycles, as previously mentioned. Figure 3.15 shows the change of SSF with number of cycles for various rapidities of cooling (as expressed in terms of convection coefficients). It is clear from this figure; SSF for any given η does not vary appreciably with number of cycles over the 1000 cycle duration. For example, SSF for $\eta = 25 \text{ W.m}^{-2}.\text{K}^{-1}$ remains virtually constant at about 90 MPa.s^{-1} over 1000 cycles. The same for $\eta = 5 \text{ W.m}^{-2}.\text{K}^{-1}$ increases only slightly from about 47 MPa.s^{-1} for the first cycle to about 55 MPa.s^{-1} after 1000 cycles. This trend of SSF remaining virtually constant over the 1000 cycles is also found in case of other factors, as typically shown in terms of the effect of substrate thickness in Fig. 3.16. It is evident from these results that although the factors considered namely the cooling rate, substrate thickness, ceramic layer thickness and heating/cooling durations, may significantly affect the rate of stress change at 7YSZ/BC interface in all individual thermal cycles; there is no cumulative effect of these factors over multiple thermal cycles.

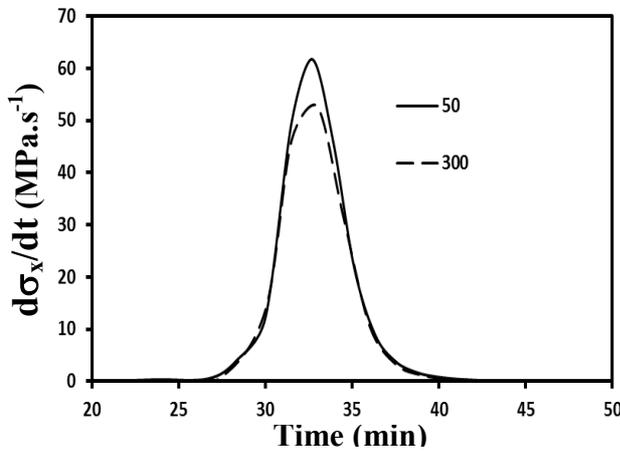


Figure 3.11 Effect of coating thickness on $d\sigma_x/dt$ when a higher η ($= 25 \text{ W.m}^{-2}.\text{K}^{-1}$) at the bottom surface of the coated sample is used.

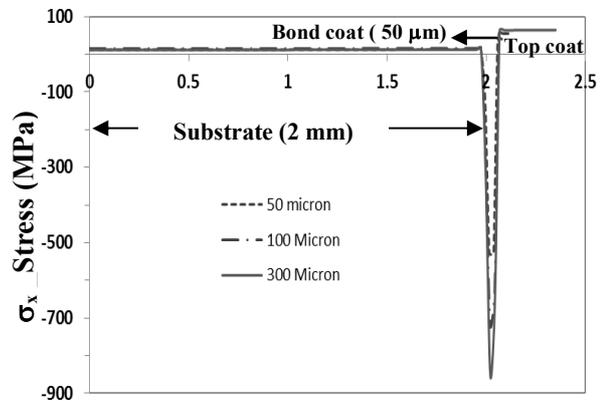


Figure 3.12. Effect of TBC thickness on stress distribution along the line B-B (Fig. 2.1)

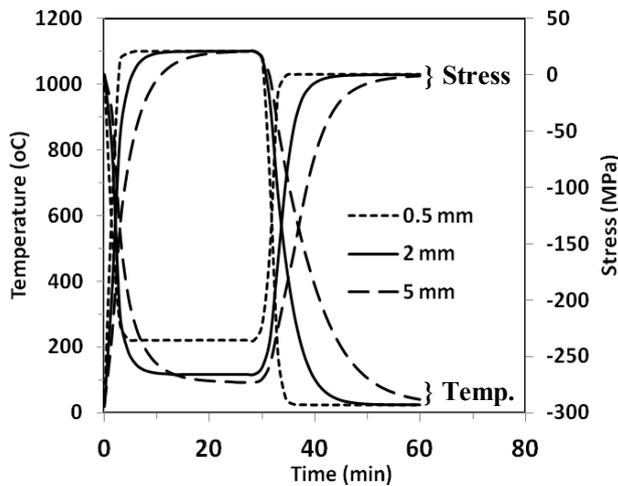


Figure 3.13. Effect of substrate thickness on temperature and stress (σ_x) distribution

