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Assessment of Thermal Barrier Effects across 8%Y_2O_3-ZrO_2 Coatings on Al-Si Substrates via Electrical Heating Source

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Abstract. Ceramic Thermal Barrier Coatings (TBCs) provide protection to metals from degradation at high temperature. A major factor deciding the effectiveness of the coating in service is the temperature drop across the thickness of the coating. Common practice to determine the temperature drop is to subject the coating with a high heat providing flame with preset velocity by using combustible gases focused towards the coated surface, that keep the surface at desired stabilization temperature and the temperature is measured at the back side of the coating, i.e. at the metal side. The challenge is to heat the complete specimen surface using the flame and to reach an accurate stabilization temperature by using the flame as the heating source. In the present work, this challenge was overcome by using a uniform source of heat i.e. an electric heater on the entire coating surface. This paper presents the results obtained by studying the thermal barrier effects across TBCs by using the electrical heating source that provided the heat on the ceramic surface in a controlled and uniform manner, thereby establishing a newer assessment method.

The TBCs were prepared by plasma spray coating commercial 8%Yttria-Stabilized Zirconia (8YSZ) as the top ceramic coat on flat plates of Aluminium 11% Silicon alloy removed from diesel engine pistons. TBC thicknesses varied between 100µm and 600µm. Air Plasma Spray coating was employed to coat the substrates which initially were spray coated with 50-75 µm thick bond coat of Nickel Aluminide. Thermal barrier test was conducted by heating the entire coated surface uniformly and by keeping the ceramic surface temperature constant till the stabilization in the range of 300^0C to 500^0C. The temperature drop achieved was in the range of 46^0C to 127^0C depending upon the coating thickness. Details of the tests conducted and results obtained are presented.

INTRODUCTION

Thermal Barrier Coatings (TBCs) on metallic components/ substrates have become widely prevalent in high temperature engineering, including automobiles and aerospace [1, 2, 3]. This is due to the ability of the TBCs to protect the temperature sensitive substrate material from high temperature degradation or the possibility of increasing the ceramic surface temperature to achieve a better thermal efficiency [1, 4]. A typical TBC system comprises of a metal substrate (or component), 50-75 µm bond coat (NiAl, NiCrAlY, CoCrAlY etc. depending upon the substrate metal) over laid by a 250-500µm top coat. The most desired TBC material in aerospace and automobile industry is 6 to 8% Yttria Stabilized Zirconia (6-8% Y_2O_2-ZrO_2), applied either by Electron Beam Physical Vapor Deposition (EBPVD) or Atmospheric Plasma Spraying (APS). APS is highly prevalent due to techno-economic considerations.

The thermal barrier effect within a TBC is a function of many variables: top coat and bond coat material, coating thickness build up, porosity developed inside the coating material during coating process (generally atmospheric plasma spray) etc. The accurate measurement of the temperature drop across a TBC is a challenging task due to the involvement of major test conditions such as (a) the stability of heat (therefore temperature) experienced by the ceramic coating surface and (b) precision in temperature measurement. In general, when assessing a TBC material for aerospace application, the ceramic surface is subjected to an extremely hostile, high temperature, high velocity

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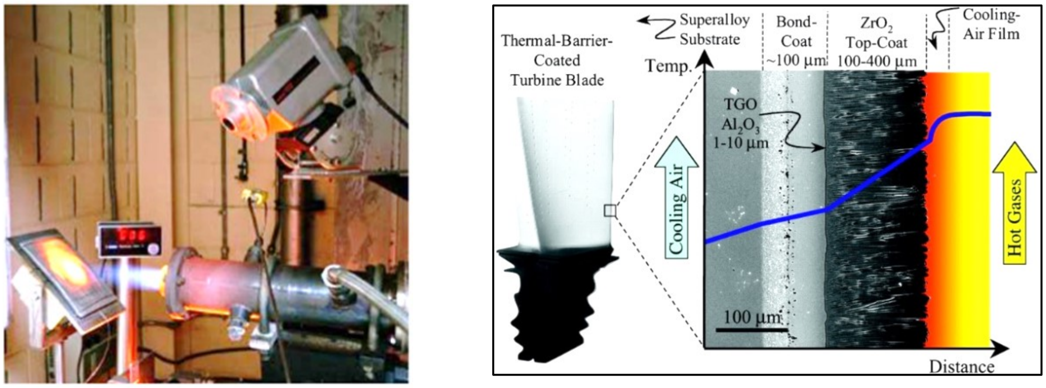
environment (generated by using pressurized air and flames) and the ceramic surfaces face 200-mile per hour flames to typically simulate the temperatures of aircraft gas turbine engines in flight [5, 6]. However, this kind of an extreme experiment is possible only in highly sophisticated laboratories where the substrates too are generally high temperature super alloys [7]. A sophisticated Burner rig facility at NASA is shown in figure 1(a) and a typical TBC schematic is shown in figure1 (b)



