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Experimental Investigation on Heat Transfer Characteristics of Thermal Barrier Coating on Aero Engine Components

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Abstract

The gas turbine blades play a crucial role in harnessing energy from the high-temperature and high-pressure gas generated by the combustor. To withstand this challenging environment, turbine blades often employ super-alloys and incorporate new manufacturing technologies such as Direct Solidification (DS) and Single Crystal (SC). Additionally, the development of advanced ceramic Thermal Barrier Coating (TBC) is imperative to achieve higher operating temperatures (>1200°C). Therefore, the primary focus of this study is on advancing TBC with reduced thermal conductivity and increased operating temperature, without imposing a significant weight penalty on components. Two sample specimens, measuring 75 mm × 75 mm × 10 mm, were manufactured from SS 316L and 8% Yttrium Stabilized Zirconia (YSZ-$ZrO_2.Y_2O_3$), as well as 8% Yttria Stabilized Alumina (YSA-$Al_2O_3.Y_2O_3$). These specimens were coated with a bond coat of Nickel Chromite (NiCr) using the Atmospheric Plasma Spray Method (APS). The temperature variations across a 250 μm layer of 8% YSZ and 8% YSA were analyzed through both simulation and thermo-mechanical tests. This analysis aims to elucidate the efficacy of TBC materials in enhancing the operational limits of components subjected to elevated temperatures, particularly in aerospace and automobile applications.

Keywords: Thermal Barrier Coating, Yttrium Stabilized Zirconia, Yttrium Stabilized Alumina. plasma spray method, heat transfer, turbine blades

INTRODUCTION

The turbine stage has both fixed and rotating blades for extracting energy from the heat, high-pressure gas created with the aid of the combustor. The development of new materials and manufacturing technology is essential to increase the operational limit of turbine blades [1]. Chromium, cobalt, and rhenium that incorporate nickel-based superalloys are mostly used in present turbine blades. The introduction of Thermal Barrier Coatings (TBC) was the most significant improvement in turbine blade material technology. Firstly, aluminized coatings were used as TBC coatings, later ceramic coatings were invented. This introduction of TBC aerated the turbine blade temperature capacity by 200°F and also the lifetime of the turbine blade is doubled, by boosting the blade life [2].

Thermal Barrier Coatings (TBCs) are one of the specialized materials systems which are applied to surfaces of metal, which operate at very high

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temperatures, by performing the important function of insulating components and increasing the operating temperature of gas turbine and aero-engine parts [3, 4, 5]. The TBCs have extremely low thermal conductivity when it is exposed to heat flow and bears large temperature gradients. Yttrium stabilized zirconia (YSZ) is the most commonly applied TBC material with good thermal shock and thermal fatigue resistance of up to 1,150°C [6].

The thickness of TBCs range from 100 µm to 2 mm, and serve for insulation of large and sustained heat loads, between the load-bearing alloys and the coating surface. Such coatings allow for higher operating temperatures and restrict the thermal exposure of structural components to reduce oxidation and heat fatigue, increasing the longevity of the product. The development of new and advanced TBCs is significant because there's an increasing demand for more efficient engines that operate at higher temperatures, better life or durability, less wear-out, and weight reduction for rotating components by applying thinner coatings [7]. The criteria for selecting an efficient TBC are low thermal conductivity, high melting point, chemical inertness, low sintering activity, no phase change, good thermal and chemical stability, good erosion resistance, high coefficient of thermal expansion, and also good adherence to the substrate [8, 9]. Thermal barrier coatings (TBCs) typically consist of four layers,i.e. metal substrate, metallic bond coat, Thermally-grown oxide (TGO) and ceramic topcoat. In this work the thermal barrier coatings prepared with four layers which two of which are the bond coat and the topcoat.The bond coat used in the project is Nickel Chromite (NiCr). The thickness of the bond coat is 50 microns. The features of NiCr are the bond strength of ceramic coatings is improved from 35 – 55 MPa (5000 – 8000 psi),oxidation resistance is good that is up to 1000°C (1832°F),it is usually useful for smooth finish applications.The topcoat is applied once after the bond coat on a substrate material. Depending on the thermal expansion coefficient, a topcoat is being used for this application. Due to its low thermal conductivity, it also offers thermal insulation. The topcoats used in this work are 8% Yttria stabilized Zirconia and 8% Yttrium stabilized Alumina (fig.1 and fig.2).

