THERMAL BARRIER COATINGS AND THEIR EFFECT ON TURBINE BLADE PERFORMANCE

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ABSTRACT

On the turbine blade, thermal barrier coatings (TBCs) are applied to lower the temperature of the underlying substrate and offer defense against hot corrosion and oxidation caused by high-temperature gases. The performance and effectiveness of the coatings can be enhanced by the blade's optimal ceramic top-coat thickness distribution. Because the goals of high thermal insulation performance, long operation durability, and low fabrication cost conflict, designing the coatings' thickness is a multi-objective optimization problem. This study created a process for designing the gas turbine blade's TBC thickness distribution, which ranges from 100 μm to 500 μm. Nickel alloy is used to create the base material for the blade geometry, and partially stabilized zirconia is chosen as the coating material. The multi-objective optimization problem in this case was solved using a weighted-sum approach after three-dimensional finite element models were constructed with CATIA and examined with ANSYS WORKBENCH. A suitable multi-region top-coat thickness distribution scheme was created while taking fabrication cost, productivity, and manufacturing accuracy into account.

Keywords: *Thermal Barrier Coatings; Oxidation; corrosion; Ceramic Top-coat thickness*

INTRODUCTION

Advanced gas turbines frequently use thermal barrier coatings (TBCs) to shield metallic substrates from high-temperature gas oxidation and heat. Turbine performance and efficiency can be greatly increased by applying TBCs. A load-bearing substrate, a ceramic top-coat (TC), a metallic bond-coat (BC), and the thermally grown oxide (TGO) that develops between TC and BC make up a typical TBC system. The material and geometrical characteristics of the TC layer, particularly its thickness and thermal conductivity, typically control the temperature drops across TBCs under particular operating conditions. As TC thickness increases for a particular ceramic material, the coatings' capacity to insulate against heat increases as well. However, the coatings' internal thermal mismatch stress might also rise at the same time. It is acknowledged that the degree of thermal stress and the capacity for thermal insulation are in balance. Finding the ideal TC thickness for the heated components turns into an optimization challenge.

The performance and efficiency of the coatings can be enhanced by designing the TBC thickness for gas turbine blades optimally. An accessible, easy-to-use, and effective method for designing coatings for engineering applications is preferred. Regretfully, there hasn't been much reported on this problem. The majority of turbine blade studies focus on the substrate without TBCs, ignoring the impact of the coatings. Examples of these studies include blade failure analysis, heat transfer simulation, and cooling channel design. Concerns regarding TBCs on the actual turbine blade were brought up in a few works. The microstructural development of TBCs in high pressure turbine blades, for example, was experimentally examined both before and after the service. Localized spallation of yttria partially stabilized zirconia (YSZ) was discovered close to the tip of the serviced blade, along with significant sintering and phase transformation. carried out hot corrosion tests on cylindrical specimens with different TBC thicknesses and discovered that an ideal TBC thickness can increase the underlying super alloy's life by roughly 600 times. To examine the failure behavior under cyclic thermal loading, a finite element (FE) model was developed for the blade using TBCs. examined how the shape of TGO affected the distribution of stress in a turbine blade with TBCs when subjected to cyclic heat loading.

The aforementioned works shed light on how TBCs affect turbine blades. None of them, though, address the problem of TBC thickness design. Actually, most numerical works used two-dimensional or simplified three-dimensional models in their simulations because it is difficult to mesh a real gas turbine blade with complex external and internal geometry shapes. utilized the simplified three-dimensional FE models, which assume a single cooling passage and uniform, straight extension of the blade airfoil from platform to tip. It should be noted that the simplified models have limited ability to represent temperature and stress fields in the actual blade, which limits the conclusions that can be drawn from them.

LITERATURE REVIEW

Zequn Du [2023] The effect of surface roughness (Ra = 0-30 μm) and thermal barrier coating thickness (0-300 μm) on the cooling properties of the high-pressure turbine blade is investigated in this work using the conjugate heat transfer method. The TBC on the turbine blade surface is simulated using a physical thin-walled structure. The findings show that the coated metal surface has a more consistent temperature distribution. The heat flux of the blade surface decreases as coating thickness increases, peaking at the leading edge. Additionally, the pressure surface is the least sensitive to variations in coating thickness, while the leading-edge temperature is the most sensitive. After coating, variations in roughness have less of an impact on the overall cooling efficacy. Increasing the surface roughness, the heat flux reduces at the leading edge and increases at other places.