(a) Burner Rig Facility at NASA [6]

(b) Schematic of TBC [2]

FIGURE 1: Burner rig facility (at NASA) and a typical schematic of TBC

TBCs are also used in automobile applications to improve the efficiencies of engines [8 - 10]. The metal components to be coated with TBCs are invariably aluminum-silicon alloys (pistons in diesel engines) with melting temperatures no higher than 600°C [11]. For such cases, assessment of thermal barrier effects requires temperature sources which are of less intensity, lower velocity and therefore more controlled so as not to melt the metal base plate. In the case of a coated specimen exposed to gas flame, uniform heating across the complete surface and also to control the flame temperature to achieve a stabilization temperature is a tedious process which may introduce inaccuracies to the measured temperature drop values across the TBCs. An improved methodology to accurately measure the thermal barrier abilities of a TBC could be to use resistance based electric heat source and to measure the temperature drop across the flat plate using suitable thermocouples. An environment created through wire wound resistance heating could be the infinite source of heat and to provide uniform and completely heated ceramic surface area and also to keep the ceramic surface temperature steady (accurate with tolerance in temperature closer to the intended temperature) at the stabilization value without thermal fluctuation.

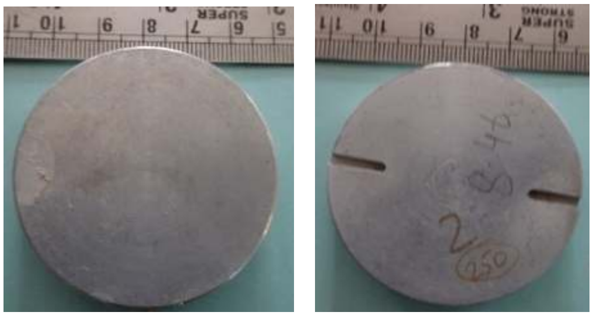
SCOPE OF THE INVESTIGATION

The scope of this investigation involved using prepared Al-Si flat plates as substrates (surface roughened, bond coated etc.), plasma spray coated with commercial 8YPSZ powders to serve as top ceramic coated layers, followed by subjecting the coated surface to electrically heated environment to desired temperatures and measurement of the temperature at the metal side (back of the coated surface) to determine the temperature drop across the coating and substrate thickness.

EXPERIMENTAL PROCEDURE

Substrate Material

In this investigation, aluminium-silicon alloy with ~11% silicon content was used as the substrate. Aluminium alloy of this composition is a commonly used material in an automobile industry [12, 13]. The flat diesel engine piston alloys (Al -11Si), machined to flat circular plates (50mm diameter x 5mm thick) were used as the substrates. Slots /grooves (10mm long x 2 mm wide x 2mm depth) were cut on back side to facilitate the fixing of thermo couples. The two thermocouple beads were inserted at the slots to ensure contact and accurately measure the temperature at two different points on the surface. The top and bottom side of the substrate are shown in figure 2.



(a) Top side view (b) Bottom side view

FIGURE 2. Al-Si Alloy flat plate substrate

Coating of substrate by Air Plasma Spray Coating Process

The front sides of the flat plates were grit blasted and degreased with solvent to generate roughened and oxidation free surface for good adhesion between coating and substrate. Photo of a typical sand blasted Al-Si specimen surface is given in figure 3. The roughening process removes the impurities and scale if any and would make the surface rough enough so that the ceramic materials will properly adhere to the substrate surface when it impinges on it at high velocity. Prior to coating, the surfaces where coating is not required were masked with adhesive tapes. The prepared surfaces were coated with a bond coat of commercial nickel aluminide plasma spray powder (trade name AMDRY956) and a topcoat of most popular commercially available spray powder, namely 8%Yttria Partially Stabilized Zirconia (8YPSZ) (trade name METCO NS204).

