Cooling of gas turbine blades by yttria stabilized zirconia based Thermal barrier coating-A review

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Abstract- **New technologies in designing and manufacturing are implemented to obtain a high grade gas turbine product to maximize the efficiency which is prime necessity in the aviation industry. The design which produces better efficiencies will be established through achieving maximum temperature at the turbine inlet. Very high thermal stress of the turbine blade makes the main barrier to achieve this maximum temperature. The effective cooling of the turbine blade will eliminate such barrier. We carried out a study to develop gas turbine blades which can withstand at a very high temperature. Special manufacturing techniques along with conventional methods will reduce the thermal stresses of the blade, which can also reduce the weight of the engine due to elimination of blade cooling setup. Thermal barrier coating over the blades is the method in which coating of elements having the same thermal expansion and least thermal conductivity is applied over turbine blades which reduces the quantity of heat conducted inside the turbine blade. Selection of material for the thermal barrier coating needs a detailed study. Alloys of yttrium, zirconium, and platinum are found to be effective materials for thermal barrier coating through our analysis. These coatings will also improve corrosion resistance, fatigue life, etc… The manufacturing method for coating the materials over the turbine should be precise since it is a challenging task. Advanced coating method of "Electron beam physical vapor deposition" is to be implemented to avoid the separation of coating from the blade during the operation of engine.**

Key words: Thermal barrier coating, Effective cooling of turbine materials, Electron beam physical vapor deposition.

I. INTRODUCTION

Gas turbine plays an important role in the present day industrialized society and aviation industry and as the demands for power increase; the power output and thermal efficiency of gas turbines must also increase. One method of increasing both the power output and thermal efficiency of the engine is to increase the temperature of the gas entering the turbine. In the advanced gas turbines of today, the turbine inlet temperature can be as high as 1500°C; however, this temperature exceeds the melting temperature of the metal airfoils. Therefore, it is imperative that the blades and vanes are cooled, so they can withstand these extreme temperatures. Cooling air around 650°C is extracted from the compressor and passes through the airfoils. With the hot gases and cooling air, the temperature of the blades can be lowered to approximately 1000°C, which is permissible for reliable operation of the engine [1] .In aero-engines, there are two types of cooling methods are used. Internal and external cooling will provide the cooling effect to blade material. Liquid and air cooling are the categories. The liquid cooling method requires some special liquid and accessories. It may increase the weight of the engine and total weight of the aircraft. So some conventional methods are used to control the weight increment and reduction of temperature. There are three basic types of coatings

1. Aluminide (diffusion) coatings
2. Overlay coatings
3. Thermal barrier coatings (TBCs)

Among that as per the research of carlos A Estrada M [5] the thermal barrier coating will provide some resistance to temperature to enter in to the inner portion of the blade material. But the effective method of coating is very important because of strong adherent property. D. S. Almeida et.al [3], has find that the "electron beam-physical vapor deposition" method has the great impact on coating method. These are made it possible to run at increasingly high gas temperatures has resulted from a combination of material improvements and the development of more sophisticated arrangements for internal and external cooling.

II. LITERATURE REVIEW

Chin, H. J., Lesley, M. W., [1] has conveyed under the title of "Enhanced internal cooling of turbine blade and vanes" the impingement cooling of the turbine blade will provide better and effective cooling. With the cooling jets striking (impinging) the blade wall, the leading edge is well suited for impingement cooling because of the relatively thick blade wall in this area. Impingement can also be used near the mid-chord of the vane. But it is economically high. Mutassim, Z., [4] conveyed in his article about new gas turbine materials and benefits of the thermal barrier coating. Estradam, C. A., [5] in "New technology in gas turbine blades" shown the importance of coating and calculated amount of heat reduced. Dr. Ingenieurs, et al [6] in his research under the title "Aerodynamic Optimization of Highly Loaded Turbine Cascade Blades for Heavy Duty Gas Turbine Applications" found the development and validation method for the automatic aerodynamic optimization of turbine cascade blades for high pressure stages of heavy duty gas turbines. Slifka, J., and Filla, B. J.,[1] in his paper "Thermal

Conductivity Measurement of an Electron-Beam Physical Vapor-Deposition Coating", conveyed that six specimens of 7 % mass fraction yttria-stabilized zirconia coating were produced by Electron-Beam Physical Vapor-Deposition Coating (EB-PVD) with nickel based super alloy substrates and its thermal conductivity have been measured. The coatings, designated PWA 266, measured here had three thicknesses. Two sets of specimens each with nominal coating thicknesses of 170 µm, 350 µm, and 510 µm on 3 mm substrates were measured. From this we will give some better ideas and integrated methods for better results..

