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THE EFFECT OF THERMAL BARRIER COATING ON THE LIFE TIME EXTENSION OF A GAS TURBINE BLADE

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ABSTRACT

The effect of thermal barrier coating (TBC) on the life time extension of a heavy-duty gas turbine blade has been evaluated. At the First step, a conjugate heat transfer analysis was done on a blade with and without TBC coating by using CFD technique. Load conditions used in the simulations are obtained using temperature distribution from conjugate heat transfer analysis and also centrifugal force on the blades. Finally, creep strain was simulated by using Norton–Bailey prediction model. The results revealed the TBC coating has a significant effect on life time extension of the blade by reducing the amount of equivalent creep strain.

Keywords: turbine blade, TBC, heat transfer, creep, life time extension

INTRODUCTION

Modern gas turbine engines are designed to operate at high inlet temperatures, which are beyond the allowable metal temperatures. In this condition, creep damage has a dominant effect. As a consequence, the analysis of creep processes has become more and more important due to the continuous rising of operating temperatures and thermal stresses, in plant components and particularly in gas turbine blades (Cali, 2010). Therefore, in order to have structural integrity, base metals need to be preserved against the high temperature and thermal loads. Complicated cooling configurations and using thermal barrier coating (TBC) are the solutions against high temperature environment (Jones, 1996).

In order to assure the adequate life of hot section parts such as blades, the accurate prediction of the blade temperature is necessary. In recent years, research efforts have focused on 3D conjugate heat transfer analysis as a means to provide more accurate and reliable prediction of metal temperature of hot parts. The conjugate calculation methods are based on a coupled calculation of the fluid flow, heat transfer at solid/fluid boundaries and heat conduction in the solid walls (Bohn, 2001). Recently, owing to huge progresses in computational capacities conjugate analysis has found major applications in thermal behavior prediction of gas turbine hot components. It was used to find the temperature field in a cooled blade with tip cooling holes (Takahashi, 2000). Hybrid unstructured grids was used in order to compute the thermal field for internally cooled turbine vanes (Han, 2000). The Glenn-HT convective heat transfer code was extended to solve conjugate heat transfer problems by meshing the solid side and setting the velocities there to zero (Rigby, 2001). The effect of thermal barrier coating on a gas turbine blade was investigated and results indicated a reduction of nearly 100 K in the substrate metal temperature (Akwaboa, 2010). Conjugate heat transfer method was applied to predict the temperature distribution in a gas turbine first stage nozzle in steady-state conditions. Predicted temperature field then used to perform a creep analysis in order to evaluate the damage of the nozzle vane (Mazur, 2006).

To predict the behavior of materials under creep conditions both rheological and analytical models are used. Simple phenomenological constitutive equations were proposed during the first decades of the last century for modeling the creep phenomena. Norton–Bailey model is a valid predicting model only in the secondary stage creep by using a function of constant equivalent stress and material parameters. As regards other laws, the creep strain is time dependent, as from Andrade and McVetty, and rupture time dependent, as from Monkman–Grant, while more recent models refer to damage mechanics coupled with creep, either in a phenomenological way or with a changing material constitutive law (Cali, 2010).
The objective of the present work at the first step is to perform a conjugate heat transfer analysis to study the effect of thermal barrier coating (TBC) on the temperature distribution of a heavy-duty gas turbine blade. Thermal effect of TBC layer is modeled by introducing a thermal resistance on external surfaces of the rotor blade. Then, the temperature distribution is extracted and transferred to the FE model in order to calculate thermal stress distribution. After the FE analysis creep strain in the blade simulated and effect of TBC coating on creep behavior of the blade is investigated.

DESCRIPTION OF ANALYSIS

1- CFD CALCULATIONS

In order to find temperature distributions and investigate the effect of TBC layer on the life extension of the first blade in a heavy-duty gas turbine, conjugate heat transfer (CHT) analysis needs to be performed. For this purpose, computational domains including hot gas flow boxes around stator and blade, solid blade and internal cooling passages inside the blade were prepared. Although hot gas flow calculation around the stator blade is not the objective of this study, it ensures the correct angle of fluid flow at the inlet of the rotor blade. The assembly of computational domains has been shown in Fig. 1. Steady state 3D Navier-Stokes equations are solved for both described domains using finite volume method and SST-kω is utilized to model turbulence characteristics of flow. Due to complexity of the domains, unstructured tetrahedral meshing technique is applied and the boundary layer mesh distribution is selected such that y^+ parameter remains well below 2 at solid wall-adjacent grids on both external and internal sides throughout the flow field. Final computational grids include 34.3 million cells.