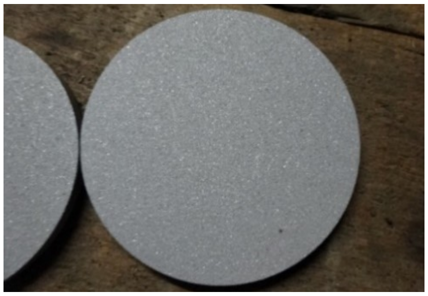


FIGURE 3. Sand blasted Al-Si alloy flat plate substrate

Adopted bond coat thickness was 50µm and five different thicknesses of 100µm, 250µm, 400µm , 500µm and 600µm were used for the top coat. The photograph of the uncoated sample (metal base plate) and coated samples are shown in figure 4.

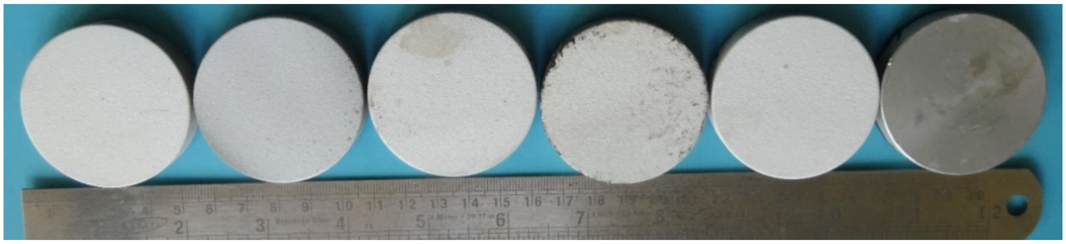


FIGURE 4. Thermal barrier coated samples (different thicknesses) and Uncoated Base metal plate (extreme right)

Coating Thickness Measurement

Cross sectional metallographic samples were removed from as spray coated samples by water jet cutting and polished progressively using different grades of emery paper and then with velvet cloth and finally diamond paste (1 µm) to reveal the microstructure of the substrate – coating interface. The polished metallographic mount was cleaned ultrasonically and etched with Keller's reagent. Microstructure analysis was carried out in a Scanning Electron Microscope (SEM). Typical microstructure is shown in figure 5.

Bond coat thickness of ~ 90 µm and top ceramic coat thickness of ~580 µm with about 10% porosity was the salient feature of the ceramic coating. Details of the specimen preparation are given elsewhere [14]. About 10% variation in the actual thicknesses and intended thickness was observed when all specimen were examined under SEM (polished and etched cross section metallography).

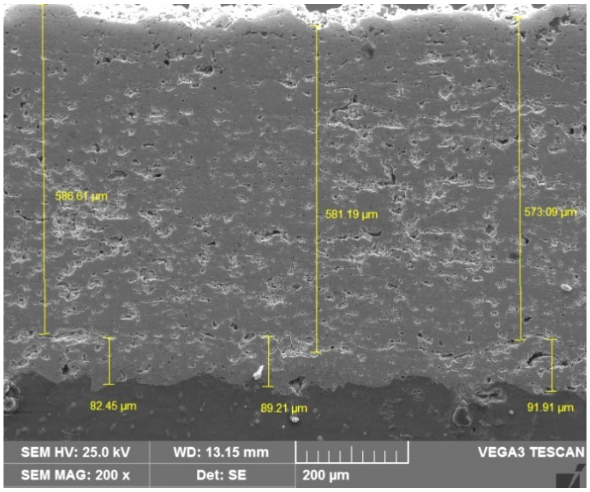


FIGURE 5. Microstructure of coated specimen (Typical): SEM Micrograph via cross sectional metallography

Thermal Barrier Test Using Oxy Acetylene Flame

The method generally adopted for thermal barrier test is by using oxy acetylene flame heating and is shown in figure 6. The flame is directed on to the ceramic coating surface. Temperature on the ceramic surface and back side (metal surface) are measured (after stabilization of the hot face temperature) by using a suitable thermocouple (K type in the present case).

(a) Heating ceramic surface by flame (b) Temp.(ceramic surface) (c) Temp.(back side surface)

FIGURE 6. Thermal barrier coating test by oxy acetylene flame

The difference between the ceramic side temperature and the back side temperature is the temperature drop (ΔT) across the ceramic TBC thickness and the Al-Si substrate thickness.

Thermal Barrier Test Using Electric Heater

The thermal barrier test arrangement, the most important feature of this investigation, using electric heating as source of uniform heat distribution is shown in figure 7. The ceramic coated surface was mounted onto the temperature controlled heating surface of the specially fabricated test instrument such that the diameter of the coated substrate was in flush with the heater. Side of the flat plate was thermally insulated with a ceramic ring. No heat was permitted to be radiated from the sides of the plate by closely packing the sides with high temperature resistant ceramic/glass wool.