III. GAS TURBINE ENGINE

A. An Engine (review)

The gas turbine engine is a machine delivering mechanical power using a gaseous working fluid. It is an internal combustion engine like the reciprocating Otto and diesel piston engines with the major difference that the working fluid flows through the gas turbine continuously. The continuous flow of the working fluid requires the compression, heat input and expansion took place in separate components. For that reason a gas turbine consists of several components working together and synchronized in order to achieve the production of mechanical power in case of industrial applications, or thrust, when those machines are used in aircraft.

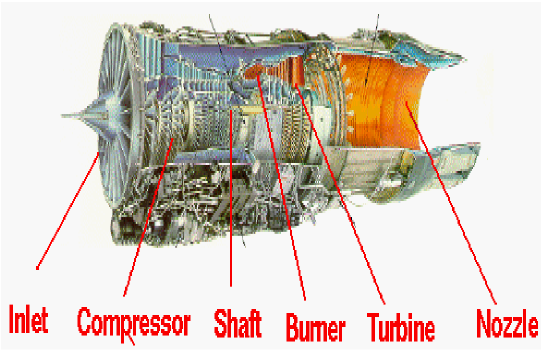

Fig.1. Location of parts in gas turbine engine.

B. Obstacles in Design

During design of engine some obstacles to be eliminated are as follows:

1. Less efficiency
2. Cooling of turbine blades
3. Weight of the engine
4. Turbine Inlet Temperature,
5. Turbine Blade material limitations, etc…

For overcoming the above obstacles, the cooling of turbine blades is the challenging task. The method of thermal barrier coating can be used for overcoming the problems associated with the conventional blade cooling methods. While selecting the material for thermal barrier coating, following points must be considered.

- Coating of alloys must have same thermal expansion as base metals
- It should have the low thermal conductivity

This alloy coating will give the better cooling and high thermal efficiency.

C. Thermal Barrier Coating

The great advantage of coatings is that it is possible to modify its response to the environment by changing only the superficial part of the component, thus providing completely different properties. Some of the benefits obtained are: reduction of maintenance costs, increase of the working temperature, reduction of thermal loads, increase in erosion and corrosion resistance and reduction of the high temperature oxidation.

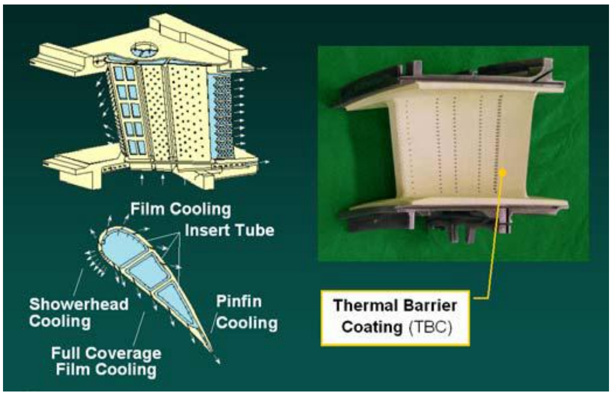

Fig.2.Cooling methods of blades [6]

Thermally deposited ceramic coating on metallic turbine blades have enabled turbine engines to operate at higher temperatures and according to the laws of thermodynamics higher efficiency. Ceramic thermal barrier coating have also provided improved performance in turbine engines for propulsion and power generation. Applying a coating of a refractory insulation made up of ceramics above the metal turbine blades and vanes allows the engine to run at higher temperatures while minimizing deleterious effects on the metal blades. Ongoing advances in high-tech materials are providing even more opportunities in these areas. By combining these new materials with a good understanding of coating engineering principles and application of technologies, coating manufacturers will be able to offer additional performance improvements in the future.

