Grenze International Journal of Engineering and Technology, Special Issue

Thermal Analysis of TBC Coated Superalloy for Industrial Gas Turbines

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***Abstract*—There is a continuous effort undergoing for improvement in efficiency of gas turbine from past few years since these engines are used in transportation, energy, power fields etc. The improvements in gas turbine efficiency can be achieved at high inlet temperature by using thermal-barrier coatings (TBCs). Due to expectations of obtaining higher efficiency there is continuous research and development happening across the globe in this field. The present paper discusses about the need of coating technologies and characteristics of TBC materials for improving the performance of gas turbines. The comparison of two types of coating process used on the blade surface of gas turbines has been explained for certain important parameters.**

***Index Terms*— Gas turbine; Thermal Barrier Coatings (TBC); Guide vanes; Super alloy.**

I. Introduction

The gas turbine is a device that converts energy obtained by combustion of fuel into mechanical power which runs a generator to produce electrical power. There exist several parts in gas turbines like combustor, blade, guide vanes which are subjected to high temperatures. Earlier the focus was on combustor of gas turbines later it shifted to blades of turbines. The efficiency of turbine is related to turbine inlet temperature, as the inlet temperature increases the efficiency also increases. In order to improve the efficiency of turbine thermal barrier coating is used. These coating (TBCs) are ceramic coatings made of refractory-oxide that are applied to the surfaces of metallic parts. TBC are applied to the parts which are subjected to very high temperatures in a gas turbine as shown in the Figures 1 and 2. Gas turbines yield more output, higher engine efficiency and thrust to weight ratio when TBC is used. There is continuous effort under progress to obtain the most efficient TBC material which gives optimum results.

Gas turbine engines are highly expensive of billion of USD industry around the globe (2010) in which 65% used for jet engines and 35% for land based engines to generate electricity [1]. The gas turbine faces challenges when improving its efficiency since the inlet temperature cannot be increased to any limit. The utilization of TBC is very much required since approximately 25% of all electricity in the United States and 20% worldwide are produced by natural gas [2]. With rapid developments in gas turbines the air traffic is expected to grow double in next 20 years [3]. Another challenge is to reduce the NOx emission caused by jet engines at higher altitude [4].

Figure 3 shows the different layers in TBC (a) Top coat (TC) (b) bond coat (BC) (c) Super alloy or base metal. The superalloy or base metal is made of Nickel,Tallium or Cobalt based alloys. Inconel alloy is ideal

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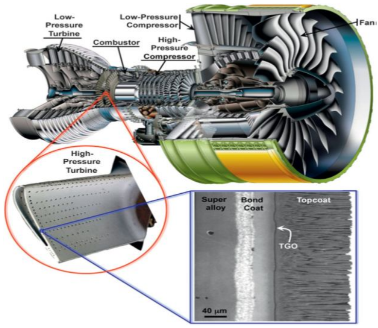

Figure 1. Pictorial view of Gas turbines showing coated with TBC super alloy

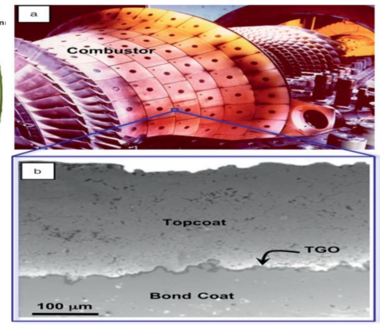

Figure 2. Pictorial view of (a) Combustor and (b) blade blade coated with TBC coat followed by bond coat and

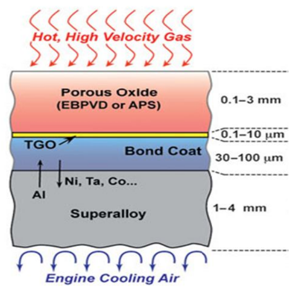

Figure 3. Different layers of coating and their thicknesses

for applications in high temperature applications. They withstand higher mechanical stresses and strains under various challenging conditions to provide protection against corrosion and creep. The melting point of Inconel is 1400^0C.BC is oxidation resistant metallic layer 75-150µm in thickness. It is generally made of NiCrAlY or NiCoCrAlY alloy. At peak temperatures the temperature of base metal exceeds 700^0C resulting inBC oxidation. Ceramic TC provides thermal insulation which is made of MCrAlY where M stands for Ni or Co. The most common type of material used in this layer is Y_2O_3 stabilized Zirconia. This material YSZ has lowest thermal conductivity 2.3 w/mK at 1000^0C for fully dense material. It also has high thermal coefficient of expansion $11x10^{-6}$ / ^{0}C, density 6.4mg/ m^3,hardness of 14GPa and very high melting point 2700^0C.

