Electrical insulation improvements of ceramic coating for high temperature sensors embedded on aeroengine turbine blade

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ABSTRACT

Intelligent aeroengine requires high temperature sensors, especially MEMS thin film sensors directly fabricated on the surface of turbine blade. For this purpose, an electrical insulation layer is needed on blade substrate metals. However, the electrical insulation of ceramic materials will degrade at high temperatures, thereby affecting the characteristics of the sensor. In this paper, ceramic material of YSZ thermal barrier coating (TBC) formulation was modified by adding a certain amount of Al2O3 to improve its insulation at high temperatures. Micro processing was carried out on the surface of the TBC, including the fabrication of platinum-point thermocouples and thermal resistor on TBC surface, and high temperature electrical insulation properties of the modified TBC were studied. Results show that electrical insulation can be improved several orders of magnitude with adding Al2O3 which meets the requirement to build reliable thin film sensors on the top of TBC surface coated on turbine blade metals. Several verification experiments were carried out to ensure the working ability of TBC layer, including robustness test, thermal shock test and high temperature retention test.

1. Introduction

Integration of temperature, stress and other sensors on the surface of the turbine blade is an urgent requirement for aeroengine intelligence. The United States implemented the Integrated High Performance Turbine Engine Technology (IHPTET) program from 1988 [1], which mainly relies on the advantages of materials, mechanical and thermal dynamic propulsion engineering. Starting from 2006, with the vigorous development of microelectronics and computer technology, IHPTET’s follow-up plan was replaced by VAATE plan [2], focusing more on commercial and intelligent advanced turbine engine. In order to achieve the “intelligence” of aero engines, it is necessary to embed a series of thin film sensors on the surface of the aero-engine parts such as the turbine blade. (see Table 3)

Traditional sensors are not good enough because of the factors such as large size, heavy weight, and single function [3]. It is difficult to install traditional sensors in a position where the aeroengine needs to be monitored, and the new miniature sensors developed by MEMS (Micro-electro-mechanical-system) [4] technology are small in size and light in weight. They can be arranged easily in many parts of the aircraft engine in order to obtain more accurate engine operating state parameters, which is beneficial to improve the performance, maneuverability and reliability of the engine. This is the core content of versatile and economical advanced turbine engine (VAATE) plan.

Microelectromechanical systems (MEMS), refer to high-tech devices that are several millimeters or smaller [5]. Microelectromechanical systems are developed based on microelectronics technology (semiconductor manufacturing technology), combining high-tech electronic machinery made by lithography, etching, thin film, LIGA, silicon micromachining, non-silicon micromachining and precision machining [6].

In order to manufacture high-temperature sensor integrated by MEMS technology on the surface of the turbine blade, it is necessary to make a high-temperature insulation layer on the surface of the turbine blade. But under high temperature environment above 500 °C or higher, the electrical insulation performance of the general ceramic material will decrease [7], which will affect the characteristics of sensors. That is because if the insulation of underlying layer starts to degrade, the electric sensors on the surface will have a short-circuit effect through the parallel resistance of the substrate, which causes error of the
measurement.

Previous research work on high-temperature insulation layer mainly used Al2O3 thin film deposited on metals by PVD, focusing on its high temperature insulation capabilities [8,9]. But this thin film will be peeled off during the temperature cycling test easily due to thermal stress mismatch between ceramic thin film and the metal [10,11], resulting in an unrepeatable measurement result and cannot meet the need for sensors.

Another way to make insulation layer is using the matured TBC (Thermal Barrier Coating) technology. TBC is a well-established surface coating technology that attaches a lower thermal conductive ceramic material to the surface of a turbine blade [12–15]. TBC is a revolutionary material improvement which greatly enhances the overall high temperature performance of the aeroengine, equivalent to the engine turbine components [16–20]. The advantage to use TBC as an electrical installation lies in that TBC is a well-developed technology, especially its thermal stress and mismatch issue between ceramic and metal material is successfully resolved after many years’ efforts.

However, the insulation of the TBC also decreases at high temperatures, which will result in the sensor not working properly [20]. This paper studies the improved electrical insulations of TBC by adding Al2O3 in coatings recipe. Results indicate that high temperature electrical insulation of YSZ-based TBC with added Al2O3 exhibits a few orders of magnitude higher electrical resistance than conventional YSZ, which can meet the need to build the smart thin film sensors on its top. Thermal resistors together with the embedded Pt/PtRh thermocouple were fabricated on the surface of TBC and characterization was carried out to study the high temperature electrical properties with different Al2O3 doping.

