Study of Electrical Insulation of Thermal Barrier Coating under High Temperatures for Aero-engine Smart Sensors

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Abstract

Traditionally most research efforts on thermal barrier coating (TBC) for aviation engine were focusing on its thermal insulation and reliability, yet little on its electrical behaviors especially under elevated temperatures. Due to the need to build smart sensors on the turbine blade the study of electrical insulation properties of TBC under high-temperature is required. Our experiments show that ordinary YSZ-based (yttria-stabilized zirconia) TBC loses electrical insulation at temperatures above 500°C and this causes the measurement error of the thin film sensors built on its surface. By adding a certain amount of alumina to the YSZ coating recipe electrical insulation can be greatly improved - up to four orders of magnitude at elevated temperatures, which meets the practical need to build thin film micro-sensors via MEMS techniques on TBC surface. Complex behaviors of electrical conductions at elevated temperatures of TBC on the metallic substrate were analyzed by computer simulation as well, using thermo-electrical multi-physics interactive models based on the data of our experiments.

I. Introduction

Thermal barrier coating (TBC) has been becoming the must-have technology in the incoming aero-engine industry for higher operating efficiencies and/or longer operating lifetimes with reduced emissions [1, 2]. Yttria-stabilized zirconia (YSZ) ceramic (a zirconium dioxide stabilized at room temperature by addition of yttrium oxide) is the basic material used for TBC coating [3, 4]. These oxides are playing a major role in the thermal protection of the Ni-Cr based turbine blade and prevent corrosion/oxidation. In order to compensate the thermal stress between the YSZ and metallic substrate, an MCrAlY (M is Ni or NiCo) bonding layer is introduced as a buffer to match the interface between the metal and TBC ceramic. After many years of efforts, this technology becomes quite matured and adopted by industry [5, 6].

On the other hand, smart sensors are needed for the IoT (internet of Things) application to build intelligent aero-engines. Starting from 2006, IHPTET (Integrated High Performance Turbine Engine Technology program started in 1988) [7] was replaced with VAATE (Versatile Affordable Advanced Turbine Engines) plan proposed by DOE, DOD, and NASA [8]. In the new plan, the intelligent aero engine was proposed for a more effective and more economical aero engine. In order to achieve this "intelligence", it is necessary to install a series of smart sensors and drivers for development and health monitoring purpose, in critical areas inside the aero-engine to characterize and monitor the working state of the engine operation. Traditional sensors are cumbersome due to their large size, heavy weight, and usually difficult to install in the critical position such as on turbine blade concave surface [9]. Taking advantage of the matured advancement in the micro-fabrication and the computer technology in the year after 2006, smarter miniature sensors become possible by MEMS (micro-electro-mechanical-system) [10] technology. These sensors are thin-film-based (less than 1μm) and light in weight, hence more efficient to implant into the aero engine system in order to obtain more accurate engine operating parameters such as temperature and stress, fulfilling the need of intelligent engines - one the key task of VAATE plan.

In order to build a thin film sensor on a metallic surface, an electrical insulation layer is at first needed to isolate the surface electronics device from the metallic substrate. TBC as a ceramic material is a by-the-way candidate for this insulation material since TBC itself is a good electrical insulation layer while serving its purpose as thermal barrier protection for turbine blade. To use TBC as electrical insulation...
saves a lot of development efforts to concour the high temperature stresss and stability of this high temperature insulation film, the key bottleneck of the previous efforts to develop the thin film sensors for surface temperature measurements on the turbine blade. Yet there is a catch to use TBC as an electrical insulation layer. Like most ceramic materials, TBC starts to lose its insulation at elevated temperatures - electrical insulation of YSZ-based ceramic starts to degrade at temperatures above 500°C (see detailed study below). The loss of electrical insulation affects sensor performance built on its surface by generating a short path via conductive TBC layer. Study on TBC’s electrical properties is necessary to understand its impact on sensor performance. The solution is also needed to improve its electrical insulation under high temperature. In this work, we proposed a method to enhance TBC insulation ability and by adjusting YSZ-based TBC coating with alumina. Great enhancement of high temperature insulation is observed. Computer simulation is also incorporated to analyze the multiple electrical conductions at a higher temperature in Sensor/TBC/Metal composite structure.

