Journal of New Technology and Materials
JNTM
Vol. 05, N°02 (2015)08-19

OEB Univ. Publish. Co.

Thermal Analysis of Partially Stabilized Zirconia and Lanthanum Magnesium Hexaaluminate as Thermal Barrier Coatings over Hastelloy X Gas Turbine Blade

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Received date: July 02, 2015; accepted date: October 03, 2015

Abstract

The sprayed partially stabilized zirconia (8 % by wt. yttria) and lanthanum magnesium hexaaluminate were investigated as materials for thermal barrier coatings over Hastelloy X as substrate for a high temperature gas turbine blade model using NiCrAlY as an interlayer bond coat material. The temperature and heat flux based steady and transient thermal analyses were performed over variable thickness models for two different coating materials using a FEM based commercial ANSYS Workbench v14.5 software package. It was found that under applied thermal loading conditions, just a 200 microns thick zirconia coating used with 150 microns NiCrAlY layer was capable to reduce steady state substrate temperatures by 35.6 % and proved to be 3.72 % more effective than an equal thickness lanthanum magnesium hexaaluminate coating. Similarly, steady state top surface heat flux was found to be 15.7 % lesser for the former as compared to later. The increased thickness of coatings observed further reductions in the substrate temperatures and top surface heat flux values, however, the zirconia coatings were found to be more effective than lanthanum aluminate coatings at higher thicknesses in terms of suppressions of heat penetration and substrate temperatures. A steady state top coat – bond coat interface heat flux analysis further helped in anticipating that thin films of zirconia could be more durable than lanthanum aluminate coatings in the high flux working conditions as prevailing inside a gas turbine system.

Keywords: *Thermal barrier coating (TBC); Partially stabilized zirconia; Lanthanum magnesium hexaaluminate; Gas turbine; Hastelloy X*

1. INTRODUCTION

Over the years in the history of gas turbines, technological advancements led efforts have been made to increase efficiency of the system. These efforts have ultimately made it possible to achieve turbine inlet temperature (TIT) of 1600 ºC and over in the modern advanced gas turbine systems as compared to 800 ºC during 1960s [1-2]. However, such elevated TITs being high above even melting point of the blade material demand for high cooling loads for the blades and advanced/sophisticated cooling techniques [3]. Due to this, high temperature materials have always been a focus of attention for the metallurgical scientists and researchers. In fact, improvements in TITs have been possible with the improvements in the field of high temperature creep resistant blade materials from conventionally cast polycrystalline to directional solidified and to single crystal materials till 2000 and then to superalloys of Ni and Cr [4-5]. As a parallel area of research, thermal barrier coatings (TBCs) have also been active in this regard [6]. These coatings are of low thermal conductivity ceramic materials which act as insulating barrier to the substrate material in the high flux working atmosphere and can be put over the metallic substrate surface using various techniques like atmospheric plasma spray (APS), chemical vapor deposition (CVD), high velocity oxy fuel (HVOF), electron beam spray (EBS) etc., using an intermediate bond coat layer of suitable material, which not only increases adherence of TBC to the substrate, but also prevents oxidation of the later and compensates for the mismatch of thermal coefficients of expansion between the two [7-8].

In the present work, two different ceramic materials, one being zirconia (ZrO_2) partially stabilized with yttria (Y_2O_3) and another being lanthanum magnesium hexaaluminate ($LaMgAl_{11}O_{19}$) were investigated as TBC materials for a gas turbine blade model made up of Hastelloy X using a popular FEM based commercial ANSYS Workbench v14.5 software package. The temperature and heat flux analysis were carried out for steady state as well as transient state heat transfers for different thicknesses of the coatings so as to investigate their effect in reducing substrate temperatures and also to anticipate a durability comparison between them in high temperature environments.

2. MATERIALS

2.1. Blade substrate

A nickel base superalloy named Hastelloy X was selected as the substrate material for gas turbine blades, which is basically an alloy of nickel and chromium (Ni-47%, Cr-22%, Fe-18%, Mo-9%, Co-1.5%, W-0.6%) possessing high resistance to oxidizing atmosphere, excellent forming and welding characteristics and good workability. As per Haynes International High-Temperature Alloys, HASTELLOY® X undergoes a per side metal loss of only 1.5 mils (0.0381 mm) excluding Continuous Internal Penetration (CIP), when exposed to an oxidizing atmosphere at 1095 ºC for 1008 hours cyclically brought down to room temperature once a week. Moreover, total metal affected per side for the same alloy exposed to a hot corrosive environment of combustion products of a fuel oil (containing 0.4 % sulfur and 5 ppm of sea salt) at a flow velocity of 4 m/s, temperature of 900 ºC, test period of 1000 hours and thermal loading applied cyclically each hour, is only 6.8 mils (0.173 mm). Table I gives some other thermo-physical properties of HASTELLOY® X as mentioned by Haynes International High-Temperature Alloys.

Property	Value
Density (kg/m^3) at 22 °C	8220
Poisson's ratio at 22 °C	0.320
Melting temperature (°C)	1260-1355
Thermal conductivity (W/m K) at 927 °C	27.2
Specific heat (J/kg K) at 1093 °C	858
Coefficient of thermal expansion (°C^{-1}) in the range of 25-700 °C	15.6 x 10^{-6}

Table I Properties of HASTELLOY® X alloy

2.2. Bond Coat and Top Coat Materials

Two different sprayed materials, namely partially stabilized zirconia (ZrO_2) with 8% wt. Y_2O_3 (so designated as 8Y-PSZ) and lanthanum magnesium hexaaluminate ($LaMgAl_{11}O_{19}$) were selected as the materials for thermal barrier coatings applied over the gas turbine blade substrate of Hastelloy X through an intermediate layer of bond coat of NiCrAlY. These materials 8Y-PSZ (melting temperature 2600 ºC) and lanthanum magnesium hexaaluminate (melting temperature 2080 ºC) were selected as the TBC top layer materials for the analysis because of their low thermal conductivity value and their compatibility with bond coat. Various thermal properties of sprayed NiCrAlY, 8Y-PSZ and Lanthanum magnesium hexaaluminate (LA) as used in this investigation are given in Table II [9-11].

