A STUDY ON THERMAL BARRIER COATINGS ON GAS TURBINE ENGINE BLADES

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ABSTRACT

Rising energy demands need development and style of novel technologies and materials. A high share of energy generation and transportation is done using gas turbines. Understanding TBC failure mechanisms is that the basis to implement changes so as to improve sturdiness. to keep up a powerful bond between TC-TGO and TGO-BC, and additionally to cut back the magnitude of residual stresses near these interfaces, intervention of before Christ composition, structure and process is accomplished. Development of heat barrier coatings applied to cooled blades is one in every of the trends for improving gas turbines. Unlike aluminised protective coatings, the ceramic coatings not solely protect blade surfaces from high-temperature oxidization and corrosion however additionally forestall base material softening at high temperatures. Thermal barrier coating application permits the reduction of the blade temperature and also the vital increase in its service life. By considering all researches before did for TBC a route cause flow process of various coatings discovered during this study.

Keywords: *Gas turbines, Coating on blades, TBC, Bonding, types of coatings.*

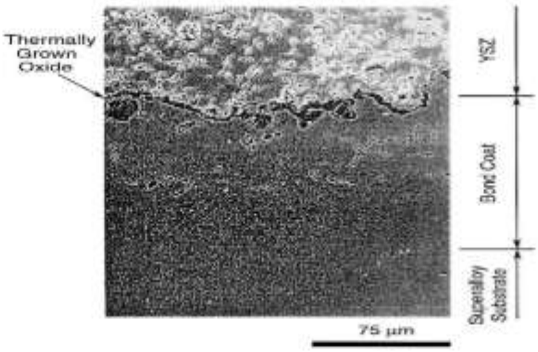
INTRODUCTION:

In the next generation of power plant technology, both oxy fuel and hydrogen fuel could also be used because the substitute for current combustion technology. both future technologies in power generation might alter advanced turbines to control a lot of with efficiency but at a considerably higher temperature condition compared to today's current station condition. Such advanced turbines with oxy fuel or H fuel operate roughly up to 1760 ^{0}C, whereas the present coal-fuelled power plants operate at a temperature solely up to 900 ^{0}C. Due to the high temperature operating condition, these technologies may require a change in its material design. One of the most important components in a power plant that will be affected is the turbine blades, since the availability of the power plant mainly depends on the lifespan of the blades. The materials used to build turbine blades will likely require high temperature resistance in order to withstand such conditions. One of the potential means of protecting the blades is by applying a thermal barrier coating (TBC) on their surfaces. Such a coating may help to protect the nickel based super alloy blade from hot gas steam. Nevertheless, the TBC layer is also in contact with both the increasing operating metal temperature and the kinetics of the base material, each of which gradually degrades TBC durability, exposing itself to damage failures such as undulation, spallation, and cracking. Thus this project will study the thermo mechanics of the TBC layer in order to predict its lifespan before failure occurs. Several approaches in modelling the TBC lifetime have been identified and applied in a finite element computer simulation. This paper intends to discuss four damage modelling approaches: TGO thickness calculation, elasticity and creep effect of

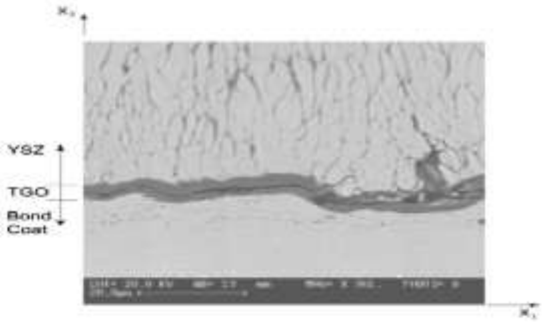
TBC, a coupled oxidation-constitutive approach and fracture mechanics approach. Of the methods, only two techniques, TGO thickness calculation and elasticity and creep effect of TBC, are employed in the finite element analysis.