Amrinder Mehta [2022] In order to enable the underlying base metal to function at a melting temperature of 1150 °C, thermal barrier coating is essential for thermal insulation technology. Engineers can enhance the thermal and mechanical performance of gas turbine blades and the piston cylinder arrangement by raising the temperature of incoming gases. The aerospace and diesel engine industries are among the many industries that can now use thermal barrier coatings (TBCs), thanks to recent advancements in the field. Its longevity and dependability are determined by changes in the microstructure of the turbine blade caused by its operating environment. Furthermore, the deposition techniques employed to produce multi-layer, composite, and functionally graded coatings have a significant impact on their efficacy.

S Ghosh [2021] Gas turbine play an important role in producing power for aviation industries. A sustainable operating life with high efficiency of a gas turbine requires very high temperature operation.

Temperature-induced increases in thermal conductivity cause high thermal stress, which results in irreversible deformation and shortens blade life and efficiency. To eliminate such negative effects, a thermal barrier coating is essential. An evaluation of gas turbine blade materials has been conducted in this work in order to investigate the impact of different coating methods on extending blade longevity. It has been discovered that coating techniques are crucial in determining how long gas turbine performance can be sustained. It was discovered that these coatings significantly lower the rate of heat penetration, extending the gas turbine blades' service life.

Oscar Tenango-Pirin [2020] Because thermal barrier coatings lessen thermal stress on turbine components, they are essential to the operational life of micro turbines. This study evaluated novel materials created to be applied as a thermal barrier coating for gas turbine blades using numerical calculations. Additionally assessed is the protection performance of the micro turbine's components. A 3D gas micro turbine model is created for material testing, and CFD and FEM are used to solve the fluid-structure interaction. The nozzle and blade's temperature fields and stress levels are computed, and the results are compared to a scenario without a thermal barrier.

Thermal barrier coating

Components that are internally cooled by channeling air are coated with thermal barrier materials. Part configuration and thickness, heat flux, heat transfer coefficients, combustion and turbine inlet temperatures, and the total cooling air permitted by the system engineers are all taken into account in designs involving TBC-coated parts. Thinner coatings are preferred in order to reduce the addition of excessive mass and cooling hole closure.

Ceramic thermal barrier coatings

Particularly active efforts have been made in recent years to introduce and apply thermal barrier ceramic coatings to various components of a high-temperature gas turbine engine system. When ZrO_2-based ceramic coatings are utilized, the material of the part is best protected from heat flux by heat barrier coatings. Under operating conditions, the thermal barrier ceramic coating's heat-protective effect reaches temperatures between 100 and 120 °C. Thermal flows in a protected detail's wall and the thickness and heat conductivity of ceramic coatings that act as a thermal barrier determine the heat-protective effect, or drop in metal temperature.

Turbine Blade Applications

The internal surfaces of the combustion chambers in aircraft gas turbines have been extensively protected by thermal barrier coatings. Such coatings result in a significant drop in metal temperature because of their low absorptivity and low thermal conductivity. Compared to the combustor, the demands on TBC in turbines are much higher. Under both transient and steady state conditions, ceramic coatings experience significant thermomechanical stress due to the turbine's high convective heat fluxes. The turbine's hot spots have high and average metal temperatures that are 50–100°C higher than those in the combustor. This puts a lot of strain on the environment.

Resistance of the bond coat. At these high surface temperatures, plasma sprayed coatings are subjected to process such as sintering and phase changes.

Structure of TBC

In addition to preventing heat transfer through the coating, modern TBCs must shield engine parts from oxidation and hot corrosion. These multifunctional requirements don't seem to be met by any one coating composition. This leads to the use of a coating system. In order to achieve long-term effectiveness in the high temperature, oxidative, and corrosive use environment for which they are intended to function, researchers have developed a preferred coating system that consists of three distinct layers.