METHODOLOGY

Selection of Metal Substrate

The metal substrate used in the work is Stainless Steel 316L, of dimension 75 mm × 75 mm × 5 mm (thickness). Grade 316L is a low carbon (0.03 max carbon) 316 version which offers good tensile strength at elevated temperature, higher creep, and stress to rupture, and resistance to sensitivity (grain boundary carbide precipitation). The metal pieces should undergo the Blasting Process before Plasma Spray Coating. It is usually done to roughen a smooth surface, vice-versa, and to remove the impurities on the metal substrate, and along with these, we can give a proper shape to a surface. Abrasive Blasting is the type of blasting used in the project.

Plasma Spray-coated Specimens

Using Atmospheric Plasma Spray (APS), plasma-sprayed coatings were produced. Commercially available Bond coat (BC) - Nickel chromite of 50 microns and plasma spray powders -8% Yttrium stabilized Zirconia and 8% Yttrium stabilized Alumina are the coatings used for plasma spray coating on the metal substrate [5]. APS is a very efficient and widely used coating method. It can spray on a wide range of materials on both small and large components, to protect from corrosion and oxidation, high electrical resistivity and low conductivity, etc. [5]. The plasma spray parameters used in the work are given in the Table 1:

Table 1. Plasma spray parameters

Parameters	Values
Voltage (V) – DC	65–72
Current (A)	500
Primary gas, Ar (1/min)	100 to 120
Power feed rate (g/min)	37
Spray distance (inches)	2” to 3”

Figure 1. YSA coated metal piece.

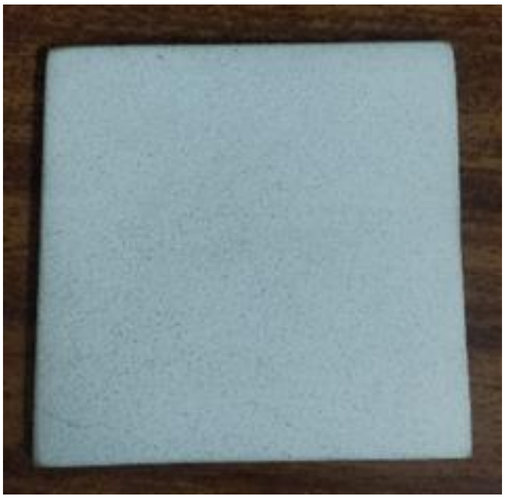

Figure 2. YSZ coated metal piece.

18% Yttrium Stabilized Zirconia

It is also called 8YSZ/YSZ-8/Yttrium-stabilized Zirconia. It is a ceramic in which the cubic crystal structure of zirconium dioxide (zirconia, ZrO_2) is made stable at room temperature by the addition of yttrium oxide (yttria, Y_2O_3). YSZ with 6-8 Wt.% Y_2O_3 stabilization having thermal conductivity ranging from 2.2-2.9 W/(m K), has a large grain size, and is full-dense. It's used as commercial material for TBC applications because its application achieves sufficiently low thermal conductivity. The melting point is around 2700°C. Which is high and the coefficient of thermal expansion is relatively high, which is 110×10^{6}/K [6].

8% Yttrium Stabilized Alumina

It is also called 8YSA/YSA-8/ Yttrium-stabilized Alumina. It is a ceramic in which aluminum oxide (alumina, Al_2O_3) is made stable at room temperature by the addition of yttrium oxide (yttrium, Y_2O_3). The Linear formula for 8% Yttrium stabilized Alumina is $Al_2O_3.Y_2O_3$. Alumina is commonly called Aluminium oxide. It is a desirable material as it possesses strong ionic interatomic bonding and also it can exist in various crystalline phases. At high temperatures, it can revert to the hexagonal alpha phase as this is the most stable phase if it finds several structural applications.