II. Experiments and Results
A plasma spray coating process is used to form the bonding layer and TBC on the surface of the nozzle guide vane – the key part bearing the highest temperature in the aero-engine. Prior to the spraying, the substrate was sandblasted by grade 24 silica grit and subsequently cleaned in the mixture of the ethanol and acetone solution, leading the mashing and pores surface during the coating process so as to improve the anti-oxidation behavior of the TBC composite layers [11]. During the spraying the NiCoCrAlY and/or YSZ powder is sent to a high temperature plasma flame, heated to a molten or highly plastic state, and then propelled forward by air flow, towards the Ni-Cr based nozzle guide vane surface. The thickness of the buffer layer is about 50 μm and about 300 μm for YSZ TBC coating. Two modified YSZ coating processes are as follows: 1. use the mixed powder of 30% Al2O3 + 70% YSZ in weight to form a 300μm TBC coating; 2. first coat 200 μm YSZ then 100 μm of Al2O3 in weight to form a 300μm TBC coating.

The concave surface of the nozzle guide vane was coated with the first recipe, and the convex surface is sprayed in the second recipe. Reference samples with ordinary YSZ coating were also prepared using formula 1 without Al2O3.

The surface of TBC after spraying is very rough (surface roughness ~ 30 μm) and needs to be polished before microfabrication. The polished roughness is in the order of few microns. Thin film sensor is fabricated by MEMS micromachining, which uses a soft template transfer method [12]. The platinum thin film thermal resistor and PtRh thermocouple thin film sensors were micro-integrated on the curved surface of nozzle guide vane using a flexible template to transfer the sensor pattern to TBC surface. Figure 1 shows the manufactured sensors and their wirings. Pt thermal resistor, PtRh thermocouple and the electrical insulation of YSZ are connected using Pt and PtRh wires with Pt and PtRh pastes (Pt : Rh ratio 90:10 in weight, same as the PtRh thin film sputtering target and PtRh wires). Wires are extended to outside multimeters for two-wired resistance and voltage measurements, to monitor and record the sensor behaviors as well as the resistance between top metal and bottom substrate during the whole thermal process.

Figure 1. Top: Connection diagram of sensors built on TBC surface coated on nozzle guide vane. Node 1 connects the turbine blade substrate as a common ground. The other nodes connect MEMS sensors to the outside for thermal-couple voltage and thermal resistance measurements; Bottom: Extension wires from the furnace to the multi-meters. The whole process of high temperature ramping is monitored.

Figure 2 shows the thermal resistance of the Pt thin film sensor on the surface of ordinary YSZ together with the YSZ insulation resistance. The Pt thermal resistance is supposed to follow the temperature linearly yet it is clearly seen that when
TBC’s insulation drops to the comparable values of the Pt sensor (~1000Ω at ~ 600°C) a parallel conduction short path is created and make the overall resistance of thin film sensor deviate from its linearity. Improving this electrical insulation of the YSZ at elevated temperature, therefore, becomes our research motivation.

To compare the temperature stability and reliability of the new YSZ processes, temperature cycling test was performed between 650-950°C as shown in Figure 4. The maximum temperature of 950°C is chosen due to the limit of the upper endurable temperature of Ni-Cr nozzle guide vane, considering our temperature test is performed in a muffle furnace.

By adding the proper amount of alumina into the ordinary YSZ coating powder the YSZ insulation can be greatly improved as shown in Figure 3. As seen the resistance of ordinary YSZ drops down to 100Ω at 800°C, yet the improved insulation resistance drops much slower with temperature and is still above 100KΩ at 1200°C. Two to four orders of magnitude resistance improvement are observed and more so in the high temperature realm. With up to 200Ω Pt thin film RTD (Resistance Temperature Detector) the error caused by the leakage of modified TBC is as low as 0.2%.

Figure 2. Thermal barrier coating insulation resistance (RYSZ) decreases exponentially with temperature, which made platinum thin film thermal resistance (RTD) vs. temperature deviates from the linear relationship.

Figure 3. Comparison of electrical insulation under the elevated temperature of improved YSZ coating recipe vs. ordinary recipe.

Figure 4. The programmed temperature cycling scheme over time.

Figure 5 shows the TBC’s electrical insulation properties of two different Al2O3 coating recipes described above. It can be seen that both TBCs have good electrical insulation at elevated temperatures (above 10 kΩ), yet the TBC on the convex surface is less reliable than that on the concave surface – peeling of TBC layer is observed after the temperature cycling (the inset of Figure 5). Detailed study shows that the spin-off happens inside the YSZ and close to Al2O3/YSZ interface, an indication of the imbalance of thermal stress in the composite layers of Al2O3/YSZ/MCrAlY/Ni-Cr alloy.