The coating act as thermal insulation to superalloy and protect them against severe conditions while working. There are many parts in gas turbines like combuster, guide vanes, blade, outer air seals and shrouds (fig-1).The developments in these parts were done earlier by several techniques like single crystal Ni-based superalloys, but developments of TBC along with cooling see much improvement in the performance. There are two main process adapted for coating gas turbine blades made of super alloy, namely,

- Air Plasma Spraying.
- Electron Beam Physical Vapor Deposition.

Air Plasma Spraying method is used commonly for directing blades, nozzle vanes and other elements of the combustion chambers. Electron Beam Physical Vapor Deposition technique is used for the rotating blades since they are under high thermal stresses. This process produces columnar grain structure which is most preferable. The comparison of APS and EBPVD process is shown in the Table 1 for coating Yittrea stabilized zirconia.

TABLE I. ROOM TEMPERATURE PROPERTIES OF YSZ TC (REF -7)

Properties	Process	
	EBPVD	APS
Surface roughness,µm	0.5-1	4-10
Thermal conductivity w/m/k	1.5-1.9	0.8-1.1
Adhesion strength, MPa	400	20-40
Young's modulus, GPa	90	200
Erosion rate	1	7

The APS and EBPVD techniques are the most effective among all since there is reduction of thermal conductivity as shown in Table 1. If the temperature of gas becomes higher than melting point of base metal, failure of TBC can cause severe damage to the engine [5].

II. EXPERIMENTAL METHODOLOGY

A specimen made of nickel based alloy Inconel 718 was used as a substrate with each sample of size 30mm diameter and 3mm thickness. Figure 2 shows cross section of a gas turbine engine and a turbine coated by thermal-barrier coating (TBC), and it also shows the cross section of the coated blade in high resolution 40µm under scanning electron microscope (SEM).The TBC coating is done by an electron beam physical vapour deposition process for 7YSZ. Figure 4 shows graph of temperature variations used in gas turbine over the period of time for Ni base superalloys. The curve at bottom level brown in colour obtained for Ni based alloys working at lower temperature having low temperature withstanding abilities. Green line shows TBC coated superalloy with maximum temperature value and red line shows superalloy cooling with tbc having better performance than earlier two methods.

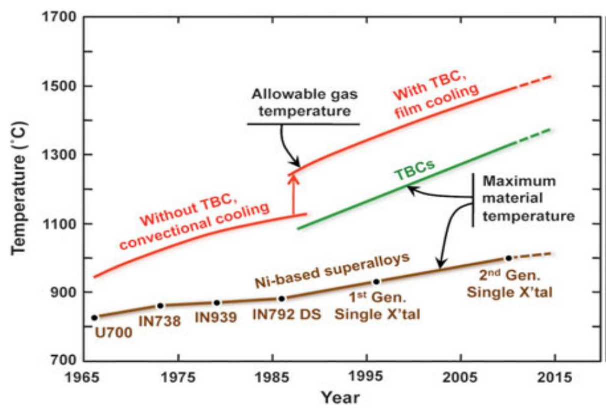

Figure 4. Temperature variations used in gas turbine over the period of time for Ni base super alloys

The YSZ tbc has certain properties like low thermal conductivity , high coefficient of thermal expansion which makes it most preferred coating material however there are more investigations needed to find alternative material other than YSZ which possess still lower thermal conductivity than YSZ.The conductivity can be changed by change in crystal structure or by change in composition. Heat transfer through the TBC coating depends upon factors such as electronic conduction, lattice phonons, and radiation. TBC materials that are selected for coating usually have low electrical conductivity. Thus electronic conduction has very less significance. And at temperature below 1250^0C less than 10% of heat transfers by radiation therefore lattice phonons has been considered for improving the performance of TBC.

III. RESULTS AND DISCUSSIONS

The platinum modified nickel aluminide BC was subjected to thermal cycles by electron beam physical vapor deposition method it shows TGO thickening and local stress shown in images taken by SEM (Figure 5.).This thermal cycles were done at 1150^0C.The photoluminescence piezo-spectroscopy technique [7] was used to measure mean stress on TC (Figure 6). When a compressive stress is applied the peak positions of photoluminescence spectrum shift to lower frequencies, if a tensile stress is applied it shift to higher frequencies. This photoluminescence piezo-spectroscopy provides a noncontact measure of the stress in alumina-containing materials.Bond coat function is to provide Al diffusion to prevent oxidation and reduce TGO thickness formation. The BC should also not react with TBC coating. There exist two types Ni-rich nickel aluminide and a more complex in composition MCrAlY alloy. Since the TC YSZ is good conductor of oxygen thus oxidation of BC is unavoidable.
In order to prevent creep TGO should remain elastic to the highest temperature.TGO should also not react with superalloy. AL2O3 is the oxide layer that grows very slowly and also has good mechanical integrity.