Background

Thermal Barrier Coating is widely used in aircraft and industrial gas turbine engines. Commercial manufactured TBC system consists of two layers, a ceramic top coat and underlying metallic bond coatthe highest coat could be a composition of yttria-stabilized zirconium oxide (YSZ) which will be composed by air plasma spraying (APS) or electron-beam physical vapor deposition (EB-PVD). The highest coat has low thermal conduction, high O porosity, and comparatively high constant of thermal enlargement. As a result of its low thermal conduction characteristic, its main perform is to supply a thermal insulation on the rotary engine blades surface from the recent gas steam. The chemical bond coat is often product of MCrAlY overlay or an atomic number 78 changed diffusion aluminide (β-NiAl-Pt). The work on this study in the main focuses on APS TBC system with MCrAlY bond coat. Since the highest coat has terribly high O porosity whereas the bond coat is wealthy with aluminum properties, each layers inevitably kind a protecting, thermally fully grown chemical compound (TGO) scale of α-Al2O3 throughout thermal operation. This TGO scale provides strong attachment between the YSZ top layer and metallic bond coat layer. All the layers existed in TBC system equip the TBC system with the capability of thermal insulation as well as oxidation resistant to protect nickel-based super alloy metal below it. TBC systems are able to create high temperature drop from about 140^{0}C up to 250^{0}C with cooling systems, which subsequently reduces the metal operating temperature. Nevertheless, the TGO is gradually thickening over the period of time during high temperature exposure. Hence, the crucial failures that associate with the TBC system area unit usually nuclear reaction and cracking of the thickening thermal growth chemical reaction (TGO) scale. Majority of the reviewed papers, then, agree that thermal growth chemical reaction (TGO) layer that's shaped attributable to bond coat chemical reaction and inter diffusion with bond coat strongly contributes to such failures. the following section will discuss the constitutes of the TBC systems in more details.



Microstructure of typical plasma sprayed thermal Barrier coating after 500 hours oxidation at 950ºC



A typical microstructure of an EB-PVD TBC system after 700 hours at 1000 ℃

Ceramic top coat layer

The layer is made of Y2O3 (yttria) stabilized ZrO2 (zirconia). Y2O3 is found to be empirically suitable to stabilize ZrO2 compared to other different oxides (MgO, CeO2, Sc2O3, In2O3, CaO) because of its structure that can exist in three different polymorphs such as monoclinic, tetragonal, and cubic. The polymorphs structures of Y2O3 vary according to the composition and the temperature condition. For example, by adding 7 to 8 weight % which is around 4 to 4.5 mol% of Y2O3 into zirconium solid solution, Y2O3 can stabilizes ZrO2 tetragonal crystal structure especially metastable tetragonal-prime structure (t'-YSZ) . This t' phase is considered as the most desirable and stable phase for TBC applications because it does not undergo martens tic transformation on cooling even after multiple thermal cycles. As a result, Y2O3 has been found as a consistent stabilizer for zirconia solid solution, subsequently makes yttria-stabilized zirconium YSZ as the most applicable composition for thermal barrier coating applications. Nevertheless, the detailed reason is not yet being explained and remains one of the important aspects of ongoing research. One of the most important material properties of the YSZ top coat is its low thermal conductivity, k at high temperature, which is around 2.3 Wm-1K-1 at 1000^{0}C. The thermal conductivity is low because of the high distribution of point defects such as oxygen vacancies and substitutional solute atoms that can scatter heat-conducting phonons (lattice waves). Heat is transferred by lattice vibrations and radiation in electric insulators such as ZrO2.Therefore, as more phonons and photons being scattered by the point defects in the lattice structure of the ZrO2 ceramic, thermal conductivity can be efficiently reduced. In addition, YSZ has a high thermal-expansion coefficient, α, which is around 11□10-6 ^{0}C-1. It is comparable to the metallic bond coat thermal expansion coefficient (14 □ 10□C-1), and thus it can lessen the thermal expansion mismatch stress between the metallic bond coat and ceramic top coat. YSZ ceramic top coat is also resistant to erosion and external impact because of its high hardness property, which is approximately 14 GPa. The density of YSZ layer is relatively low just about 6.4 Mg·m-3, yet it is useful for parasitic weight consideration in moving engine components. Another crucial aspect of the YSZ top coat is its high melting point. This ceramic layer is resistant to elevated temperature up to approximately ~2700 ^{0}C which makes YSZ as the most significant component in TBC system. There are two most important types of YSZ top layer coating depositions, air plasma spraying (APS) and electric-beam physical vapour deposition (EB-PVD). This paper, however, focuses on the APS TBC system life damage simulation since it is commonly used in power plant turbines.