Thermal Barrier Test

The thermal barrier test involved exposing the ceramic surface to high temperatures for a pre-fixed amount of time and suddenly withdrawing the specimen to rapidly quench the hot ceramic surface [8]. The similar process is carried out in this work by exposing the metal with ceramic coated surface of TBC to Oxy-Acetylene gas of high temperature with 800ºC to 1000ºC.The temperature drop is measured using a thermal gun. The metal piece or component was placed on an insulated surface and the heat from the Oxy-Acetylene flame was applied at one point on the surface of TBC up to 1000°C and the temperature was measured simultaneously using a temperature gun. Once the temperature reaches up to 1000ºC, the component is rotated and the temperature drop is measured at the same point behind the TBC coated metal within a fraction of seconds. Therefore the same procedure was carried out for both 8% Yttrium stabilized Zirconia and 8% Yttrium stabilized Alumina at different temperatures ranging from 500ºC to 1000ºC [10, 11, 12]. Finally, the results were compared.

Fem Analysis

Finite Element Analysis simulates the loading conditions in a model and evaluates the design's response. Thermal analysis is used to evaluate the distribution of temperature in an entity. Certain value amounts contain heat lost or restored, thermal gradients, and thermal flux. It is possible to analyze all three principal heat transfer modes,i.e. conduction, convection, and radiation. In this work, 1D Thermal analysis is carried out using ANSYS 19 Mechanical APDL.

RESULTS AND DISCUSSIONS

Fem Analysis

Boundary Conditions

Thermal conductivity:

- 8% Yttrium stabilized Zirconia (8YSZ, YSZ-8) = 2.2 W/mK
- Stainless steel 316 = 22.5 W/mK
- Input Temperature: 500°C