Property	8Y-PSZ	LA	NiCrAlY
Thermal conductivity (W/m K)	1.0	2.2	11.6
Coefficient of thermal expansion (°C^{-1})	10 x 10^{-6}	10.7 x 10^{-6}	12 x 10^{-6}
Specific heat (J/kg K)	500	900	500

Table II Thermal properties of sprayed/coated materials

3. MODELING AND ANALYSIS

A typical gas turbine blade of height 75 mm was modeled by using Pro E v5.0 as geometric modeling tool. A total of eleven such models were created to do thermal analysis for one uncoated blade and ten coated blades for 8Y-PSZ and lanthanum magnesium hexaaluminate in five different TBC thicknesses as mentioned in Table III. Further, all the models were kept to be dimensionally same and NiCrAlY was used as the bond coat interlayer in all ten coated models.

Model designation	Specifications	
	Bond coat material (thickness in microns)	Top coat material (thickness in microns)
0/0	–	–
150/200 PSZ	NiCrAlY (150)	8Y-PSZ (200)
150/200 LA	NiCrAlY (150)	LA (200)
200/400 PSZ	NiCrAlY (200)	8Y-PSZ (400)
200/400 LA	NiCrAlY (200)	LA (400)
250/600 PSZ	NiCrAlY (250)	8Y-PSZ (600)
250/600 LA	NiCrAlY (250)	LA (600)
300/800 PSZ	NiCrAlY (300)	8Y-PSZ (800)
300/800 LA	NiCrAlY (300)	LA (800)
350/1000 PSZ	NiCrAlY (350)	8Y-PSZ (1000)
350/1000 LA	NiCrAlY (350)	LA (1000)

Table III Models formed for thermal analysis

Fig. 1 shows a typical model of gas turbine blade used in this analysis with TBC set up employed over it while cross sectional details of the blade are shown in Fig. 2.

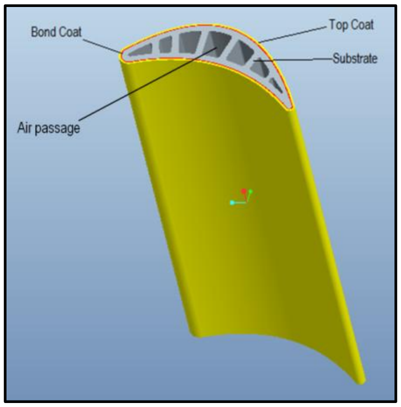

Fig. 1. Gas turbine blade model

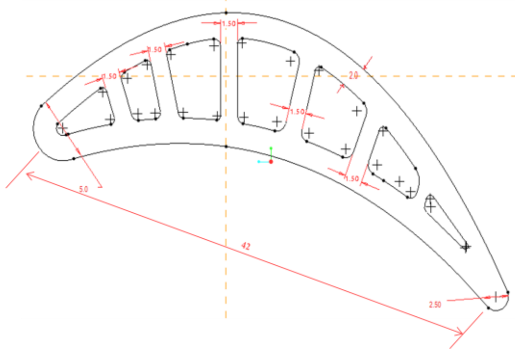

Fig. 2. Cross section of blade model

ANSYS workbench v14.5 commercial analysis package was used for steady state and transient state analysis of various coated and uncoated models. The convective thermal conditions of 1800 K with a convective coefficient of 1681 $W/m^2 K$ were used for the hot gases flowing over the blade. Similarly, cooling of the blade was simulated with convective conditions of 300 K (assumed intercooled) and a film coefficient of 203 $W/m^2 K$ for coolant air passing through the air passages. These particular heat transfer coefficient values were considered from the approximate calculations since objective of this paper was to establish a comparative effect of investigated TBC materials. Further, convection coefficient for coolant air was kept low to illustrate the significance of cooling in gas turbine blades as temperatures within the blade go very high beyond the limiting value under this insufficient cooling and effect of TBC is highly significant in this regard.

Under Steady-State Thermal and Transient Thermal analysis systems of ANSYS, program controlled meshing was done for the models as shown in Fig. 3

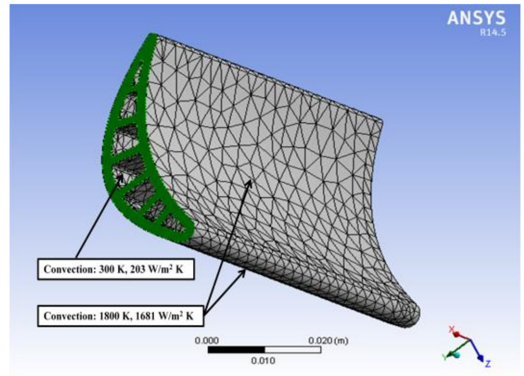

Fig. 3. Meshed blade model with applied thermal loading

4. RESULTS AND DISCUSSION

Simulations were performed over ANSYS workbench v14.5 as analysis module for all different models of coated and uncoated blades by taking thermal loading conditions as mentioned earlier. All the models were solved under steady state thermal and transient thermal analysis systems for temperature as well as heat flux values. Further, the thermal analysis for temperatures was done for the complete coated models, only substrate parts of the models, top surface of the top coat and that of substrate. Similarly heat flux variations were found for the complete coated models, only substrate parts of the models, top surface of top coat, bottom surface of top coat and top surface of bond coat.