For all these coated samples, temperature drop across the two flat surfaces, i.e. coated and uncoated surfaces were measured using electric heating and K type thermo couples, for a temperature range of 300^0C to 500^0C and temperature drop across the coatings as a function of thicknesses were measured. The thin bead K type thermocouple was mounted on the ceramic coating side in close contact with the surface. High temperature conducting paste/adhesive was used to establish the contact without offering any additional heat resistance. Two K-type thermocouples were mounted at the backside of the metal plate (opposite end of coated side) (again with high temperature adhesive) on the grooves provided for the purpose. The thermocouples measured the ceramic surface temperature which was in the electric heat ambience at the intended stabilization temperature (say 350°C). The two thermocouples (one was for verification of the others reading) kept cemented to the back surface indicated the temperature of the uncoated surface.

Figure 7 shows (a) the heating and temperature measurement arrangement and (b) the readings on stabilized ceramic surface temperature on the PID controller and the temperature reading of one thermocouple at the back side on the data logger.

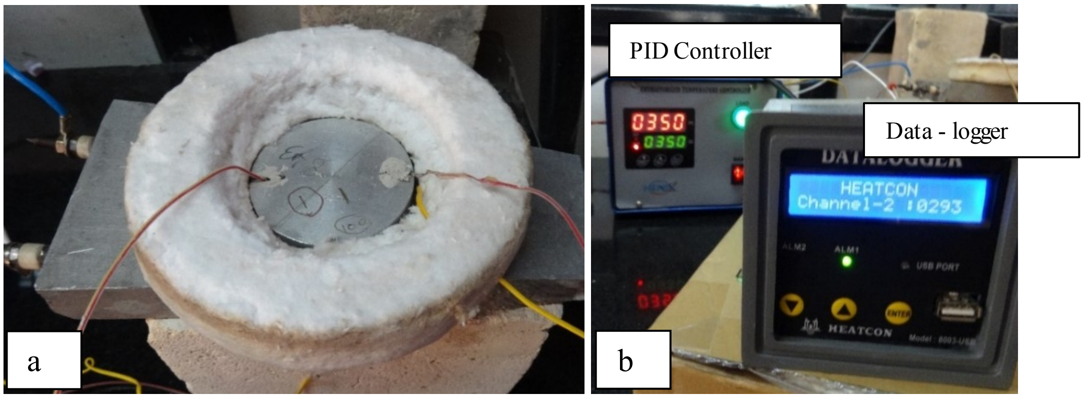


FIGURE 7. Thermal barrier test (a) Specimen mounted in electrical heating arrangement (b) Temperature indicators.

Figure 8 shows the complete test set up for the thermal barrier test. The specifications of the measuring instruments are listed below:

Thyristorized PID Controller	**Data-logger**		
Input: Universal	Model	-	HI – 8003 – USB
Output: Direct heater	No. of Channel	-	3
Rating ; 3KW / 230V	Input	-	K type Thermocouple
Display; Seven Segment LED	Temp. Range	-	up to 1200°C
Enclosure: Powder Coated MS	Display	-	LCD
Control Mode: PID	Interface	-	USB Mass storage
Supply: 230V	Supply	-	230V

The thyristor shows the set temperature at the ceramic coated surface. The digital temperature indicator shows the temperature at the back side of the Al-Si plate, measured by two thermocouples, which has to be same or very close for the authentic measurement. The time taken to reach the stabilization status (no further change in temperature) after reaching the set temperature also was noted using a digital clock.

Electrical heating Arrangement

FIGURE 8. Thermal Barrier test arrangement including heater (red arrow) and temperature indicators

RESULTS AND DISCUSSION

Temperature Drop across Coating Thicknesses

Test results obtained after performance of the thermal barrier tests, i.e. after assessment of the thermal barrier effects when carried out under electrical heating arrangement are shown in Table 1.

As has already been pointed out, the ceramic coating thicknesses were 100, 250, 400, 500 and 600µm. When these coatings alone on the specimen were subjected to a heated and closed environment maintained at steady temperatures ranging from 300 till 500°C, the temperature drop across the thicknesses of the coatings are depicted in the table. It is worthwhile to mention here that all the heat transfer took place through the coating thickness i.e. negligible heat was lost via convection or radiation. This exercise made the test to determine the temperature drop across the coating via conduction alone and that was worthwhile because the errors generally introduced due to experimental anomalies (uneven heating, radiated heating of the metal side of plate etc.) could be eliminated to a large extent.