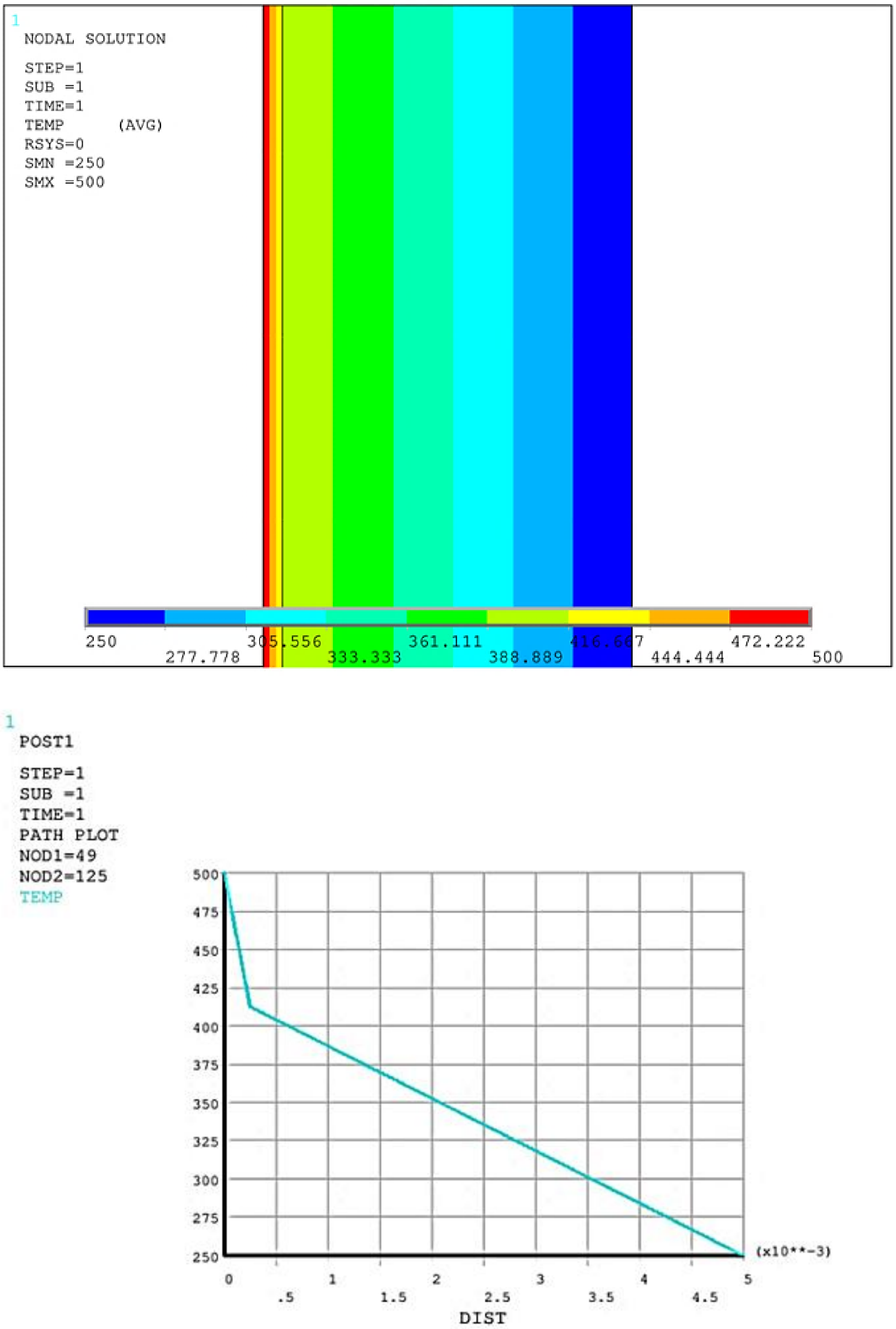

Figure 3. Contour plot and graph (Dist v/s Temperature) at 500°C.

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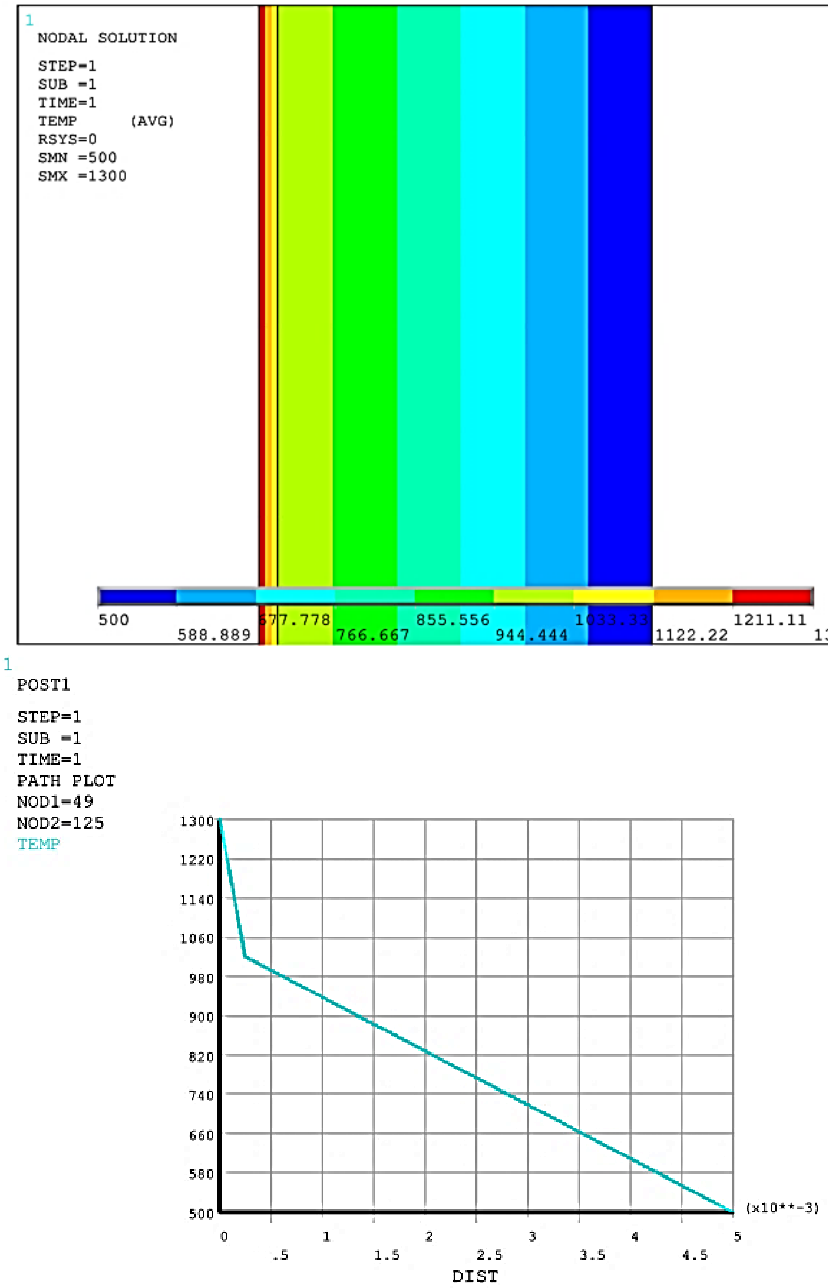