4.1. Temperature Analysis

While analyzing steady state temperature results of various selected models for a particular top coat material, it was observed that the temperature maxima for the complete substrate material and substrate surface were exactly same for all the models. Similarly, temperature maxima for the complete coated models and their corresponding top ceramic surfaces were also found to be alike. This is an obvious observation otherwise also since heat penetrates within the turbine blade from surrounding working atmosphere of hot gases. Fig. 4 shows steady state temperature variation for substrate surface (top surface) of uncoated (0/0) model. The effects of 8Y-PSZ/NiCrAlY TBC on the steady state temperature variations over substrate top surface and top surface of each coating model are shown in Fig. 5 and Fig. 6, respectively. Similarly, steady state temperature variations at the substrate top surface and TBC top surface for different thickness models of LA/NiCrAlY TBC are shown in Fig. 7 and Fig. 8, respectively.

The results found in steady state thermal analysis under ANSYS were compared for all the models to observe the effect of thermal barrier coating over gas turbine blade and to realize the effect of thickness of TBC in performance of system.

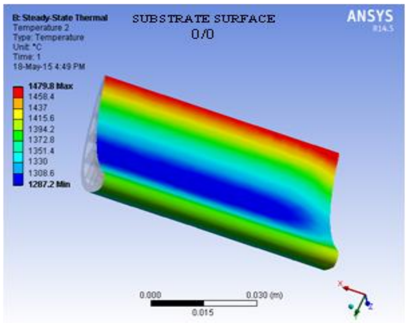

Fig. 4. Steady state temperature variation over substrate surface of uncoated model

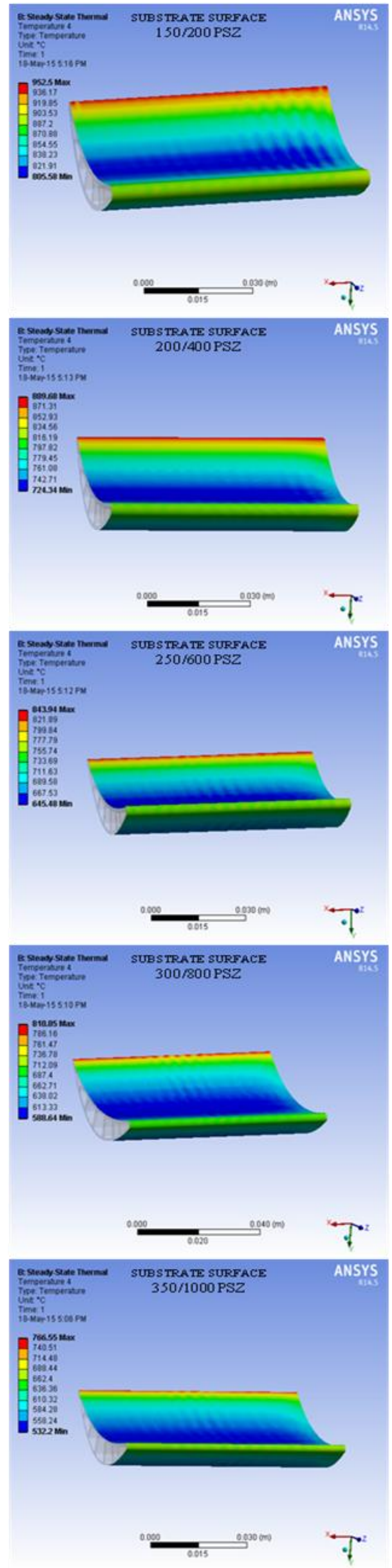

Fig. 5. Steady state temperature variation over substrate surface for 8Y-PSZ/NiCrAlY coated models

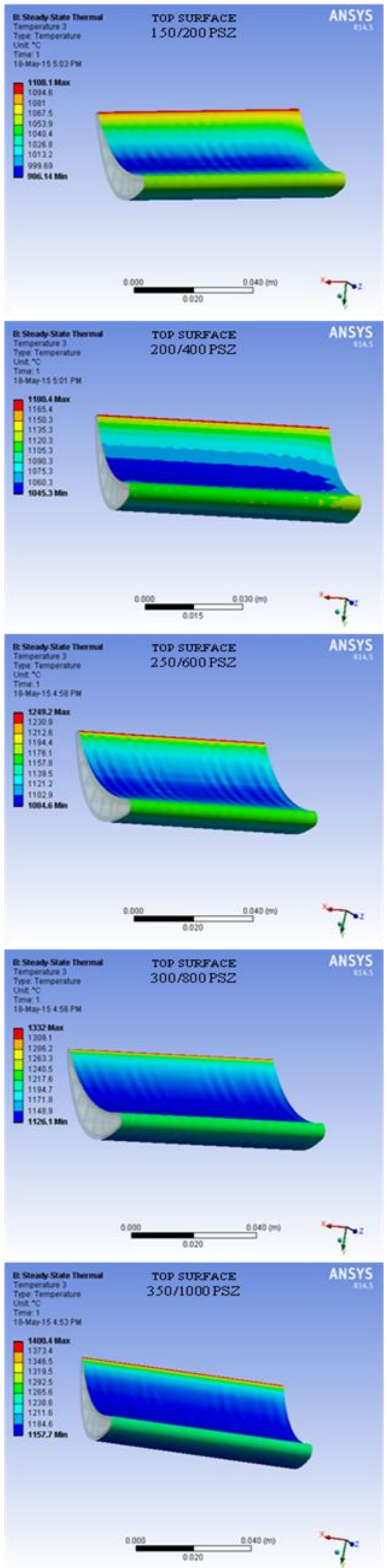

Fig. 6. Steady state temperature variation over top surface for 8Y-PSZ/NiCrAlY coated models