2. Experiments

There are three portions of our experiments: the preparation of TBC samples with different Al2O3 doping and their SEM/EDS characteristics, the micro-fabrication of TBC thermistors on the samples with different Al2O3 doping, and high temperature measurements to characterize the electrical insulation properties of these TBC samples.

2.1. Spraying of YSZ thermal barrier coating

The thermal insulation coating of the engine turbine components is mostly a binary coating system consisting of two parts: a bonding layer and a ceramic layer. Wherein the bonding layer is a mixed alloy of MCrAlY (M is Ni or NiCo), which is usually formed by conventional PVD or vacuum plasma spray process. The different material components in the alloy enable the matrix and the ceramic layer to have good stress matching and bonding properties under high temperature conditions of more than 1000°C. At the same time, the substrate is protected against corrosion and oxidation effectively. On top of that, 6%–8% Y2O3 mixed partially stabilized ZrO2 material, referred to YSZ, is used to conduct TBC and plays a role in thermal protection of the matrix body.

A thermal barrier coating was formed on the surface of the circular steel block by a plasma spraying process. The metal or ceramic powder was sent to a high-temperature plasma flame, and heated to a molten or highly plastic state. Then the material was propelled forward by an air current, and finally impacted the surface of the substrate with a certain kinetic energy to form a coating and instantaneously solidify. A NiCrCoAlY transition material was deposited on the nickel-chromium-based aeroengine turbine blade material to increase the high-temperature thermal stress buffer between the blade metal substrate and the ceramic layer. The YSZ ceramic material was sprayed on the transition material by plasma spraying then. In the specific spraying process, the surface was first blasted with alumina powder, and then the ultrasonic cleaning was carried out before spraying was performed in ethanol. The bottom layer was commercially available CoNiCrAlY powder (AMDRY 9951, USA). During the spraying process of YSZ, APS (Atmospheric Plasma Spraying Technology) system was used for spray deposition and adjustment of spraying parameters. This caused the coating material to be layered in a molten state on the surface of the sample to form a coating relatively and densely. The particle size of the powder is 30–70 μm. The spray angle, speed and other process conditions were adjusted multiple times to make the coating thickness as uniform as possible. The thickness of the buffer layer is about 50 μm, and the thickness of the YSZ surface coating is about 300 μm. The spray equipment is Sulzer Metco Unitcoat (spray gun F4-MB, Switzerland) and the spray parameters are shown in Table 1.

2.2. Making thermal resistors on TBC surface

After the TBC coating thermistors were micro-fabricated on the surface of TBC, platinum wires welding technique was used in order to measure the electrical properties at elevated temperatures.

The surface of the thermal barrier coating that has just been sprayed has a roughness of about 30 μm so it must be polished before micro-fabrication. A ceramic fiber that can withstand high temperatures is used as a mat. Circular steel blocks with thermal barrier coating were embedded in the ceramic fiber, and grooves for fixing the platinum wires were cut on both sides. Platinum wires were then soldered to the surface of three different TBC coatings by using a high temperature conductive platinum paste after 20 min of 800°C high temperature burning. As can be seen in Fig. 1, platinum wires were firmly welded to the thermal barrier coating, and the resistance characteristics of the

| Table 1 |
| Spray parameters. |

<table>
<thead>
<tr>
<th>Spray parameters</th>
<th>Metal layer</th>
<th>Ceramic layer</th>
</tr>
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<tr>
<td>Plasma Gas Flow Rate (SLPM) Ar/H2</td>
<td>46/8</td>
<td>35/12</td>
</tr>
<tr>
<td>Carrier gas flow rate (SLPM)</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Cooling gas flow rate (SLPM)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Current/A</td>
<td>650</td>
<td>600</td>
</tr>
<tr>
<td>Spray distance/mm</td>
<td>100</td>
<td>100</td>
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</table>

Three TBC formulations were selected as following: 1. spray powder formed by 30% Al2O3 + 70% YSZ ratio; 2. spray powder formed by 50% Al2O3 + 50% YSZ ratio; Spray powder formed by the ratio of 70% Al2O3 + 30% YSZ.