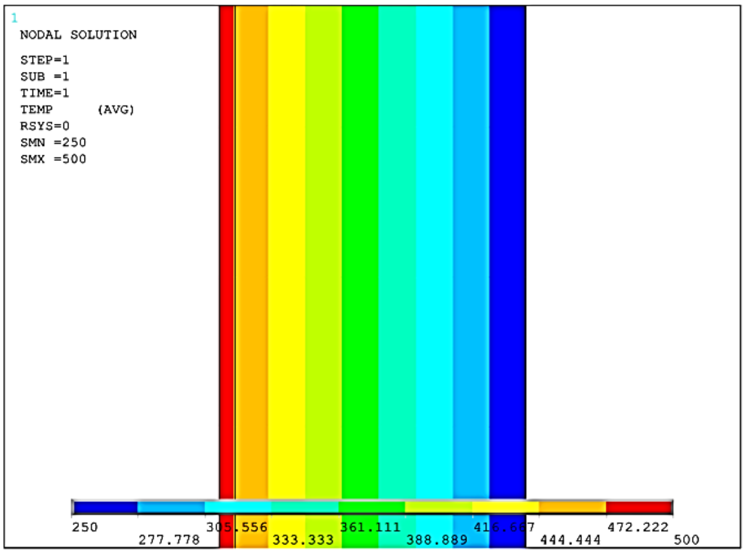
Figure 4. Contour plot and graph (Dist v/s Temperature) at 1300°C.

Boundary conditions:

Thermal conductivity:

- 8% Yttrium stabilized Alumina = 8.5 W/mK
- Stainless steel 316 = 22.5 W/mK
- Input Temperature: 1300°C

From Figures 3, 4, 5 and 6 we can understand the temperature distribution across the thickness of the coated flat plate. From the contour plots, it is understood that the decrease in temperature for YSZ is greater than that of YSA. After comparison between the 2 TBCs, we can conclude that 8% Yttrium stabilized Zirconia can withstand high temperature and for a long time as it has low thermal conductivity than 8% Yttrium stabilized Alumina.



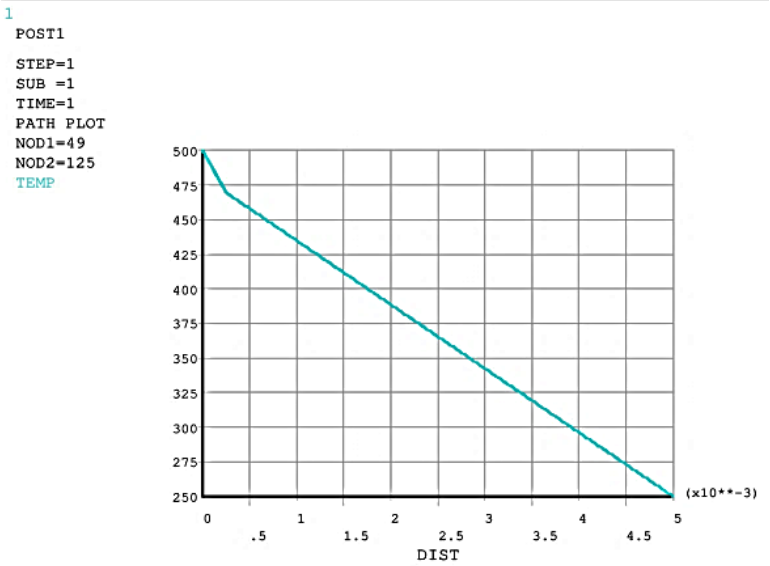
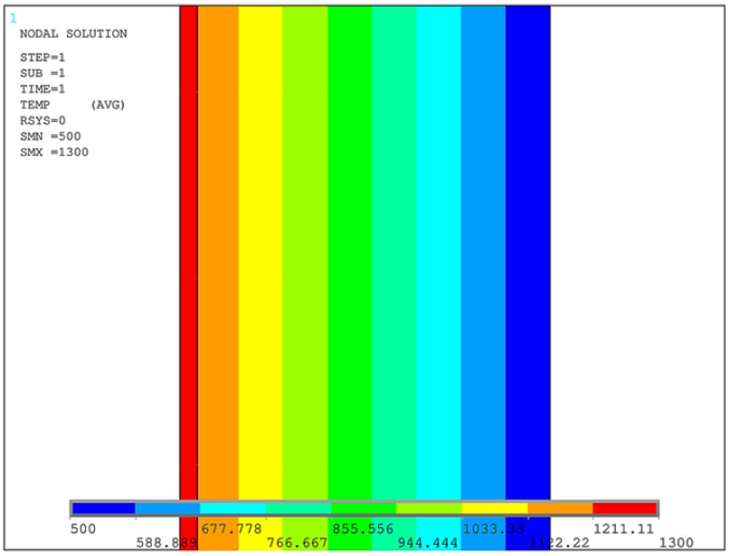