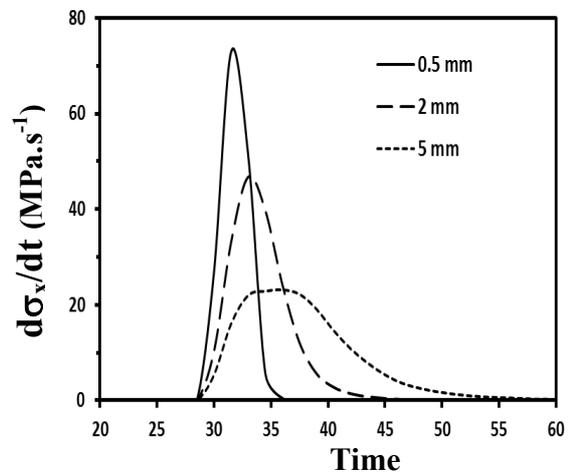


Figure 3.14. Effect of substrate thickness on stress severity factor

In the present simulation study, the effect of temperature changes during thermal cycling on the change in stresses in a typical TBC system has been considered. It is important to point out that many factors other than temperature variation also cause change in stresses in the TBC. Prominent among these factors are TGO growth, rumpling in the bond coat, microstructural changes in the bond coat and ceramic coating. Even sintering of the columns in the ceramic layer over long periods of high temperature exposure [26, 37- 39] and creep deformation [33] can also lead to changes in stresses in the TBC. The present simulations have not considered all these factors. Therefore, the results obtained in this study are only indicative. However, the results do provide a quantitative feel for the effect of thermal stresses develop in TBC during thermal cycling. For example, a five time increase in the value of convective coefficient (from 5 to 25 $\text{W.m}^{-2}.\text{K}^{-1}$) increases the SSF value by about two times (Fig. 3.4). A ten time of increase in the substrate thickness (from 0.5 mm to 5 mm) on the other hand decrease the SSF by a factor of about 4.5 (Fig.3.9)

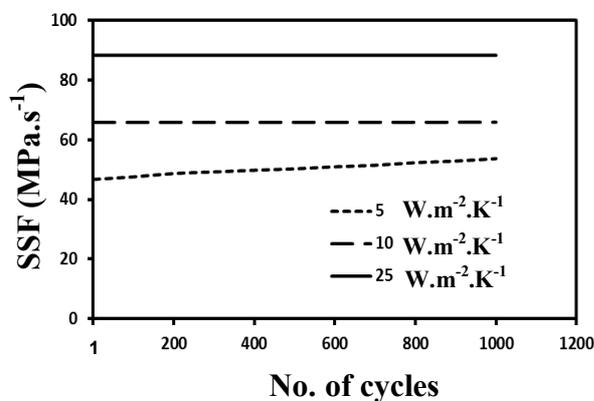


Figure 3.15. Effect of rapidity in cooling on SSF at 7YSZ/BC interface (point A in fig. 2.1).

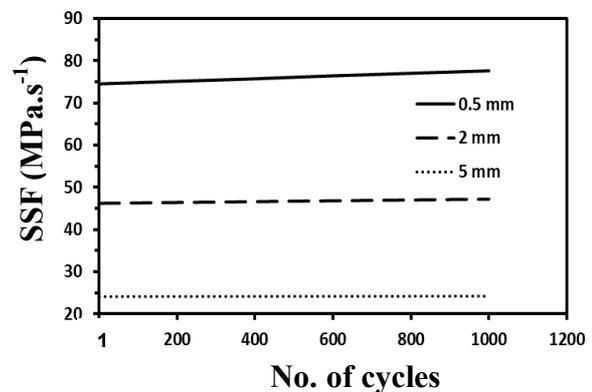


Figure 3.16. Effect of substrate thickness on SSF at 7YSZ/BC interface (Point A in Fig. 2.1)

4. Conclusion remarks

A two-dimensional coupled-field plane strain, transient finite element simulations have been carried out to evaluate residual stress build-up in a thermal barrier coating during thermal cycling. Parameters which affect the life of thermal barrier coatings, such as substrate and top coat thickness and cooling rate have been considered for simulating the residual stress build-up during 1000 thermal cycles. Stress severity factors are calculated to quantify the significance of these parameters on residual stress build-up. Among the three parameters considered for the study it is observed that substrate thickness and cooling rate affect the life of these coating severely. However, it can be noticed as illustrated in section 3.4 in actual situation turbine blades are designed with cooling channels to provide efficient cooling system. Thus proving a higher convective coefficient at bottom line showed the effect of coating thickness also. All these three parameters change the stress profile and stress severity factor increases non-linearly. Overall, the predictions of the model agree with the experimental as well as simulated reported results. The modelling work presented in this study contributed to a better understanding of the residual thermal stresses build-up during 1000 thermal cycles.

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