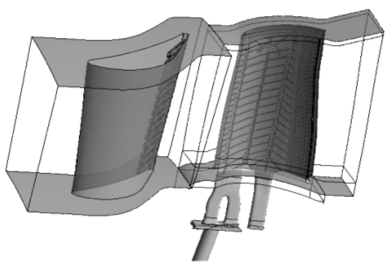


Fig. 1 Computational domains assembly

Another important step prior to solve the domains is to set boundary conditions. As it is evident from the domains in Fig. 1, boundary conditions comprises stator Inlet, rotor outlet and blade coolant specification. Total pressure and total temperature as well as static pressure radial profiles are set at stator inlet and rotary blade outlet boundaries respectively. The averaged values of these profiles are shown in table 1. Blade cooling flow rate is also specified by an iterative process as the total pressure of coolant air extracted from compressor has been known.

Table 1 Boundary conditions

Inlet averaged total pressure (bar)	11.15
Inlet averaged total temperature (K)	1419.2
Outlet averaged static pressure (bar)	7.2

Important thermo-physical characteristics of computational domains, on both fluid and solid sides are defined as function of temperature according to their impact on CHT simulation results. Thermal conductivity and thickness of TBC layer are also necessary to simulate the impact of the coating on heat fluxes to and temperature distribution of the blade. Nevertheless, TBC layer properties could not be explicitly stated due to numerous uncertainties existing in coating processes. Therefore, a range of variations in thermal conductivity and thickness is defined. According to available data, thermal conductivity and thickness of TBC layer lies in range of 0.7 to 1.4 W/mK and 200 to 300 micron respectively. From view point of heat fluxes to the blade, these ranges can be reduced to worst and best conditions of TBC layer. The worst and the best conditions correspond to minimum and maximum heat flux resistance through the TBC layer and are named as TBC1 and TBC2 respectively. This will give a reasonable range in which the metal temperature is expected to decrease as a result of adding a TBC layer.

Based on these evaluations, three CHT run cases have been defined. First, the blade with no TBC coating was modeled to evaluate the temperature distribution inside it. Then, in order to evaluate the influence of TBC layer on the metal temperature, separate CHT simulations were performed applying TBC1 and TBC2 layers on external surfaces of the blade. The effects of TBC layer on heat fluxes and a temperature distribution was modeled through defining a contact resistance on the coated surfaces of the blade.

2- STRUCTURAL ANALYSIS

The predicted temperatures obtained in the thermal analysis were applied as body forces to calculate thermal stress throughout the blade. The main source of thermal stress is temperature gradients. In conjunction with the thermal load previously described, the centrifugal load at 3000 rpm was applied to calculate overall stress experienced by the blade.

The resulting stress was calculated based on linear superposition of mechanical and thermal loads. Centrifugal stresses show the major contribution close to the blade root, while thermal stresses become more and more relevant close to the blade tip (Gazzino, 2006). As a result of unstructured meshing technique a FE model with nearly 1.7 million tetrahedral elements was formed.

1- CREEP ANALYSIS

In engineering practice, numerous models for prediction of creep strains are used. Some of these are applicable to many materials and geometries; some others are restricted, in terms of empiric parameters, to a particular creep phase (primary, secondary or tertiary) and to a certain temperature range (Cali, 2010). The Norton-Bailey law describing the relationship between creep strain and time was derived to perform creep calculations:

$$\overset{\circ}{\varepsilon}_{cr} = A\,.\sigma^{n}.\,\exp\,(-Q/RT).$$

In this equation A and n are material dependent parameters following from uniaxial tests; $\mathring{\varepsilon}_{cr}$ and σ denote strain rate of secondary creep phase and stress, respectively. Temperature-dependent thermal parameters and structural material properties of Ni-based superalloy IN738LC are used, In order to carry out creep simulation. Finally, in order to evaluate the effect of TBC coating on the life time extension of the blade, equivalent creep strains were calculated to assess the creep damage over a certain period of time.