Figure 5. Contour plot and graph (Dist v/s temperature) at 500°C.



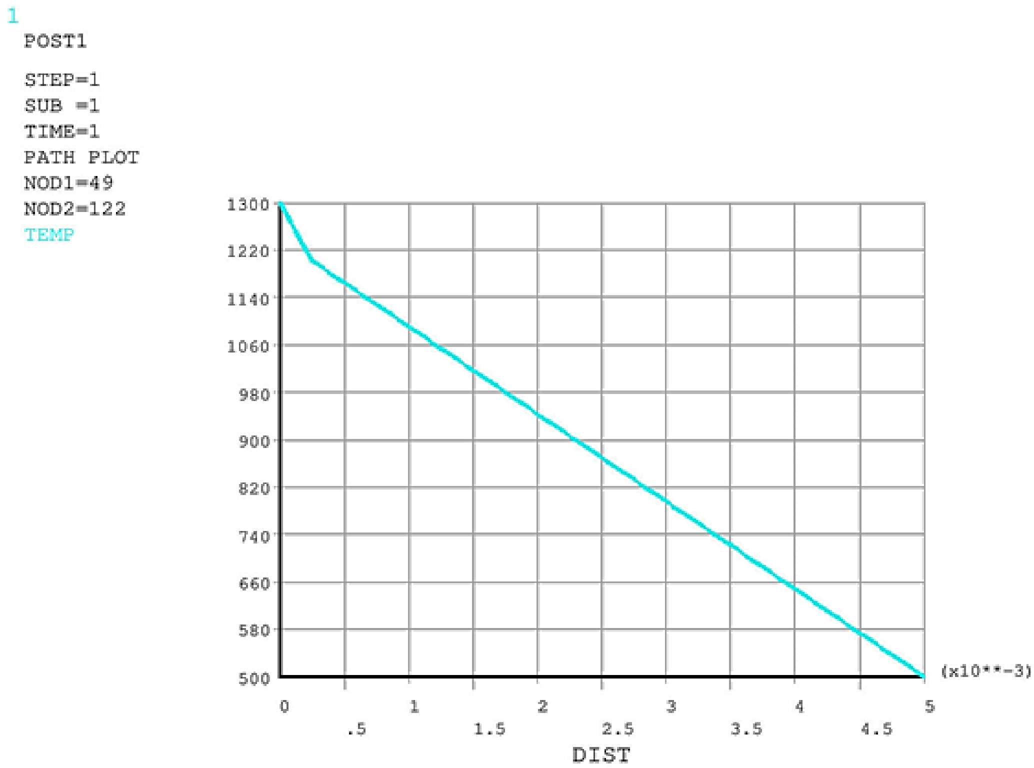


Figure 6. Contour plot and graph (dist v/s temperature) at 1300°C.

THERMAL BARRIER TEST

The readings were obtained by applying the heat on the coated surface (T1) and immediately noting down the temperature across the metal surface (T2).The difference between the temperatures,i.e. T1 and T2, results in the Temperature drop across the metal. Therefore by the values obtained we conclude that 8% yttrium stabilized zirconia is a better TBC than 8% yttrium stabilized alumina.

The readings obtained at the following Tables 2, 3.

