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Error and modification in thermal barrier coatings measurement using impedance spectroscopy

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ABSTRACT

In impedance spectroscopy testing of metal/ceramic multi-layers, such as thermal barrier coatings (TBCs), in order to avoid electric leakage, asymmetric electrode is widely adopted. However, how is electric field distribution in asymmetric electrode system, what error does it bring to measurement results, and how to modify these errors etc., are still not understood. In this study, electric field divergence in TBCs measurement induced by asymmetric electrode is investigated through solving a three-dimensional electric field equations numerically. The results show that the asymmetric electrode inevitably triggers divergence of electric field line, and as frequency decreases the divergence increases considerably. When Pt electrode diameter is chosen as 1 mm in ceramic coating, the errors in thickness measurement for both YSZ and TGO are 26.20% and 89.3%, respectively. The errors rise as both YSZ and TGO thicknesses increase, while the errors decrease as Pt electrode size increases. The error in thickness measurement for TGO layer is much larger than that for YSZ. Through present research, a scheme to eliminate the effect of electric field divergence on measurement error is proposed.

1. Introduction

Thermal barrier coatings (TBCs), as one of the most important key techniques for thermal protection of aero engines, have been developed as the most feasible solution to improve the service temperature of aero engines, which can improve the efficiency of power generation gas turbines and prolong the lifetime of turbine blades [1,2]. Due to their low thermal conductivity, a temperature drop can be attained up to 200 °C through thermal isolation in TBCs as well as an inner cooling system [1,2]. During service of gas turbines, TBCs is subjected to high temperature exposure, sintering and corrosion, which can lead to a change in the microstructure for TBCs, such as, the formation and growth of thermally grown oxide (TGO) at interface, phase transformation, porosity decrease in coating [3–5] The TGO formation results in a large compressive stress, which leads to TGO undulation, crack formation, propagation, coalescence and eventually top ceramic coating spallation [6,7]. Phase transformation, such as, the metastable t' phase undergoes transformations, changing from t' YSZ into monoclinic (m) YSZ, which results in a volume expansion in TBCs [8]. The porosity decrease in a top ceramic coating reduces the strain tolerance, which is detrimental to the lifetime of thermal cycling [9]. Furthermore, the porosity decrease and pore redistribution can lead to an increase in thermal conductivity, which implies the loss of thermal insulation to the substrate [5]. Therefore, it is essential to develop non-destructive techniques to evaluate the microstructure change in TBCs and TGO growth for predicting the lifetime and failure of TBCs on engine components.

Impedance spectroscopy (IS) is developed as a non-destructive technique which can be used to investigate the TGO growth, phase transformation and degradation of TBCs [10–12]. Wang et al. [13] use the IS testing technique to investigate the TGO growth in TBCs after oxidation at 1100 °C. Anderson et al. [14] study the effects of heat treatment on microstructure, phase composition, and mechanical properties by using IS technique combined with X-ray diffraction, scanning electron microscopy, and microindentation. The IS technique has been applied to several aspects successfully by measuring impedance of a TBC system, such as the degradation of TBCs [15] and failure detection [16]. However, most reports are given about the effect of microstructure features on the impedance of TBCs, whereas less attention is paid on the IS measuring conditions. Based on our previous

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work [17], it is found that the impedance response is strongly affected by measurement parameters including voltage amplitude, specimen temperature and electrode size. The temperature greatly changes the resistivity of specimen, and results in significant influence on impedance spectra. The influence is ascertained once the relationship between material resistivity and temperature is determined, and thus does not produce measurement error. There is no obvious influence of voltage amplitude on impedance spectra as long as it can ensure that the current is greater than the range of instrument. However, the electrode size brings large error in the measurement error, which also is founded in Ogawa' IS experimental investigation on layer thicknesses of TBCs [18], causing 330% the maximum measurement error. Therefore, it is necessary to quantify the measurement error for precise quantitative evaluation.

In IS testing technique for TBCs, asymmetric electrode is usually adopted to avoid electric leakage. For example, one is a Pt film electrode with 5 mm in diameter on ceramic coating, and the other is metal substrate. Consequently, it is reasonable to present the following questions: whether the impedance results are affected by asymmetric electrode, how to affect impedance feature, and how to overcome the errors of measurement results induced by asymmetric electrode. Several experimental investigations find that both electrode geometry and size have the significant effect on impedance feature [9,19,20], and sometimes asymmetric electrode geometry can lead to the spread of an electrical conduction region in TBCs, while it is not reliable to find it in experiments and not to present to measure the divergence of electric field quantitatively. Using finite element method, Deng et al. [21] investigated the effects of TGO growth and conductivity on the IS distribution of TBCs produced by the electron beam physical vapor deposition. The finite element simulation is an effective method to study the influences of asymmetric electrode on IS distribution.