To improve coating performance, several important engineering principles must be considered regarding the quality of the ceramic coating. First, the coating material should be selected so that it is refractory enough to resist the high temperatures at the surface and have a low bulk thermal conductivity to minimize heat transfer to the metallic blade underneath. In addition, the thermal expansion of the selected material should closely match that of the metallic substrate to minimize potential stresses. Yttrium stabilized zirconia (YSZ) is the industry standard "first generation" coating material in use today. And in the second one, the coating must have a grain and pore Structure that will minimize thermal conduction to the metal-ceramic interface. A low-density coating is commonly formed using a state-of-art deposition processes and is excellent for providing an insulating

barrier. The coating should have enough porosity, so that it reduces the thermal conductivity while simultaneously adhering to the metal turbine bond-coat layer. A significant research in thermal barrier coatings in the field of micro structural engineering is ongoing, example of this reality, is the
availability of double and triple-layered microstructures for special applications. Finally, the coating should stick to the turbine blade during operation. Failure of the adhesion (spalling) would suddenly expose the metallic blade to high temperatures, causing severe corrosion, creep or melting. Generally, a metallic bond coat shows good adhesion to both the metallic turbine and the ceramic coating is applied.

By the convective law

$$Q=hA\,(T_w-T\infty) \qquad (1)$$

Where h-local heat transfer coefficient, W/m^2K
A-Surface area, m^2
T_w-wall temperature, K
$T\infty$-temperature of fluid, K

It is clear that the convection is directionally proportional to the heat transfer co-efficient. Form the above law, it can be seen that low heat transfer co-efficient material can conduct only low amount of temperature. Hence, such materials should be used for coating purpose.

D. Improved materials

The improved gas turbine materials are tabulated in the Table (1). Various components of the gas turbine engines are casted with the following materials which can adapt the high temperature operation. Thermal barrier coatings have been used for several years on static parts, initially using magnesium zirconate but more recently yttria-stabilised zirconia. On rotating parts, the possibility of ceramic spalling is particularly dangerous, and strain tolerant coatings are employed with an effective bond coat system to ensure mechanical reliability. For coating the yttria-stabilised zirconia, more advanced can be implemented. Electron beam-physical vapor deposition (EB-PVD) is one of the most advanced coating methods suggested by Daniel Soares de Almeida, et.al. [8] The TBCs provide enough insulation for superalloys to operate at temperatures as much as 150^{o}C above their customary upper limit. TBCs are ceramics, based on $ZrO_2 - Y_2O_3$ and produced by plasma spraying.[9]

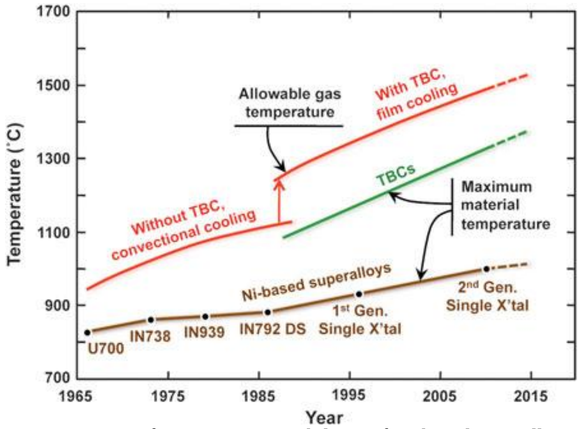

Fig.3. Progression of temperature capabilities of Ni-based superalloys and thermal-barrier coating (TBC) materials over the past 50 years. The red lines indicate progression of maximum allowable gas temperatures in engines, with the large increase gained from employing TBCs. Based on a diagram from the late Professor Tony Evans.[10]

E. Electron Beam vapor deposition method

The electron beam-physical vapor deposition (EB-PVD) process enables to attain coatings with unique properties. The process parameters are adjusted so that the deposit has a columnar grain structure perpendicular to the interface. This morphology maximizes the resistance to strains that arises from difference in thermal expansion coefficients. There are four primary constituents in a thermal protection system. They comprise

(1) The thermal barrier coating (TBC) itself based usually on ~8 wt% (8.7 mol % $YO_{1.5}$) yttria stabilized zirconia
(2) The metallic component, treated here as the substrate
(3) An aluminum containing bond coat (BC) located between the substrate and the TBC
(4) A thermally grown oxide (TGO), predominantly a-alumina that forms between the TBC and the bond coat.