RESULTS ANALYSIS AND DISCUTION

1- CFD RESULTS

Results of CHT run cases (namely uncoated, TBC1 and TBC2) in terms of the normalized temperature on the outer surface of the blade has been shown in Fig. 2. According to temperature contours of uncoated blade, peak temperatures are located in a region around the mid-span of the leading edge which is associated with the peak temperature on the inlet temperature profile. There are also high temperature zones near the trailing edge on the pressure side and on the tip area due to the poor cooling effectiveness. A similar trend can be found in other run cases (TBC1 and 2) expect that the temperature levels are decreased due to the thermal resistance induced by TBC layers.

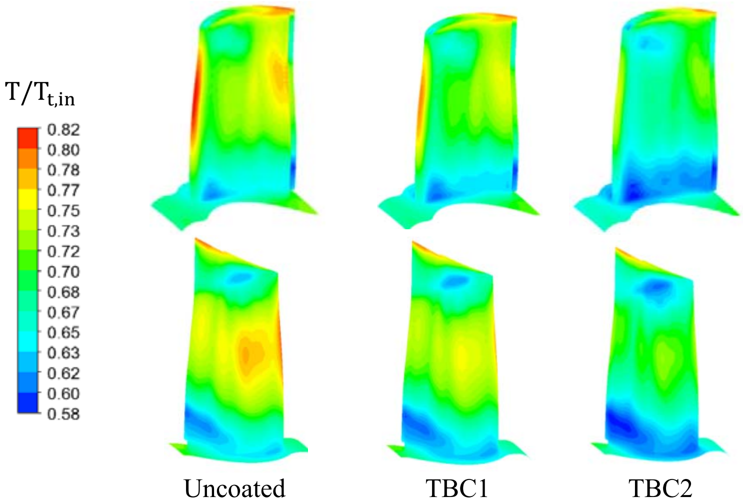


Fig. 2- Blade external surface temperature

Temperature distribution inside the solid blade at mid-span section has been depicted in Fig. 3. It can be seen that the temperature levels and gradients are decreased inside the solid blade as TBC layer is added to the blade. However, temperature reduction depends on local cooling effectiveness and is not expected to be uniform all over the blade. It can be also concluded that thermal stress level, caused by temperature differences between internal and external surfaces, is reduced in case of coated blades owing to lower temperature gradients. Stress analysis results are reported in the coming part.

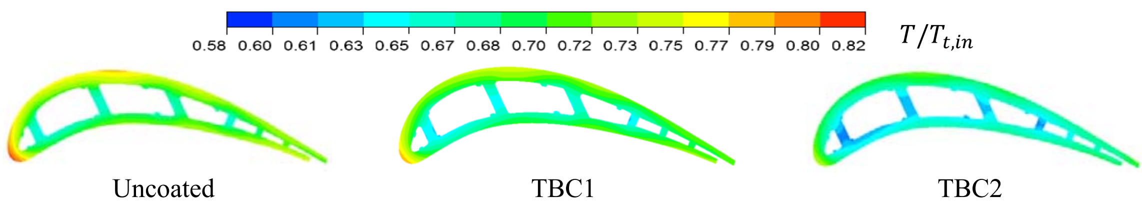


Fig. 3- Blade metal temperature at mid-span

2- STRESS DISTRIBUTION RESULTS

Fig. 4 shows the overall stress pattern of the blade which has a sophisticated distribution. This figure also reveals the effect of TBC coating on the stress pattern of the blades. It should be mentioned that fir-tree root results were not considered due to low temperature which was unable to activate creep mechanism.

Comparing stress pattern of three types of coating, it was demonstrated that platform fillet and middle parts of leading edges had the highest stress levels in all cases. The stress level at the platform fillets is of less concern due to the lower temperatures that are involved. Moreover, a stress reduction of 60-100 MPa in different regions of the blade was observed with considering TBC coating on the surface of the blade. In fact TBC coating has a significant effect on the reduction of thermal stresses. The stress reduction had been mostly occurred in the leading and the trailing edges. Considering that these regions are the most critical regions of airfoil, TBC coating had a noticeable effect on the blade life, which is discussed in following sections.