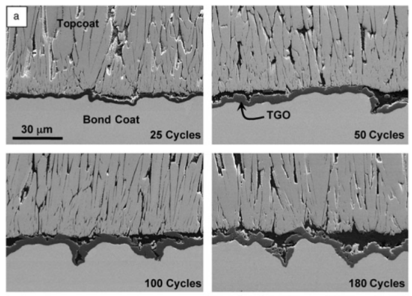

Figure 5

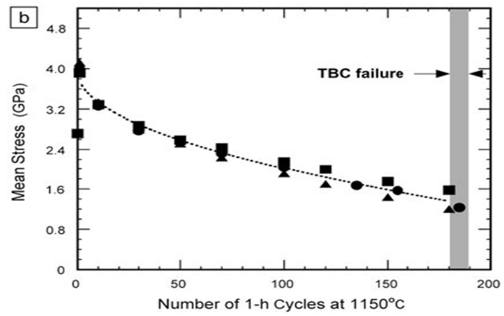

Figure 6

The most rigorous constraints are forced on the BC in many respects. To form a protective α -Al_2O_3 TGO, BC's primary function is to provide a reservoir from which Al can diffuse while maintaining cohesion with the TBC without reacting with it. Mechanics modeling [8] indicates that, ideally, the TGO should remain elastic to the highest temperatures and not creep to prevent "rumpling" [9 ,10] or cavitation on thermal cycling [11] would happen into separations of bond and TC at the TBC interface (Figure 5). Also, it has to operate at the highest possible temperature along with reduced air quantity which requires for cooling the vanes and blades without reacting with the underlying super alloy and melting. This means that the maximum bond-coat temperature cannot be allowed to exceed 1150°C. There are two main bond-coat alloys currently in use, a Ni-rich nickel aluminide and a more complex in composition MCrAlY (M=Ni, Co + Ni, or Fe) alloy. While these are alloys metallurgically differ to face the similar challenges such as to minimize deformation at intermediate and operating temperatures, minimizing inter diffusion with the underlying super alloy which prevents the formation of brittle inter metallic, and delivering critical elements along with Al, Hf and Y, to the increasing Thermal gas oxide (TGO) layer for minimizing inelastic plastic deformation under thermal fatigue.

Estimation of the TBC system's performance is very essential in terms of the configuration, growth, and properties of the TGO developed beneath the 7% YSZ topcoat due to oxidation of the BC alloy. TBC microstructures revealed surface flawed with porosity and a crack, 7% YSZ is an oxygen conductor, that allows the oxidation of the BC. The BC compositions are required to develop very slow growing oxide at high temperatures like α -Al_2O_3 TGO which forms non porous act as adhesive layer with exceptional mechanical reliability. As TGO grow beyond a critical thickness, the failure of TBC occurs due to the loss of consistency of epitaxial thin films which discharge the elastic strain energy stored in the TGO film grown beyond the fracture strength [12]. Two reasons for the stress induced in the TGO layer due to (1) development of strain of new oxide film and (2) the disparity of stress level between the stress induced by super alloy and differences in thermal expansion upon cooling.

TGO develops due to two components of strain growth leading to (1) simple thickening and (2) tangential TGO growth which causes decrease in plane stabilities and resistance to mechanical properties [11]. Tangential growth of strain initiation is difficult to understand and endorsed to the opposite movement of inside diffused oxygen and outside of the layer Al^{3+} result into the coating of new Al_2O_3 inside the TGO grain boundaries [13]. Studies revealed that a number of measurements on the TGO growth of strain did not consider TBC itself using x-ray synchrotron experiments and not enough to follow the progress during thermal oxidation or cycling. Photoluminescence piezo-spectroscopy measurements revealed the details of TGO strain growth when measured from the TC [14] where a laser beam penetrates the TC to stimulate the *R* -line luminescence using traces of Cr 3+ ions which are invariably exist. The average TGO stress is relative to the frequency change of the *R* -lines. The correlations by mapping the luminescence shifts and the growth of dent as the BC and TGO rumple are shown in Figures 5 and 6.

IV. CONCLUSION

In this paper, thermal analysis of TBC coating using TGO growth has been explained in respect of YSZ coating. Various terminology and parameters involved in growth TGO layer has been discussed and some important measurement processes are explained. various unattempted questions remained on the tangential strain growth whose decree could influence oxidation of other than super alloys including size of elements effecting the growth and mechanical properties. mostly study of the elements Y, Zr, and Hf that separate each other due to their difference between ionic radii on the TGO grain boundaries are to be carried out. These elements to be tested whether they alter the anti diffusion along the TGO grain boundaries creating tangential strain growth effect the high-temperature creep and plasticity.

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