Figure 5. Insulation resistance of different thermal barrier coatings on the front and back of turbine blades. Temperature cycling is shown in Figure 4, the highest temperature point is 950°C.
On the concave surface with the TBC coated with a mixed powder of 30% Al₂O₃ + 70% YSZ, we did further hush test by spraying cold water onto the hot TBC surface which just experienced 1200°C heat (Figure 6). No peeling was observed after 5 times of such sharp temperature stress – a comparable result as our matured YSZ coating technology. It is then recommended to use alumina-mixed YSZ powder to form the TBC instead of spraying the Al₂O₃/YSZ layered structure in order to avoid more thermal stress related weakness.

Figure 6. Temperature stress test setup. Cold water is sprayed on the vane surface just after the hot flame is removed.

III. Simulation analysis

The electrical conductance of the TBC layer will cause a short path to the sensor built on its surface. COMSOL simulation was conducted to understand the electric conduction behaviors of sensor/ceramic/metal composite layers. Simulation structure was formulated based on our real sensor test structure shown in Figure 7: a Pt thin film thread is laid on the top of YSZ ceramic layer coated on the metallic substrate with a 1V voltage applied on the two nodes. The simulation meshes are denser on the top metal/ceramic interface for better convergence during the finite element mesh calculation.

Figure 7. Simulation structure and grid distribution of Pt thin film, YSZ ceramic layer, and Cr-Ni substrate metal.

Thermal-electrical multi-physics models were used to study the electrical conductance under the influence of high temperature. The resistance vs. temperature relationship of YSZ is based on our measurements above, which is incorporated into the above simulation model. Electrical potential and current density are obtained through solving the Poisson equation and the electric current is obtained by integrating the current density across the area of Pt thread (A), YSZ layer (B) and the substrate metal (C) shown in Figure 8, which also illustrates the situation of electric potential and current density under high temperature.

Figure 8. Simulated electric potential and current density and the cross-section for the electric current integrations. The bowl-shaped layers are the electrical potential and the red arrows are the current flows.

Compared in Figure 9, there is indeed an electric current flow in the YSZ at high temperature comparing to the room temperature: electrons start to flow via the YSZ to another end instead of just flowing via the top metals. Figure 10 shows the current flow via the YSZ and the total electric current as a function of temperature/dimensions (the length of the structure). The total current is the sum of the top Pt sensor, the TBC layer and via the turbine blade substrate by integrating the current density over the cross-section A, B, and C (Figure 8). It is interesting to see that the current flowing inside the YSZ layer at higher temperatures only happens when the structure is short in length, yet the total current is indifferent with the length. This is because there exist two electric conduction paths in this composite structure at high temperatures,

1. via the YSZ TBC layer laterally and,
2. flow via TBC vertically then via the metal substrate laterally.

When the conduction length increases electric current prefers to flow vertically towards the metal substrate via the YSZ, and then flow to the other end through the bottom metal substrate, which renders a
similar total current regardless of the length. Detailed simulation on the thickness of YSZ together with the length in different temperature fields (top and bottom surface in different temperature profiles) reveals a more comprehensive conduction mechanism in this layered structure. In here computer simulation method is very helpful and effective to understand the comprehensive behaviors or conduction mechanism in thermal-electric interactions in composite structures like this.

**Figure 9** Comparison of electric potential and current densities (the red arrows) when:
Left: at low temperature;
Right: top surface at high temperature 1400K and bottom surface at 300K.

**Figure 10** YSZ and total electric current under high temperatures:
Left: Current flowing in the YSZ layer;
Right: Total current between two electrodes.

IV. Conclusions
In this work, the electrical characteristics of the thermal barrier coating on the turbine blade surface and its associated thin film sensor under high temperature environment are studied experimentally and by computer simulation. The main conclusions are as follows:

1. At high temperature, the electrical insulation of YSZ with conventional coating formula starts to degrade at 500 °C exponentially, and resistance reduces to several hundred ohms at 900 °C.

2. Adding alumina to the original YSZ coating powder can significantly improve the electrical insulation properties up to 4 orders of magnitude and satisfies the insulation need to build thin film sensors on the top of turbine blade metals.

3. Thermal-electrical computer simulation is an effective tool to analyze/anticipate the comprehensive electric behaviors of metal/ceramic composite structures at high temperatures.

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References