![Fig. 1. Thermal resistor connections by platinum welding wires on the surface of TBC for thermal resistor measurements. Inset is a 3D view of sample – a metal plate coated with TBC.](image)
thermal barrier coating can be measured in this way.

In the meantime, a platinum point thermocouple was manufactured on TBC surface to obtain an accurate surface temperature. As shown in Fig. 2, 13% rhodium doping platinum slurry was applied on one of the platinum solder joints and a 13% rhodium doping platinum wire was fixed on it to form an R-type thermocouple, which is convenient to measure the exact temperature of TBC surface.

2.3. Measurement of high temperature electrical properties of YSZ thermal barrier coating

Fig. 3 shows the connection of the thermal barrier coating resistance measurement and the MEMS temperature sensor on the surface. The high-temperature wires were connected with the external multimeters to measure the resistance changes of TBC samples in the high-temperature furnace and the voltage values of the thermocouple, and a computer was used to record the measured values. The high-temperature furnace can be programmed to control the temperature inside. Temperature cycling was performed during the experiment to verify the temperature stability of the thermal barrier coating and the platinum point thermocouple.

3. Result and discussion

3.1. SEM/EDS analysis of three different Al2O3 doping ratio thermal barrier coatings

The surface of these three thermal barrier coatings was subjected to electron microscopy and EDS composition analysis. The results are shown in Fig. 4. It can be observed from the SEM image that the structure of the surface sprayed layer is particle-bearing, and the EDS analysis results show that the composition of Al and Zr is basically consistent with our spray ratio.

In the 30% doped sample, based on the ratio between the aluminum element and the zirconium element, it can be inferred that the weight ratio of Al2O3 to ZrO2 is 0.99495. It can be calculated for the same reason that in the 50% doped sample, the ratio is 1.49853 and in the 70% doped sample it is 3.49667. Based on this conclusion, the ratio of the weight of Al2O3 to ZrO2 in the three samples is approximately equal to $\frac{7}{5}$, which is in line with expectations.

It should be pointed out that if the EDS detection is performed at a smaller area, it will be found that the element of some places is mainly Al or Zr, rather than the expected ratio as shown in Table 2. It is indicated that a large amount of Al2O3 and ZrO2 were discrete particles rather than compound components.

3.2. Sensor calibration

At first, the performance of the above platinum point thermocouples sensor needs to be verified before being used to measure the TBC temperature. This is performed by comparing the thermo-voltage vs.

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Table 2

<table>
<thead>
<tr>
<th>Element</th>
<th>30% doping</th>
<th>50% doping</th>
<th>70% doping</th>
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<tbody>
<tr>
<td>O K</td>
<td>39.18</td>
<td>41.93</td>
<td>46.51</td>
</tr>
<tr>
<td>Al K</td>
<td>13.44</td>
<td>17.36</td>
<td>26.86</td>
</tr>
<tr>
<td>Y L</td>
<td>8.99</td>
<td>13.48</td>
<td>19.5</td>
</tr>
<tr>
<td>Zr L</td>
<td>43.4</td>
<td>37.22</td>
<td>24.68</td>
</tr>
<tr>
<td>Al2O3:ZrO2</td>
<td>0.99495</td>
<td>1.49853</td>
<td>3.49667</td>
</tr>
</tbody>
</table>

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Fig. 4. (a) SEM result of the TBC surface with 30% Al2O3 doping. (b) SEM result of the TBC surface with 50% Al2O3 doping. (c) SEM result of the TBC surface with 70% Al2O3 doping.
temperature property with the standard R-type wired sensors. The platinum point thermocouple was fabricated directly on the surface of the 30% doped YSZ sample, and the standard R type thermocouple was placed in close proximity. It can be seen from Fig. 5 that the platinum point thermocouple has the same working performance as the standard thermocouple, and the voltage value and temperature of the two have a linear change.

The voltage value of the platinum point thermocouple at the same temperature is selected as the abscissa, and the voltage value of the standard thermocouple is plotted as the ordinate. The result of fitting by Origin shows that the slope of Fig. 5 is 1.01747, which means the curve is almost coincides with the y = x line to form a proportional function relationship. It shows that the platinum point thermocouple has a good contrast relationship with the standard R-type thermocouple voltage value. The platinum point thermocouple can be used for temperature measurement and has good performance.