The TBC is the thermal insulator in which bond coat provides oxidation protection, since the zirconia is essentially transparent for the oxygen at high temperatures and the metallic component, usually nickel based super-alloy sustains the structural loads. The TGO is an oxidation reaction product of the bond layer, and plays an important role in the metal/oxide adhesion. Each of these elements is dynamic and all interact to control the performance and durability.

When ZrO2 is utilized for technical applications, the high-temperature polymorphs cubic (c) and tetragonal (t) phases should be stabilized at room temperature by the formation of solid solutions, which prevent deleterious tetragonal-to-monoclinic (m) phase transformation. The alloying oxides, which lead to the stabilization, are alkaline-earth, rare-earth, and actinide oxides. It has been suggested that factors which may influence the stabilization are size, valency, concentration of solute cations and crystal structure of the solute oxides, where the valency and concentration determine the number of oxygen vacancies created by the formation of substitution solid solutions.

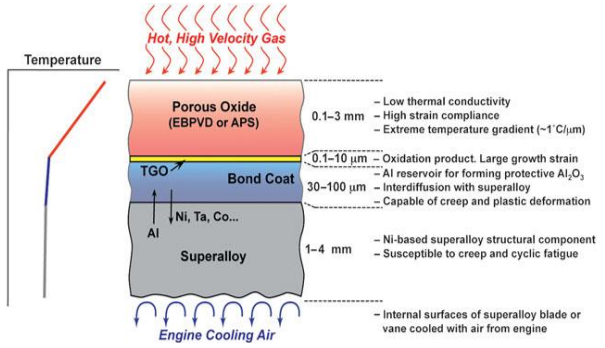

Fig.4. Schematic illustration of the multilayer, multifunctional nature of the thermalbarrier coating system (not to scale). The ceramic topcoat is deposited by electron beam physical vapor deposition (EBPVD) or air plasma-spraying (APS). Sandwiched between the topcoat and the metallic bond coat is the thermally grown oxide (TGO). Properties/ functions and approximate thicknesses of the different layers are indicated.[10]

F. Topcoat ceramics

The majority of TBCs in use today are ZrO_2 -based having a composition containing ~ 7 wt% Y_2O_3 (7YSZ). Originally, this ceramic was selected empirically based on its low thermal conductivity, high melting point, resistance to sintering, a demonstrated manufacturing capability for depositing it with constant composition, and long life in the resulting TBCs. Unlike the cubic ZrO_2 used in oxide fuel cells, oxygen sensors, and fake diamonds, which have higher Y_2O_3 content, 7YSZ is a metastable tetragonal phase (t). 7YSZ has been shown to have unusually high fracture toughness due to ferro elastic toughening. Unlike other transformation-toughened ZrO_2 -based ceramics, so-called "ceramic steels, used in bearings, cutting tools, and knives, the toughness in 7YSZ does not arise from the martensitic transformation (an irreversible and diffusion less collective movement of atoms) from the tetragonal to monoclinic phase but rather from reversible ferroelastic domain switching from one tetragonal variant to another when stressed. Also, unlike transformation toughening, ferroelastic toughening can operate at high temperatures, typical of those at engine temperatures. High fracture toughness in TBCs is important not only for resisting impact and erosion but also spallation.[10]