Table 2. Thermal barrier test for YSZ

Temperature given on the surface of TBC,T1 (°C)	Temperature behind the metal surface,T2 (°C)	Temperature drop (T1-T2) (°C) YSZ
1016	811	205
921	705	216
809	597	212
723	581	142
618	522	96

Table 3. Thermal barrier test for YSA

Temperature given on the surface of TBC,T1 (°C)	Temperature behind the metal surface,T2 (°C)	Temperature drop (T1-T2) (°C) YSA
1020	885	135
942	802	140
816	664	152
705	623	82
643	584	59

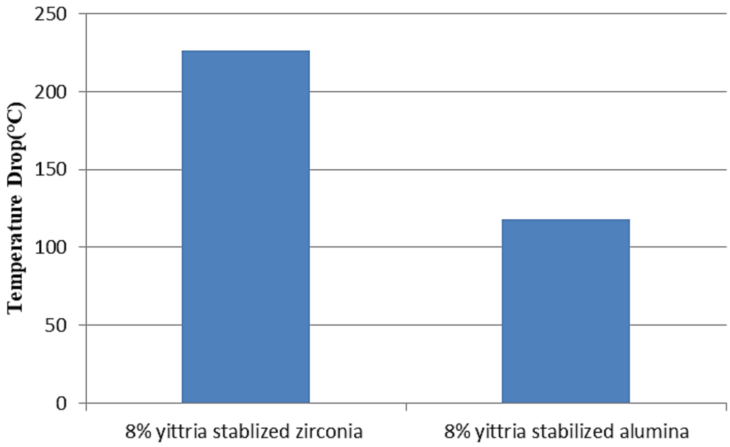


Figure 7. Comparison of temperature drop between 8YSZ and 8YSA.

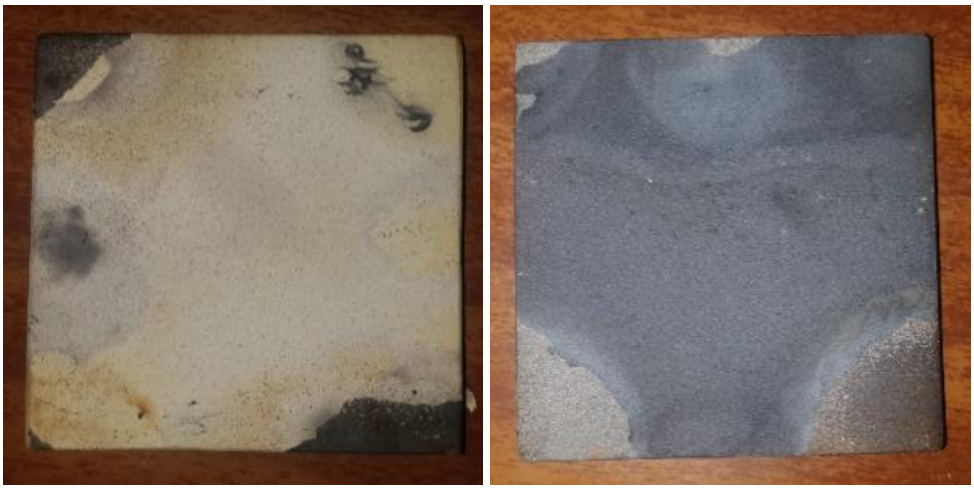


Figure 8. Images obtained after thermal barrier test.

This was concluded by understanding and comparing the temperature drop between 8% YSZ and 8% YSA, i.e. the temperature drop for 8%YSZ is greater than the temperature drop for 8% YSA (fig. 7 & Fig.8). hence it can be concluded that the aero engine components coated with 8%YSZ can with stand higher temperatures in comparison with other TBC's tested in the work [10].

CONCLUSION

Thus, the observations made from the above results will be useful to improve the operational limit of the turbine blade at very high temperatures above 1200°C. 8% Yttrium stabilized Zirconia (YSZ) and 8% Yttrium stabilized Alumina (YSA) were used as a topcoat on substrate material and results were compared by conducting Thermal Barrier Test and FEM analysis.The FEM contour plots indicate that a temperature drop of 8%YSZ is greater than that of 8%YSA, showing that 8%YSZ is more efficient as TBC material in the area of high-temperature applications. Similarly, Thermal Barrier Test result indicates that the temperature drop for 8% YSZ is ~220°C and for 8% YSA is ~120°C. Hence, both simulation and experimental results proved that 8% Yttrium stabilized zirconia performs better as a Thermal Barrier Coating than 8% Yttrium stabilized alumina, as it can withstand high operating temperatures for turbine blades materials. Also, the elements like rare-earth elements which is having lower thermal conductivity can be used as efficient TBCs for future applications.

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