Tbc's Failure Mechanisms

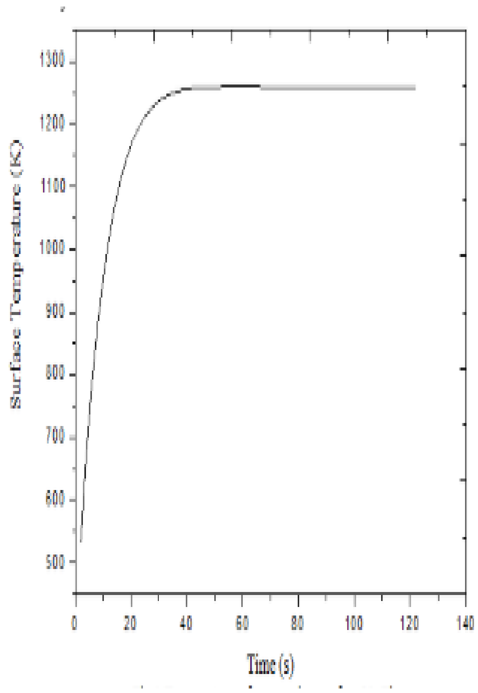
The primary defense against the action of erosive agents at high temperatures for gas turbines is provided by TBC systems. Wear, cracks, and TC delamination can result from mechanical loads and thermal cycling, which impairs their functionality. A number of variables, including TC microstructure and chemical composition, are linked to typical failure mechanisms in TBCs. The TBC's mechanical and thermal reaction to various operating conditions, such as temperature, cycling time, and combustion gases, also influences failure.

METHODOLOGY

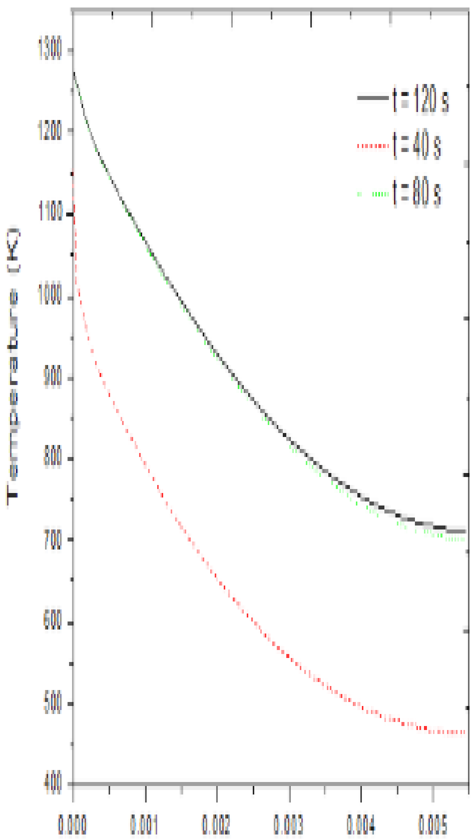
The gas turbine blade model is created in CATIA, and ANSYS WORK BENCH is used for analysis. In ANSYS Workbench, meshing can be done in default mode with sizes ranging from 2 to 22 mm. Following a mesh study using five design points, the mesh sizes of 15 mm for the blade without coating and 3 mm for the coating surface were chosen. The bottom face of the turbine blade is fixed, and the convex surface is the high pressure side, where a force of 980N will be applied. It displays the support between the hub's slot and the blade root. The gas turbine uses forced convection as its heat transfer mechanism, and its heat transfer coefficient is 200W/(m2K). The ambient temperature is assumed to be 1500°C, and we know that the exhaust temperature following combustion ranges from 1200°C to 1500°C. The results of the steady state thermal analysis and static structural analysis performed in the ANSYS workbench are deformation, stress, and heat flux.

RESULTS

The impact of thermal barrier coating on the temperature distribution and potential decrease in the gas turbine blade's surface temperature have been examined through numerical simulations. Two simulation runs were performed to ascertain the time needed to reach the steady-state solution, and the outcomes are shown in Graphs 1 and 2. According to Graph 1, the blade surface's maximum temperature reaches the steady state condition after about 60 seconds. Graph 2 displays the temperature distribution at various times, and it takes 60 to 80 seconds to reach the steady-state distribution.