Electron-beam physical-vapour deposited TBC

The EB-PVD top coat is approximately 125 µm thick. The micro structural features of the top coat consist of a thin region on polycrystalline YSZ with equated grains near the ceramic/metal Interface. The EB-PVD top coat is deposited into columns of YSZ grains with diameter of 2 to 10µm. The columnar YSZ grains grow outwardly from the equiaxed-grain region to the top surface. Within the columnar YSZ grains, there are nanometre-scale porosity, and channels, normal to the ceramic/metal interface that separates the YSZ columns. This columnar grains separation can disconnect at elevated temperature, alleviating the effect from the stress that rises from thermal expansion mismatch. This behaviour is known as "strain tolerance". The EB-PVD top coat is smoother than APS deposition. Plus, it is more durable and expensive compared to APS case. Thus, it is typically used in the most harsh temperature condition like in aircraft engines.

Air-plasma-sprayed TBC

Unlike EB-PVD top coat, a typical APS top coat is slightly thicker than EB-PVD top coat with a thickness of 300 µm to 600µm. The APS top coat structure consists of "splat" grain morphology which each "splat" has 1 to 5 µm thickness and about 200 to 400 µm diameter. Besides inter "splat" boundaries, there are also cracks that exists parallel to the ceramic/metal, creating 15 to 25 vol% porosity within the APS TBC that contributes to low thermal conductivity and low elastic modulus of the system. The weakness of the APS TBC is the undulating nature of the ceramic/metal interface that is actually needed in sticking together the top coat and the metal bond coat. This nature is found to be the cause of the undulation failures due to the stress it creates. The commercial production cost of APS system is relatively low. Hence, it becomes a preferable choice for applications that operate in slightly lower temperature condition and fewer thermal cycles such as in conventional power plant gas-turbine engines. However, the thermal-cycle life of APS top coat is usually shorter than EB-PVD TBC's live because of the growing micro structural defects parallel to the interface and also the roughness of the interface within the APS TBC.

Below shows the material properties comparison of APS and EB-PVD TC systems at a room temperature

Property	*Deposition Method*	
	APS	*EB-PVD*
Thermal Conductivity ($Wm^{-1} K^{-1}$)	1.5-1.9	0.8-1.1
Surface Roughness, µm	0.5-1	4-10
Adhesion Strength, (MPa)	400	20-40
Young's Modulus (GPa)	90	200
Erosion rate (normalized to PVD)	1	7

Room temperature properties of YSZ top coats

Bond coat layer

Metallic coatings for super alloys are typically NiCrAlY type which contains 15 to 25 weight % Chromium (Cr), 10-15% Aluminium (Al), and 0.2-0.5% Yttrium (Y) and β-NiAl phase. The bond coat has a typical thickness of 40 to 100µm, depending on the deposition method. Similar to YSZ top coat deposition, the metallic coatings are commonly deposited by using EB-PVD method or low pressure plasma spraying (L PPS) in today's gas turbines applications. The LPS process is relatively cheaper than EB-PVD and becomes a favourable selection. Nonetheless, EBPVD has a quality advantage over LPPS.

The key physical property of the bond coat is its oxidation behaviour. The metallic bond coat should be able to oxidize in order to form a nonporous and adherent oxide layer, which is called thermal growth oxidation layer. Therefore, the composition, microstructure, and surface condition of metallic bond coat is considered important to study in order to observe its influence on a TGO formation. Below shows the mechanical properties of NiCrAlY bond coat at room temperature.

Properties	*Values*
Young's Modulus, E (GPa)	200
Poisson Ratio	0.3
Thermal Expansion Coefficient, α ($\times 10^{-6}$, °C^{-1})	12.3
Material Strength, σ_Y (MPa)	226

Mechanical properties of NiCrAlY bond coat at room temperature.