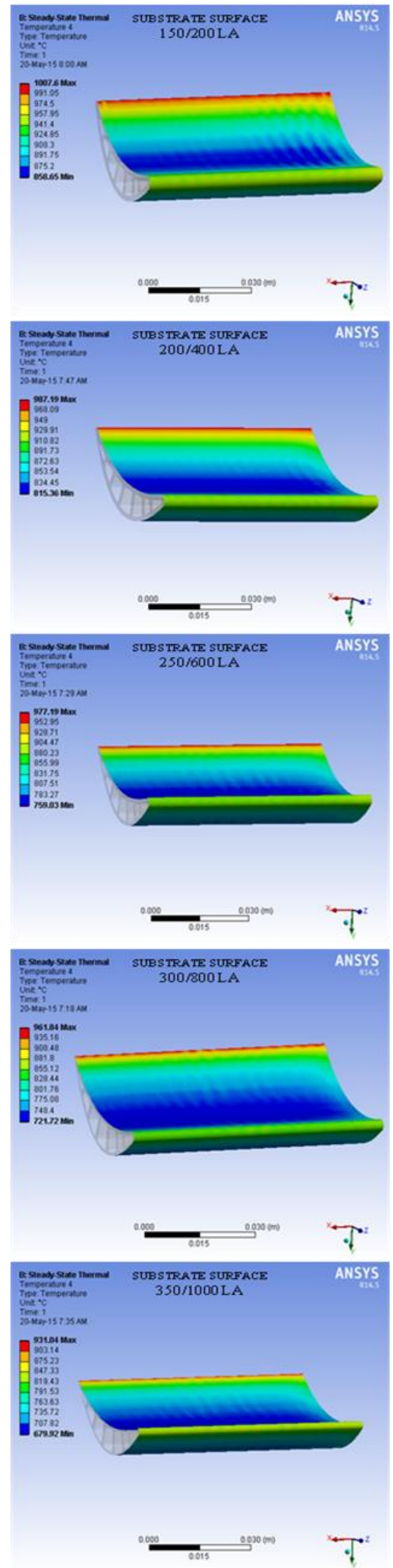

Fig. 7. Steady state temperature variation over substrate surface for LA/NiCrAlY coated models

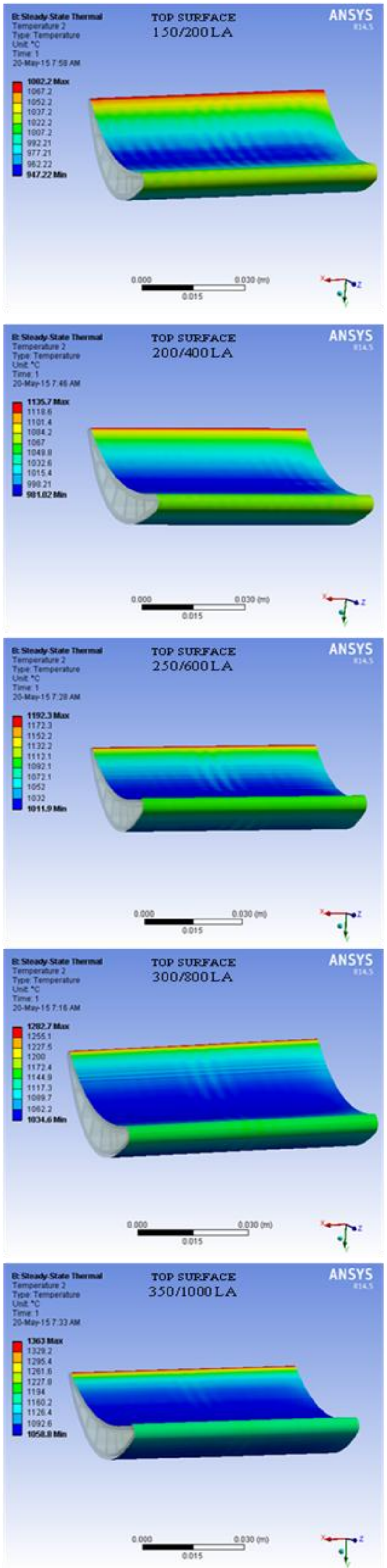

Fig. 8. Steady state temperature variation over top surface for LA/NiCrAlY coated models

The comparative results for different thickness models for 8Y-PSZ and LA coatings have been shown in Fig. 9. The comparison has been carried out with reference to the maximum temperature prevailing at the substrate surface of model and its top surface at steady state conditions. It is clear from both the figures that as compared to the uncoated blade model (0/0), TBC coated models experience lesser temperatures at substrate surface. Also, as the coating thickness increases from 150/200 model to 350/1000 model, the maximum temperature of top ceramic coat surface also goes on increasing for both types of coatings. This data is supporting to the statement that thermal barrier coating helps in reducing substrate temperatures by acting as a resistance to heat penetration and by retaining maximum of the heat of the surrounding working fluid of the high temperature thermal system within fluid itself.

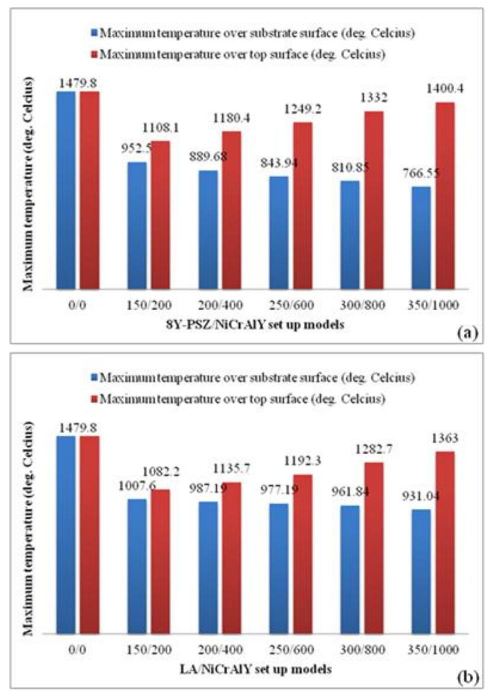

Fig. 9. Steady state maximum temperature over substrate surface and top surface (a) 8Y-PSZ/NiCrAlY coated models and, (b) LA/NiCrAlY coated models

The increase in thickness of coating significantly decreases temperatures of the substrate surface. A 150/200 PSZ model coating is sufficient enough to lower down maximum temperature of the substrate surface from 1479.8 ºC to 952.5 ºC, giving thereby a decrease of 35.63 %. It is worth noting here that taking into account the melting temperature of Hastelloy-X, temperature of 1479.8 ºC is undesirable at all as compared to 952.5 ºC. Similarly, 350/1000 PSZ model coating has the potential to reduce substrate temperature by 48.5 %. In case of 150/200 LA model, substrate surface maximum temperature was found to be 31.91 % less than uncoated model. This effect of thickness of PSZ and LA coatings in decreasing maximum temperature of gas turbine blade material has been plotted in Fig. 10, which shows that 8Y-PSZ/NiCrAlY TBC is more effective than LA/NiCrAlY coating in lowering substrate temperatures. Moreover, a thicker 8Y-PSZ coating behaves still more effectively in this regard than a similar thickness LA/NiCrAlY coating.