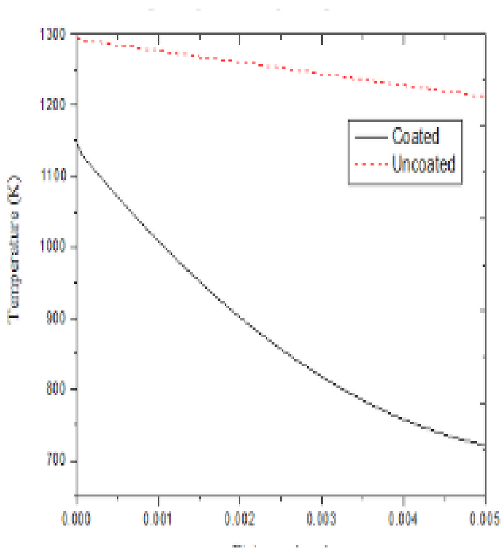


Graph: 1 temperature of top coating surface vs time



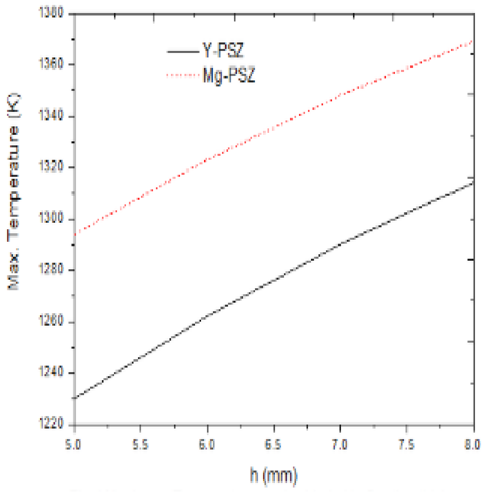
Graph: 2 distribution of temperature at different times

This work's primary goal was to examine how coating affected the blade wall's temperature profile. The simulation results for coated and uncoated conditions are displayed in Graph 3. It is evident that bonding a layer of low thermal conductivity significantly lowers the temperature across the blade wall. It is observed that the reduction is more noticeable at the plate's far end, which is next to the cold side. This decrease in temperature brought on by the use of TBC may lessen thermal stresses and fatigue, extending the material's lifespan (durability). At the extreme locations where elevated temperatures are more noticeable, a temperature drop of 160 oC was accomplished in this work. It should be mentioned that the maximum allowable operation temperature of the Ni-superalloy substrate is within the limit of 1250 oC.



Graph: 3 temperature distribution with coating without coating

For the ceramic coating thicknesses of 5 mm, 6 mm, 7 mm, and 8 mm for both Mg-PSZ and Y-PSZ, Graph.4 displays a plot of temperature versus coating thickness under the same conditions. Maximum temperatures on the coating surface are observed to be 1294 K, 1323 K, 1348 K, and 1369 K for Mg-PSZ and 1230 K, 1262 K, 1290 K, and 1314 K for Y-PSZ. It is commonly known that temperature affects a material's strength. As the temperature rises, it falls. Lowering operating temperatures increases the gas turbine blade's strength and lengthens its lifespan. Because of this, it is crucial that the substrate's temperature be lower.



Graph: 4 Maximum temperature on the blade vs coating thickness

CONCLUSION

A review of thermal barrier coating performance from the standpoint of long-term operational sustainability has been provided. A number of thermal barrier coating techniques have been examined to determine their potential uses. According to the study, TBC coating is necessary to shield gas turbine blades from extended high-temperature operation, which is essential for producing electricity efficiently. Because of the pores created during the coating process, the thermal conductivity also decreases. Excessive pores also degrade other mechanical characteristics. Choosing the right coating process is crucial when applying to pre-existing materials or creating a new coating. In order to increase the longevity of gas turbine blades and enable sustainable power generation, thermal barrier coating development is essential.

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