Thermal growth oxidation layer

The thermal growth oxidation layer α-Al2O3 is formed during the thermal operation and the oxidation of the metallic bond coat. The Al in bond coat slowly depletes and thickens the TGO layer. This TGO layer is considered the most crucial layer in the TBC system. Its growth during the thermal operation is responsible for the spallation failure of TBC system in many ways. One of the causes is from the stresses created inside the TGO. As the TGO thickens, the volume expands and at the same time the volume expansion is restrained by the top coat and bond coat layers. The restriction creates compressive "growth" stress (< 1GPa) within the TGO. Another source of stress is from thermal expansion mismatch between the TGO and the bond coat during cooling process. This thermal compressive residual stress is quite high as it can reach a maximum stress value that is about 2 to 6 GPa when the TGO is cooled down to ambient temperature. All these internal stresses can initiate and aggravate the development of micro cracks inside the TGO during thermal operation. As a result, total damage failure due to TBC spallation will occur from micro cracks coalescence. Thus, one way that can be used to predict the damage failure of TBC is by investigating the stresses created inside the TGO layer.

3.0 METHODS

For providing the above-indicated heating conditions, there are various ways of heating such as gas dynamic heating and radiant heating, for example, in a reflective furnace electrical current (AC or DC) or induction heating with the use of high-frequency currents.

Gas dynamic (flowing hot gas) heating has been used for more than 50 years. When using this method, a more accurate simulation of the heat exchange conditions from gas flow to the part is realized relevant to the gas-turbine engine. The rigs with gas dynamic heating enable a high heating rate to be provided to the part, to investigate the influence of oxidation in gas flow, but at the same time it is difficult to provide mechanical loading of parts. The cost of tests using such rigs is very high and the bench equipment needs to be frequently repaired or replaced. Alternating current (AC) or direct current (DC) resistance heating is effective for testing solid and tubular specimens. In accordance with this method, there is no need to use expensive and complex equipment. It enables tests to be conducted both at in-phase and at out-of-phase change of temperatures and mechanical loads. This methodology provides ease for review of the specimen surface. At identical time, this methodology can't be used for tests of gas-turbine engine components. The direct passing of electrical current will influence on the mechanical properties of the specimen material. Additionally, this methodology doesn't change the {particular} conditions for part heating in gas flow to be simulated. Once a specimen with a heat barrier coating is heated by direct passing of electrical current, the coating temperature is not up to the bottom material temperature. Warming of components is of bound use once conducting the thermo cyclic tests for specimens with a TBC. In so doing the surface is heated at a high rate, however, because of radiation focusing during test of a part (or a part model) it is difficult to simulate the required temperature field. Additionally, the heaters have a low cyclic lifetime. Evidently, induction heating with the use of high-frequency currents in the surface of a part is of greatest use to heat parts and models of parts when conducting tests for thermo mechanical fatigue. Such a method may be used to test both standard specimens and engine parts. When it is used, the surface part heating realized under service conditions is well simulated. In so doing, heat releases directly in the part. There is no need to use expensive heating equipment, and the equipment used features of high durability. The mechanical loading device can be used in the rig with inductor heating. It provides the possibility of conducting thermo mechanical fatigue tests of turbine blades. In so doing, with the use of a special inductor the temperature field is simulated for the blade section under the service conditions of which the strength margin is minimum and with the use of a suitable loading device, the centrifugal load is simulated in this section. It is worth noting that induction heating is only effective for testing of metallic alloys. For tests of parts made of ceramic materials, it is recommended in a number of papers to use dielectric heating (in Mega Hertz frequency range) or heating with the use of a susceptor. In the latter case, it is not possible to provide suitable heat-up rates for the temperature of the part. As conducted investigations showed that when using currents of more than 400 kHz to heat a metallic part with a TBC, both heating of metal located under the external layer coating and the effective heating of the dielectric (TBC) take place. Correlation of heat shared depends on the thermo physical properties of the base and coating materials and the frequency at which heating is performed, and a number of other factors. The experiments showed that the ceramic $ZrO2$ -based thermal barrier coatings on specimens and parts made of high-temperature nickel based alloys are effectively heated at frequencies between 0.4 and 2.0 MHz . Use of a higher frequency requires a complicated rig design. Consequently, it seems that in spite of a lack of data concerning the absence of a knowledge of the influence of induction heating on mechanical properties of the materials under investigation, this method of heating can be successfully used for tests of specimens and engine parts (primarily for comparative tests for selection of coatings and materials, design solution, manufacture and repair of engine parts with a TBC by production processes). The cost of the tests conducted with the use of high frequency heating is by an order lower than the cost of the tests conducted on a gas dynamic rig.