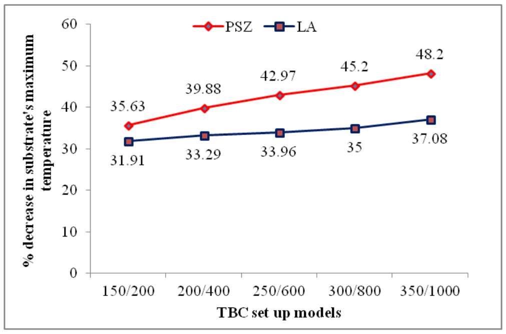

Fig. 10. Effect of TBC thickness in reducing substrate's maximum temperature

Under transient thermal analysis system, all the models were solved for an exposure time of 10 seconds to the applied thermal loading conditions. The results of analysis for 8Y-PSZ/NiCrAlY and LA/NiCrAlY coatings are plotted in Fig. 11 and Fig. 12. Fig. 11 gives time-wise variation in the maximum temperature built up over the substrate surface of each coated model as compared to that in case of uncoated model for both types of coatings. It is clear that temperature at the substrate surface grows at a very fast rate in case of 0/0 (uncoated) model in comparison to all coated models of PSZ or LA. As the coating thickness increases, falling slopes of the transient curves indicate that the temperature maxima over the substrate surface goes on decreasing. This clearly supports that a higher thickness TBC set up applied over the base material has a higher potential of decreasing temperatures of the later. Moreover, lower slopes of the transient curves in case of PSZ coated models as compared to LA coated models as observed in 10 seconds transient analysis, indicate that PSZ coatings serve more effectively than the later ones. It is further observable from the temperature curves for both types of coatings that 150/200 TBC coating set up causes a high temperature suppression within the substrate material, which is even higher than that caused by 350/1000 coating set up over 150/200 one. This particular result is useful in context with the fact that as coating thickness increases, its material as well as spray costs do also increase significantly with decrease in the life of coating in its high temperature working atmosphere.

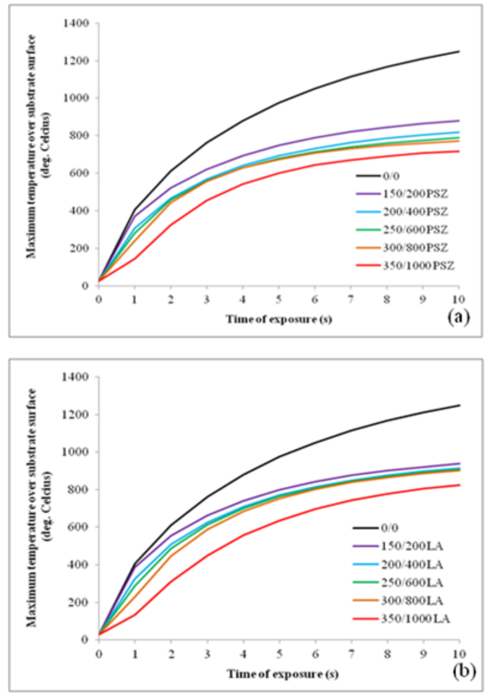

Fig. 11. Transient variation of maximum temperature over substrate surface (a) 8Y-PSZ/NiCrAlY coated models and, (b) LA/NiCrAlY coated models

To visualize the performance of TBC over substrate, growth of maximum temperature over top TBC surface of each coated model for both types of coatings was also plotted against time of exposure and is shown in Fig. 12. It is clear from the figure that just during the earlier phase of exposure of the gas turbine blade to high temperature operating atmosphere of hot gases, thickest coating model of PSZ (350/1000 PSZ) experiences a very high maximum temperature over its top surface. This temperature maxima over the top surface of coating is lesser in case of thinner coating models and is minimum in case of uncoated 0/0 model. Also, in the succeeding phase of exposure to hot gases, slope of 150/200 PSZ coating model curve is significantly lesser than that of 0/0 model and slopes of transient curves can be clearly observed as decreasing with increase in thickness of TBC. This again means that the temperature growth over the top surface of coating in most of the exposure time period is lesser for thicker PSZ coating as compared to thinner one and the thicker coating has therefore more effect in resisting heat penetration into the substrate from surrounding hot media.

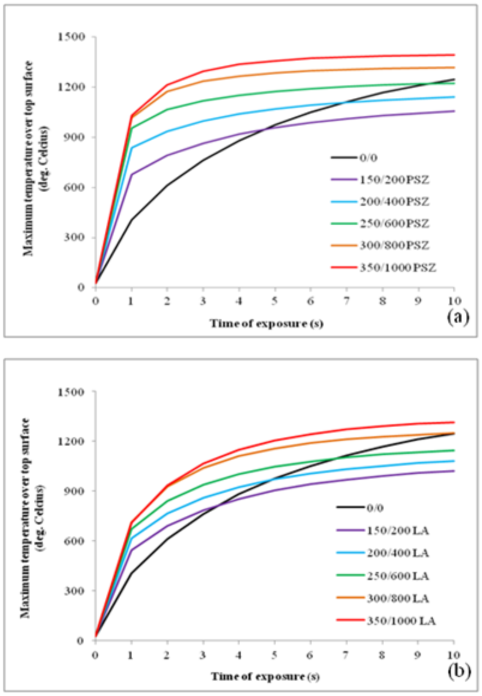

Fig. 12. Transient variation of maximum temperature over top TBC surface (a) 8Y-PSZ/NiCrAlY coated models and, (b) LA/NiCrAlY coated models

Similar observations can be made from transient curves of LA coating models of Fig. 12. However, it is here important to note that as compared to PSZ models, it takes longer for the top surface temperature maxima of LA coated models to settle down to a steady value. This again claims PSZ coatings as superior to LA coatings in reducing the heat penetrations. Further, it is again a general observation from transient curves for PSZ and LA coating models of Fig. 12 that effect of 200/400 LA over 150/200 LA is lesser than that of 200/400 PSZ over 150/200 PSZ. Same observation is also true for higher thickness models of PSZ and LA.