Grade designation	**Chemical composition**
IN 713	74.2Ni12.5Cr4.2Mo2Nb0.8Ti6.1Al0.1Zr0.12C0.01B
IN 100	60.5Ni10Cr15Co3Mo4.7Ti5.5Al0.06Zr0.18C0.014B
Rene 100	62.6Ni9.5Cr15Co3Mo4.2Ti5.5Al0.06Zr0.15C0.015B
MAR-M200	59.5Ni9Cr10Co12.5W1.8Nb2Ti5Al0.05Zr0.15C0.015B
MAR-M246	59.8Ni9Cr10Co2.5Mo10W1.5Ta1.5Ti5.5Al0.05Zr0.14C0.015B
IN 792	60.8Ni12.7Cr9Co2Mo3.9W3.9Ta4.2Ti3.2Al0.1Zr0.21C0.02B
M 22	71.3Ni5.7Cr2Mo11W3Ta6.3Al0.6Zr0.13C
MAR-M200+Hf	Ni8Cr9Co12W2Hf1Nb1.9Ti5.0Al0.03Zr0.13C0.015B
MAR-M246+Hf	Ni9Cr10Co2.5Mo10W1.5Hf1.5Ta1.5Ti5.5Al0.05Zr0.15C0.015B
Rene 41	56Ni19Cr10.5Co9.5Mo3.2Ti1.7Al0.01Zr0.08C0.005B
Rene 77	53.5Ni15Cr18.5Co5.2Mo3.5Ti4.25Al0.08C0.015B
Rene 80	60.3Ni14Cr9.5Co4Mo4W5Ti3al0.03Zr0.17C0.015B
Rene 80+Hf	59.8Ni14Cr9.5Co4Mo4W0.8Hf4.7Ti3Al0.01Zr0.15C0.015B
IN 738	61.5Ni16Cr8.5Co1.75Mo2.6W1.75Ta0.9Nb3.4Ti3.4Al0.04Zr0.11C0.01B
Udimet 700	59Ni14.3Cr14.5Co4.3Mo3.5Ti4.3Al0.02Zr0.08C0.015B
Udimet 710	54.8Ni18Cr15Co3Mo1.5W2.5Ti5Al0.08Zr0.13C
TMD-103	59.8Ni3Cr12Co2Mo6W5Re6Ta0.1Hf6Al

TABLE: 1 Conventionally cast nickel-base super alloys for gas turbine blading applications in aircraft gas turbines[9]

F. Benefits of coatings

As stated earlier, TBCs can be used to reduce liner wall temperatures. A TBC consists of a metallic-bond coating applied directly onto the component surface followed by the application of a ceramic top coating. The function of the metallic-bond coating is to provide oxidation protection to the metallic substrate to minimize thermal expansion mismatch, and to provide strain compliance between the substrate and the ceramic layer. The ceramic layer with low thermal conductivity creates the thermal gradient needed across the TBC system. Model calculations and instrumented rig tests carried out by Daniel Soares de Almeida, et.al. [8] determined a temperature reduction at the turbine surface of 13°C/0.1 mm to 14°C/0.1 mm (6°F/0.001 inch to 7°F/0.001 inch) of ceramic coating. This level of temperature reduction could be significant to component life. An alternative material of construction for combustor liners is the application of ceramic matrix composites in place of the metallic liners. The use of the ceramic combustor allows increased firing temperatures without degrading combustor durability. The material of a choice for ceramic liners is a Continuous Fiber-reinforced Ceramic Composite (CFCC) material based on a silicon carbide with Nicalon as reinforcement and silicon carbide (SiC) as matrix material which is incorporated by chemical vapor infiltration. CFCCs were selected over more conventional monolithic ceramic materials due to their superior fracture toughness, which gives them a distinct advantage over conventional monolithic materials for large structures such as combustor liners.

Rapid oxidation (in few thousand hours) due to environmental degradation is a challenge for the SiC material. An Environmental Barrier Coating (EBC) system was developed under the NASA High Speed Civil Transport, enabling Propulsion Materials Program in the mid- 1990s to successfully overcome this problem. The EBC system was scaled up and optimized for combustor liners. It has proven itself in a single engine test for operation of over 15,000 hours. Barium strontium aluminum silicate provides the oxidation barrier for the EBCs. An alternative system based on alumina ceramics has been developed and tested. The oxide composite by itself does not have the temperature capabilities of silicon carbide composite. The addition of a Functionally Graded Insulator that acts as a thermal barrier creates a higher temperature system than the silicon carbide material with EBC. The system has now logged over 20,000 hours in a field test for an outer combustor liner. Field experience has been demonstrated on a number of units in various industrial applications.

Some of the benefits of thermal barrier coating are: reduction of maintenance costs, increase of the working temperature, reduction of thermal loads, resistance increase to erosion and corrosion and reduction of the high temperature oxidation.

IV. CONCLUSION

The challenges facing the modern industrial gas turbine are numerous. The environmental and mechanical conditions demand materials and processes that can survive thousands of hours of service without serious degradation. Advances in material technologies have often provided the capability to achieve success. New alloys, coatings and processes have provided technological advancements for many components. Combustor liners and turbine blades are a few of the components that have bended from these advancements. Better performance, higher efficiencies, and lower lifecycle costs are often attained with material technologies. Development and implementation of new material technologies are necessary to meet the challenges of tomorrow.

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