3.3. High temperature resistance characteristics of different Al₂O₃ doped YSZ

Results are as follows

Fig. 6 shows the change of resistance of TBC samples doped with 30%, 50%, and 70% Al₂O₃ ratios at high temperatures. The temperature values were measured from the R-type thermocouple and the platinum point thermocouple placed on the surface of the TBC samples. The curves in Fig. 6 were fitted by Origin, and the fitting results are obtained as follows:

\[
30\% : \quad R = 2.408 \times 10^{13} \times \exp(-x/39.698) + 25533.943 \\
50\% : \quad R = 7.705 \times 10^{10} \times \exp(-x/59.170) - 326010.622 \\
70\% : \quad R = 9.720 \times 10^{10} \times \exp(-x/89.345) - 971436.273
\]

Fig. 6 illustrates that as the doping ratio increases, the resistance of TBC sample increases at the same temperature. On top of that, as the temperature increases, the resistance of all YSZ samples decreases exponentially. When the temperature reaches 800°, the resistance of 30% sample is 4385 Ω, which cannot meet the requirements for MEMS sensors. At the same temperature, 50% doping sample is 70000 Ω, and the 70% sample is 107 Ω. According to the result, as the temperature value rises, the resistance value of the 30% doped sample drops sharply, which means the insulation cannot be guaranteed. So, the 30% doped TBC is not suitable for being used as an insulating layer. The 50% doped and 70% doped samples maintain a good insulation before 800°, so they can meet the requirements of MEMS sensors. However, in the actual test, the 70% doped sample showed a phenomenon of TBC shedding, which was due to the deterioration of the coating adhesion after the content of Al₂O₃ was increased, which is consistent with the literature report. For the above reasons, 50% doped TBC is the best choice for MEMS sensors.

3.4. Verification

3.4.1. Robustness test - vibration and shocking test

Robust electrical insulation layer and embedded MEMS sensors capable of measuring high temperature in aero-engine combustion environment play important roles in developing efficient and intelligent aero-engine. In this paper, various tough vibration and shocking tests...
were performed on TBC. The TBC layer (including sensor and the wiring on it) is capable of standing for up to 40 g 10–2000 Hz vibration and 100 g shocking test. The electrical components on the TBC layer remain intact, so the TBC coating can fully withstand these extreme environments.

We also put turbine blade with TBC onto the hot engine combustion chamber. The TBC layer survived hot gas turbine test with pressure gas flow of 1200 °C/0.5 MPa and the sensor on TBC exhibits reliable temperature readings. It is verified that TBC layer survived after two cycles of combustions while staying for 10 min duration at peak temperatures (~1200 °C). This development is very useful to quantify the temperature on the sensitive spot of turbine components for aero engine purpose.

3.4.2. Thermal shock test

In order to test the working condition of TBC under extreme temperature changes, water cooling experiment was taken. As shown in Fig. 7 (a), a film thermocouple was fabricated on the surface thermal barrier coating of turbine blade and burned by a flame spray gun. Then one liter of water was sprayed to the surface to cool it quickly after burning to a high temperature. The thermal barrier coating was visually observed to remain intact after the water-cooling test. Results of the film thermal resistance thereon are as follows.

Fig. 7 (b) shows that after burning and water cooling, the MEMS thermocouple still works properly (the TBC layer does not fall off/being damaged) under this extreme condition. It has been confirmed that the TBC layer developed in this paper has good adaptability to extreme temperature changes.

3.4.3. Reliability of data during high temperature retention

In order to verify the reliability of thermal barrier coating resistance data collected during the high temperature retention, 30 sets of 50% sample resistance data were collected for 100 min maintained at 800°. And the resonant frequency summary was plotted in Fig. 8. Readings of platinum point thermocouple made on the surface of thermal barrier coating were also collected.

Fig. 8 shows that at 800 °C, the thermal barrier coating resistance data collected in this paper has good stability and correct reading. On top of that, the thermal barrier coating layer has a good working life in high temperature environments.

4. Conclusions

Electrical installation of original TBC ceramic thin film at high temperatures can be greatly enhanced by adding Al2O3 to its coating recipe, which can meet the insulation requirement to build thin film sensor on metallic substrate. High temperature characterizations of various doped TBC were carried out by fabricating the platinum joint resistors and point thermocouples on TBC surface. Results show that the 50% doped TBC coating can meet the insulation requirements to build MEMS sensors. Adherence robustness and thermal barrier property of doped TBC were also verified by a series of vibrating/shocking tests, combustion infiel test and abrupt temperature shocking test.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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