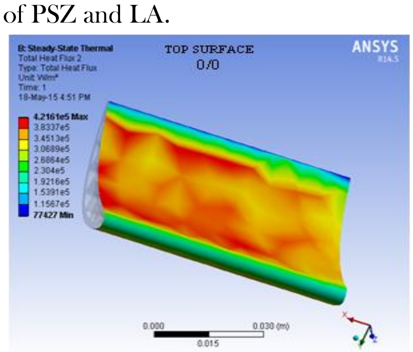

Fig. 13. Steady state heat flux variation over top surface for uncoated model

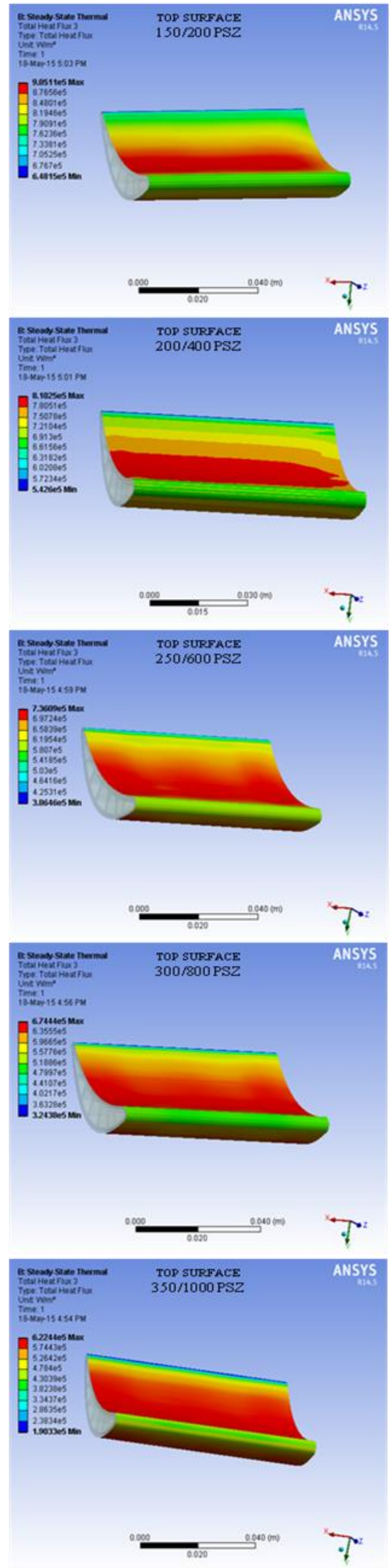

Fig. 14. Steady state heat flux variation over top surface for 8Y-PSZ/NiCrAlY coated models

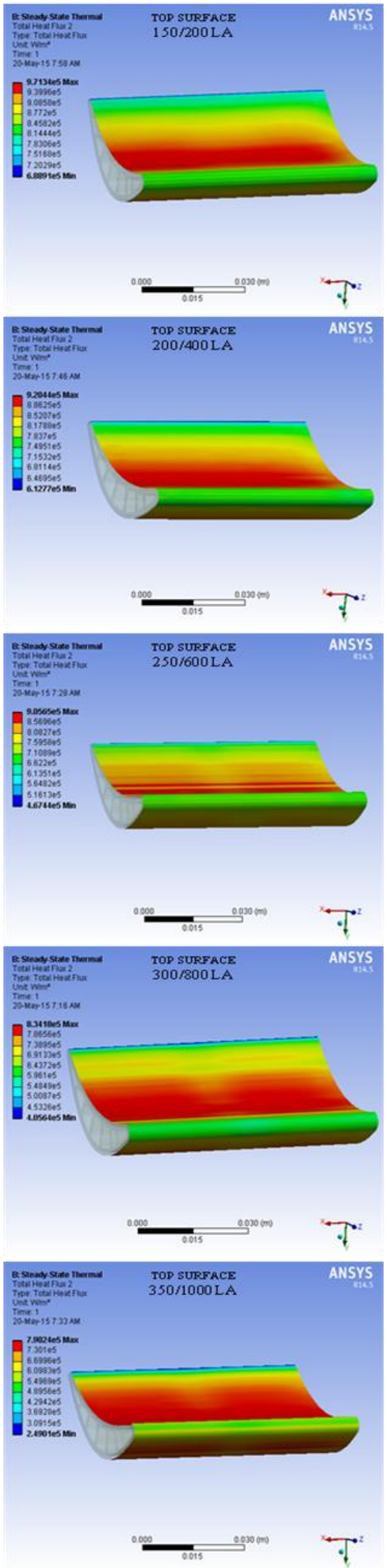

Fig. 15. Steady state heat flux variation over top surface for LA/NiCrAlY coated models