In the present research, a three-dimensional model has been developed to investigate the effects of asymmetric electrode on IS of TBCs. First of all, the distributions of electric field lines, for different frequencies and Pt electrode sizes, are calculated by using the finite element simulation. Then, thickness measurement errors for YSZ and TGO layers due to asymmetric electrode are analyzed quantitatively. Finally, an empirical equation is proposed to modify the thickness measurement errors.

2. Modeling

2.1. The theory foundation

According to the complex form of Maxwell-Ampere equation, the relationship between magnetic field intensity ($\boldsymbol{H}$), conduction current density ($\boldsymbol{J}$) and electric displacement ($\boldsymbol{D}$) can be represented in the following form:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D} \tag{1}$$

where ω is the angular frequency, and j is the imaginary unit. Because magnetic field is a no-source field, from Eq. (1) one can obtain

$$\nabla\cdot(\nabla \times \boldsymbol{H}) = \nabla\cdot(\boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D}) = 0 \tag{2}$$

According to the definition of electric displacement ($\boldsymbol{D}$) in the uniform medium and Ohm's law, the electric displacement ($\boldsymbol{D}$), current density ($\boldsymbol{J}$) and electric field intensity ($\boldsymbol{E}$) are specified, respectively by

$$\boldsymbol{D} = \varepsilon_{\mathrm{r}}\varepsilon_0\boldsymbol{E} \tag{3}$$

$$\boldsymbol{J} = \sigma\boldsymbol{E} \tag{4}$$

$$\boldsymbol{E} = -\nabla V \tag{5}$$

where ε_{r} and ε_0 are the relative permittivity and vacuum permittivity, respectively. σ is the conductivity and V is the electric potential. By combining the above equations, the Eq. (2) can be rewritten as [22]

$$\nabla\cdot((\sigma + \mathrm{j}\omega\varepsilon_{\mathrm{r}}\varepsilon_0)\nabla V) = 0 \tag{6}$$

Then, the Eq. (6) can be deduced as

$$\nabla^2 V = 0 \tag{7}$$

For three-dimensional model depicted in Eq. (7), the control equation is expressed as

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \tag{8}$$

The electrical potential distribution can be obtained by solving the Laplace's equation using the finite element method. In the finite element simulations of IS distribution of TBCs, both conduction currents and displacement currents are used in the frequency domain and the time dependent study types dynamic formulations. And the finite element simulations are carried out by using COMSOL 4.3 software. Based on the Eqs. (3), (4) and (5), as the electrical potential is obtained, the complex current density ($\boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D}$) can be calculated. The complex current (I) can be calculated by integration of the complex current density ($\boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D}$) in the normal direction of the interface under consideration, $I = \int (\boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D})\cdot d\boldsymbol{n}$, where $\boldsymbol{n}$ represents the normal direction of TBCs interface. Then, the impedance (Z) can be obtained by $Z = U/I = U/\int(\boldsymbol{J} + \mathrm{j}\omega\boldsymbol{D})\cdot d\boldsymbol{n}$, where U is the applied AC voltage.

2.2. Geometric and material parameters

As illustrated in Fig. 1, a specimen with dimensions of 10×10 mm^2 is used in the experiment. A platinum (Pt) electrode is prepared on the top ceramic coating surface by ion sputtering (ETD-3000). The typical structure of TBCs used in this paper is consisted of four layers: ceramic

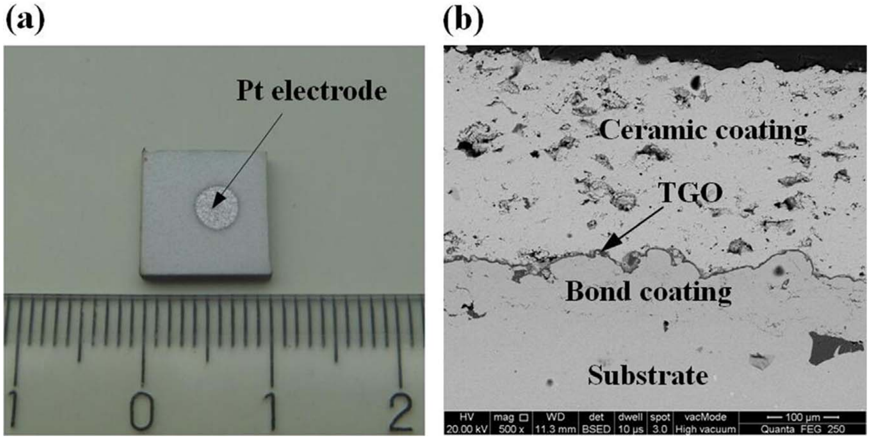

Fig. 1. (a) The sample with dimensions of 10×10 mm^2 used in the experiment; (b) the scanning electron micrograph for the cross-section in the APS TBCs.