HF induction heating of ceramic thermal barrier coatings of parts

At present, the cyclic fatigue life of thermal barrier coatings in the course of their development has been studied using radiant heating with a low rate (less than 20 K/s), which does not correspond to actual operating conditions. At such low heating rates, thermal stresses are almost completely absent and the main damage factor is the oxidation of a sub-layer, which leads to spelling of the coating. Actually, these processes are heat resistance tests at variable temperatures. Under real conditions, the rate of change in the temperature of parts lies in the range 100-200 K/s. In this case, there arise cyclic thermal stresses and deformations of the base material and coating, which are accompanied by the appearance of alternating stresses. The results of tests for thermal fatigue of parts with thermal barrier coatings can differ significantly from the results of tests for cyclic heat resistance, which have been obtained by developers at a low rate of change in temperature.

Therefore, in the design of thermal barrier coatings, it is necessary to investigate their heat resistance together with a protected material under the conditions providing high rates of heating and cooling. The tests performed in a gas-dynamic flow are expansive and require a long time. The high-frequency induction heating is significantly lower in cost and requires a shorter time. The process of high-frequency heating involves not only induction heating of conductive materials but also heating of dielectrics, including ceramic materials. The dynamics of heating of the coating and the base material depends on the electro physical and thermo physical properties of the material, its volume, the cooling conditions, the rate of heating of the object, the dielectric properties of the ceramic coating, and the frequency of the electric current used for heating. The calculated simulation of the heating conditions for parts with thermal barrier ceramic coatings has not been adequately developed as compared to thermal calculations of the parts operating in a gas dynamic flow.

4. Results of investigations

The design-experiment method involves complex interrelated physical processes (such as heating of metal and ceramic materials in a high-frequency electromagnetic field, dielectric heating of the ceramic material, and interactions of non-stationary fields of temperatures and thermal stresses in a metal-ceramic part with cooling holes) and takes into account the electro physical and thermo physical properties of the materials in thermal cyclic tests New tasks on the determination of the ratio between the processes of high-frequency and dielectric heating's and on the identification of the dielectric heating effect and its influence on the distributions of heat fluxes and temperatures.

When engineering a thermal barrier coatings system, TST uses its strong expertise in materials engineering and its strength of understanding of the processes of thermal spray. The combination of this knowledge provides application specific solutions to our customers' thermal management problems.

In plasma spray devices, an arc is formed in between two electrodes in a plasma forming gas, which usually consists of either argon/hydrogen or argon/helium. As the plasma gas is heated by the arc, it expands and is accelerated through a shaped nozzle, creating velocities up to

MACH 2. Temperatures in the arc zone approach 36,000°F (20,000°K). Temperatures in the plasma jet are still 18,000°F (10,000°K) several centimeters form the exit of the nozzle.

High-velocity, oxy-fuel, (HVOF) devices ar a subset of flame spray. There ar two distinct variations between standard flame spray and HVOF. HVOF utilizes confined combustion associated an extended nozzle to heat and accelerate the fine coating material. Typical HVOF devices operate at hypersonic gas velocities, i.e. greater than MACH 5. The intense velocities offer mechanical energy that facilitates manufacture coatings that are terribly dense and very well adhered within the as-sprayed condition.

Flame spray is split into three subcategories, supported the shape of the feedstock material, either powder-, wire-, or rod-flame spray. Flame spray coating utilizes flammable gasses to make the energy necessary to soften the coating material. Combustion is actually unconfined, therein there's no extension nozzle within which acceleration will occur. Common fuel gases embody element, acetylene, propane, gas, etc. The lower temperatures and velocities related to typical flame spraying generally lead to higher oxides, porosity, and inclusions in coatings.

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