4.2. Heat Flux Analysis

Steady state heat flux variations for the top surfaces of uncoated model, 8Y-PSZ/NiCrAlY coated models and LA/NiCrAlY coated models as obtained from ANSYS investigation are shown in Fig. 13, Fig. 14 and Fig. 15, respectively. The figures show that value of maximum heat flux at the top surface of a TBC coated model exposed to hot environment is more than that in case of uncoated model. These results were used to compare different thickness coated models of two different types of TBCs and the illustration is shown in Fig. 16 for the percentage increase in maximum heat flux value at the top TBC surface of each coated model. As compared to a maximum thermal flux of 421.61 kW/m^2 for uncoated model, it is 905.11 kW/m^2 for 150/200 PSZ coated model and 971.34 kW/m^2 for 150/200 LA coated model, giving thereby hikes of 114.68 % and 130.39 % respectively. This huge rise in the heat flux at top surface is because of the fact that in case of TBC coated model, maximum temperature at the top surface is very lesser as compared to that in the uncoated case. Top surface maximum heat flux for LA coated models being more than PSZ models are further because of same reason that as compared to later, the former coated models experience lesser temperatures at their top TBC surfaces. But since increase in TBC thickness causes more and more temperatures over the top ceramic surface, so the temperature gap between hot media and top TBC surface goes on decreasing resulting into fall in heat flux value over the top surface. For the thickest PSZ model (350/1000 PSZ), top surface experiences a heat flux of 47.63 % higher than top surface of an uncoated model. While for the same thickness LA model, the value is 87.43 %. It is again significant here to conclude that higher thickness of TBC helps better in preventing heat loss from the working hot media into the coated material by reducing heat flux entering into the same. This effect of TBC may be taken in terms of improvement in the thermal efficiency of gas turbine system by increasing the turbine inlet temperature with/without reduced cooling loads. However, it is a clear observation from Fig. 16 that 8Y-PSZ/NiCrAlY TBC coatings have more potential to enhance thermal efficiency of the system than LA/NiCrAlY coatings and in particular, this potential gap between two different types of coatings increases with increase in thickness of coating.

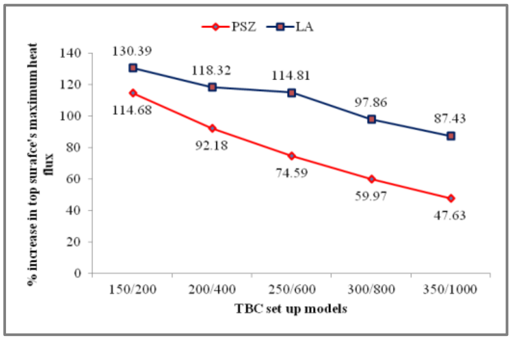

Fig. 16. Effect of TBC thickness over maximum heat flux at top surface

Transient state variation in the maximum heat flux was also plotted for a time period of 10 seconds for the top surface of each of the models and the graphs are shown in Fig. 17.

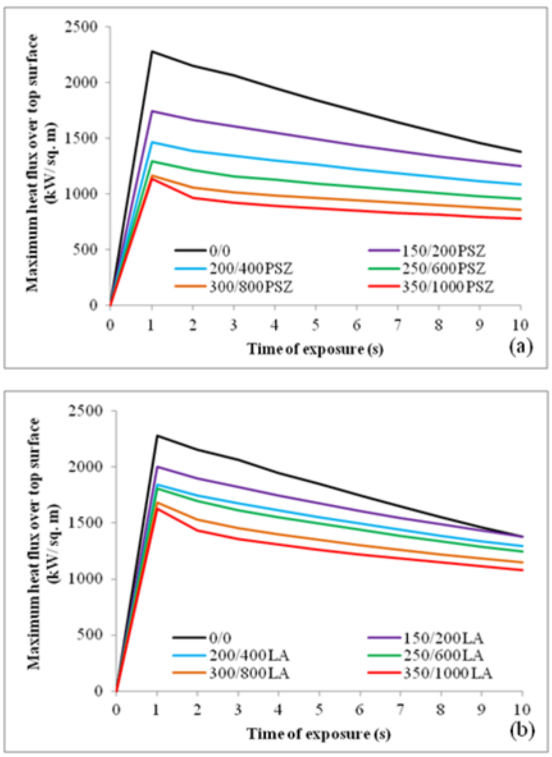

Fig. 17. Transient variation of maximum heat flux over top surface (a) 8Y-PSZ/NiCrAlY coated models and, (b) LA/NiCrAlY coated models

Fig. 17 shows that sudden exposure to the high temperature working atmosphere immediately throws a high heat flux over the exposed surface of the blade which further decreases with the passage of time till it would approach to steady conditions. However, uncoated blade model experiences highest thermal flux of 2280.2 kW/m^2 whereas peak flux value for 150/200 PSZ coated model is 1743.4 kW/m^2, causing thereby a decrease of 23.5 %. The thicker 8Y-PSZ coatings are further responsible for reducing this peak flux value by 35.8 %, 43.4 %, 48.9 % and 50.3 % for 200/400, 250/600, 300/800 and 350/1000 models, respectively. Similarly, as compared to the uncoated model, peak flux values at top surface of LA coated models are found to reduce by 12.0 %, 19.1 %, 20.7 %, 26.2 % and 28.6 % for 150/200, 200/400, 250/600, 300/800 and 350/1000 models, respectively. These data clearly highlight that a thicker TBC has higher potential of suppression of heat penetration than a thinner one, the effect being more for 8Y-PSZ coatings as compared to LA coatings.

4.3. Durability comparison

Although life of TBCs and their durability in high temperature working conditions depend upon many factors but here in this analysis focused upon temperatures and heat flux calculations, particularly interface between top coat (TC) and bond coat (BC) was investigated for both different types of coatings since generally this interface has been an initiative spot for TBC failures in many of the observations by the researchers worldwide [12-13]. The steady state heat flux variations for TC/BC interface were found for 8Y-PSZ/NiCrAlY as well as LA/NiCrAlY coated different thickness models using same previous analysis tool. The interface was considered both the ways as TC bottom surface and BC top surface, to find the flux mismatch and its pattern for various thickness models and the results are shown in Fig. 18.