TABLE 1: Temperature Drop across Coating Thicknesses (data pertaining to thermal barrier effects)

Serial No.	CERAMIC SURFACE TEMPERATURE vs. TEMPERERATURE DROP					
	Coating thickness, µm	100	250	400	500	600
	Ceramic surface temperature, ^{0}C	TEMPERATURE DROP ACROSS THICKNESS, ^{0}C				
1	300	46	50	53	47	77
2	350	57	61	64	56	89
3	400	66	68	72	66	103
4	450	78	79	88	76	120
5	500	82	89	92	89	127

The data shown in Table 1 is represented in the form of a column graph for better clarity for comparison purposes.

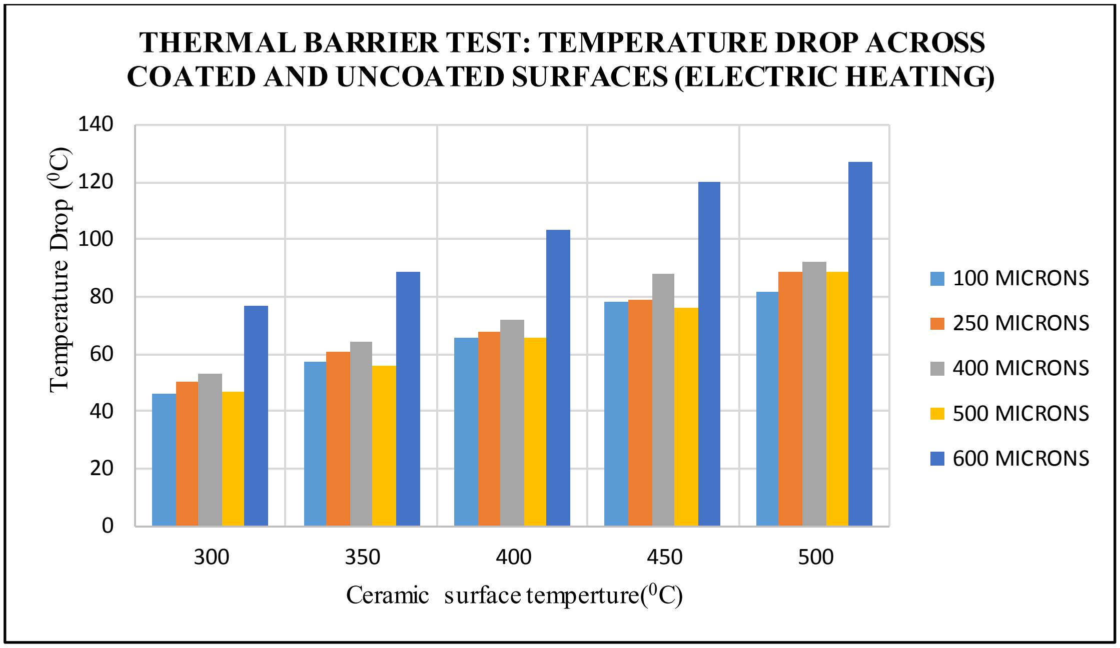


FIGURE 9. Temperature Drop (at Steady State) across different coating thicknesses and hot face temperatures.

The following features are most striking when the data shown in figure 6 is analyzed. Regardless of coating thicknesses, the temperature drop follows a definite pattern. Details of findings are given below.

(a) As the temperature of test increases, the temperature drop (ΔT) increases as well. This closely matches with the expectations because the thermal conductivities of the stabilized zirconia (under identical conditions of processing and properties such as porosity etc.) reduce with increase in temperature.
(b) While the range of temperature drops at all hot face temperatures ranging between 300 and 500°C were very similar to the coating thicknesses between 100 and 500μm: large increase in ΔT (as high as 60%) were observed for all temperatures of measurement for the 600 μm thickness. The reason for the 600μm thick coating to be the threshold for providing the maximum temperature drop i.e. ΔT within this framework of experiments was not clear.
(c) The consistency in the data obtained provided with a strong potential for the authenticity of the test method which may be used especially when coatings of different materials and thicknesses are to be graded amongst a batch.

CONCLUDING REMARKS

Temperature drop or thermal barrier effects of 8YPSZ coatings across various thicknesses were measured by using a fabricated test facility that involved a resistance type electric heater as a source of uniform heat. The heating of the substance by radiation or the heat loss through the circumference was reduced by ceramic wool insulation. The potential of this test method was found to be superior to the conventional method of determination of temperature drop measurements across coating thicknesses which uses a gas flame to heat the ceramic surface.

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