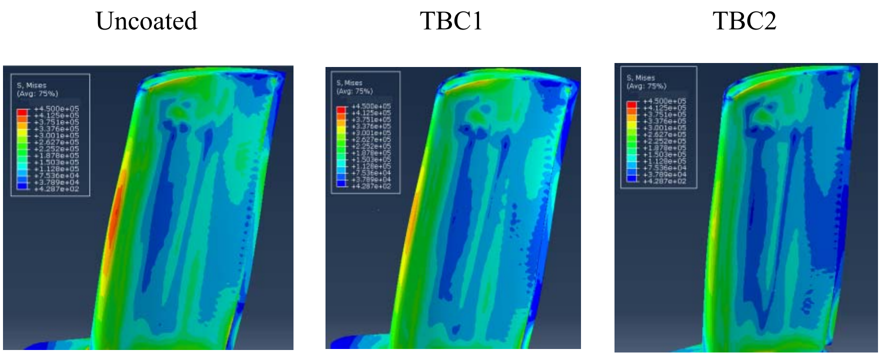


Fig. 4- TBC effect on misses stress distribution of blade

3- CREEP RESULTS

A creep analysis was performed by applying relevant thermal and mechanical loadings to the blade model. The predicted creep strain distributions after 10,000 hours are shown in Figure 5. Results from the creep analysis are summarized as follows:

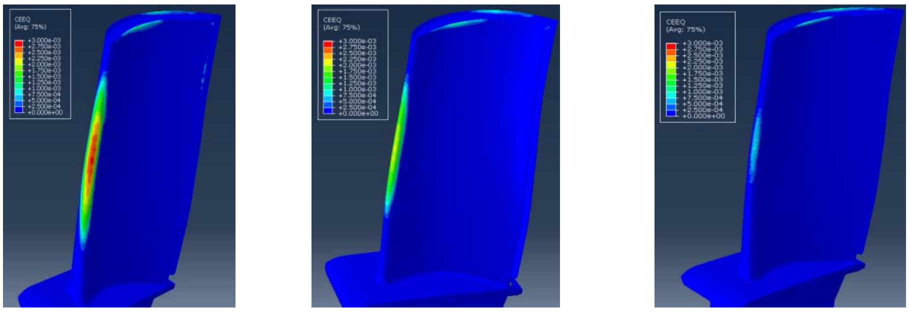
• Creep strain pattern of uncoated blade revealed that leading edge and tip are the most vulnerable regions (Fig. 5-a). In fact, these locations were susceptible to creep cracking, promoted by a significant problem of lifting for the blade.

• The creep response of TBC coated blades have been depicted in Figs. 5b & 5c. According to the results, TBC has a positive influence by lowering the creep strain. In fact, leading edge - the most critical region of blade- was experienced much lower creep deformation.

• On the other hand, creep damage of the tip of the blade did not become much lowered. Considering that the tip of the blade is neither coated nor effectively cooled, the results seem logical.

• Increasing the thickness of thermal barrier coating and lowering the amount of thermal conductivity has a significant effect on the creep damage of the part which is efficiently cooled.

Uncoated TBC1 TBC2



(a) (b) (c)

Fig. 5- TBC effect on creep strain of blade

Figure 6 shows the time history of creep strain at leading edge- the most critical region of blade. In particular, the creep strain estimated in case of uncoated blade is higher than that estimated with TBC coating, during most of the calculation time range, while the time of first stage creep in blade with TBC coating increases in comparison to uncoated blade. Finally, in the secondary stage of creep the strain rate, evaluated for model with TBC coating, is lower than that obtained with no TBC coating.

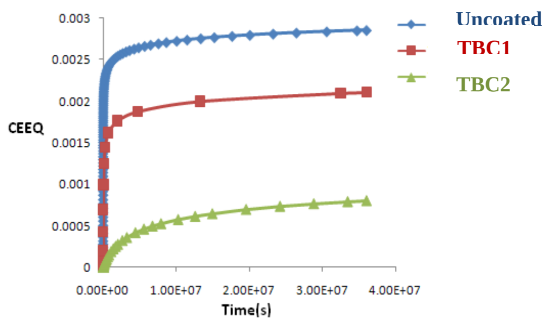


Fig. 6 Creep rate curves for three different coating types

CONCLUSION

Results of the studies reveal that the creep damage accumulated in the leading edge is quite critical in terms of determining the design life of the blade. The creep analysis results indicate that the creep strain level is lower in case of TBC coated blade in comparison with uncoated one at most critical locations of the airfoil. Applying TBC coating also reduces thermal stress levels effectively.

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