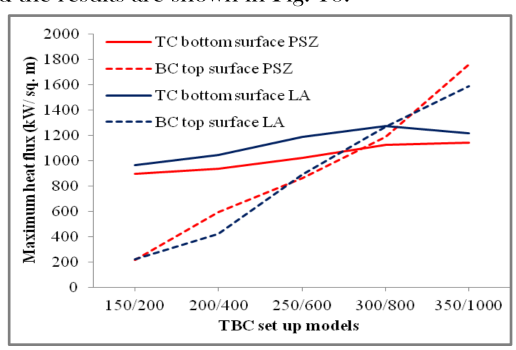

Fig. 18. Effect of TBC thickness over maximum heat flux at TC/BC interface

Basically heat flow rate should decrease within TC or BC with increase in coating thickness as it was also observed at the top surface for heat flux results. But Fig. 18 shows that interface heat flux here was rather found to increase from either side i.e. top coat side as well as bond coat side. It is because interface surface area associated with heat flux calculations goes on decreasing with increase in thickness of coating causing dominance over reduced heat flow rate with thickness increase. Further, rate of increase of heat flux is slower for TC bottom surface than BC top surface for both types of coatings since top coat material is highly resistive (having very less thermal conductivity value) than bond coat material. However, when TBC thickness is very high, resistive effect of TBC material starts dominating over decrease in surface area and heat flux starts decreasing for TC bottom surface.

The results found above were used to calculate changes in maximum steady state heat flux values between TC bottom surface and BC top surface for different thickness models of both 8Y-PSZ/NiCrAlY and LA/NiCrAlY coatings. Fig. 19 shows variations in such flux mismatch values at TC/BC interface with thickness of each type of coating.

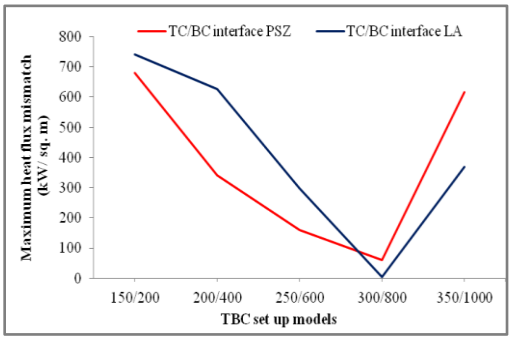

Fig. 19. Effect of TBC thickness over maximum heat flux at TC/BC interface

Fig. 19 shows that for the lower coating thicknesses (up to 250/600 model), 8Y-PSZ/NiCrAlY coatings experience less thermal flux mismatch at TC/BC interface than LA/NiCrAlY coatings. But this is reverse for higher thickness coatings. The mismatch was found to be minimum for 350/800 models with values of 60.6 kW/m^2 (for PSZ) and 5.1 kW/m^2 (for LA). It is further important here to establish that such interface thermal flux mismatch could be one of the factors leading to the observed TBC failure phenomena at TC/BC interface like cracks, delamination, spallation etc. Further, it can be concluded here that neglecting all other possible and established failure modes/causes of TBCs, 8Y-PSZ TBC coatings used with a bond coat of NiCrAlY are expected to serve longer at lower coating thicknesses while LA coatings might be lasting longer at higher coating thickness values. However as clear from Fig. 18 also, it is worth noting that at higher coating thicknesses, heat flux at the bond coat surface is getting very high and it even exceeds the flux value at the bottom surface of top TBC coat, which is undesirable since high heat flux at the bond coat may itself deteriorate it in due course of time. So as a whole, it is expected that 8Y-PSZ/NiCrAlY TBCs would be lasting a longer life while operating in high temperature applications of gas turbine as compared to the LA/NiCrAlY coatings.

5. CONCLUSION

Thermal barrier coatings of suitable materials applied over substrate materials working in the high temperature environments like gas turbines or diesel engines have high potential to lower the temperatures within substrates by providing thermal insulation to them and hence increase their service life also. Partially stabilized zirconia (8% by wt. yttria) and lanthanum magnesium hexaaluminate were investigated as such ceramic coatings using popular analysis software of ANSYS Workbench v14.5 over Hastelloy X as substrate material for a typical gas turbine blade model. An intermediate bond coat of NiCrAlY was used for both types of coatings. The analysis was carried out for variable coating thickness models in steady state as well as transient state modes using convection conditions of 1800 K, 1681 W/m^2K for hot gases and 300 K, 203 W/m^2K for coolant air. It was found that zirconia coatings suppressed the substrate temperatures to a greater extent than lanthanum aluminate coatings. Even a 200 microns top coat of the former with a 150 microns bond coat (referred as 150/200 PSZ model) was capable to lower steady state maximum temperature of substrate by 35.63 % against 31.91 % for the later (referred as 150/200 LA model). The increased thickness of coatings observed further reductions in the substrate temperatures. A 350/1000 PSZ model enhanced substrate temperature reductions to 12.57 % more than a 150/200 PSZ model against 5.17 % enhancement for similar thickness LA models. During heat flux analysis of various models of two different coatings, PSZ coatings were found to experience lesser heat flux at their top surfaces than equally thick LA coatings, meaning thereby that PSZ coatings are more effective in suppressing heat penetration within the material. Under steady state heat flux calculations, it was observed that top surface heat flux reductions for PSZ and LA coatings were improved respectively by 67.05 % and 42.96 % as the coating thickness increased from 150/200 to 350/1000. This again suggested that a particular increase in thickness makes PSZ coating more effective than LA coating. Further, a steady state maximum heat flux analysis was done for the bottom surface of top coat and top surface of bottom coat considering the importance of this interface in governing life of TBCs in high flux atmospheres. It was anticipated that the deterioration at bond coat would likely be happening earlier in case of low thickness LA coatings and high thickness PSZ coatings due to a large mismatch in thermal flux values calculated from the two sides of interface. However, high thickness coatings (PSZ or LA) were individually found to experience high heat flux values at the interface, which itself might become a failure cause for any TBC. So, it was concluded that low thickness PSZ coatings would be better than LA coatings in all the aspects.

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