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Experimental testing and FEM calculation of impedance spectra of thermal barrier coatings: Effect of measuring conditions

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ABSTRACT

Impedance spectroscopy (IS) is a nondestructive evaluation tool for examining degradation of thermal barrier coatings used in the hot section of aeroturbine engines. Key factors controlling IS include microstructure features and measuring conditions. Here we systematically investigate the effect of several measuring conditions on IS via experiment and finite element method (FEM). The results show that the most significant factor affecting the spectra is the temperature, followed by the silver electrode area, while both exert more obvious effect than the voltage amplitude. Furthermore, suitable values for the measuring parameters are optimized based on the results of experiment and FEM calculation.

1. Introduction

Thermal barrier coatings (TBCs) have been widely used in the aeroturbine engines for protecting the hot-section metal components from high temperature gas, thus effectively enhancing the turbine efficiency [1–4]. These coatings typically consist of a yttria-stabilized zirconia (YSZ) ceramic top coating, a MCrAlY alloy (M denotes Ni, Co, or Fe) bond coating (BC), and a nickel-based superalloy substrate [5–8]. Since the TBCs unavoidably suffer from the shock of turbine gas with high temperature, oxidation is a critical issue and it accelerates the formation of a thermally grown oxide (TGO) layer at the interface of bond/ceramic coatings [9,10]. A continuous TGO layer (usually α-Al_2O_3) effectively protects the substrate from further oxidation [11]. However, as the TGO grows at the YSZ/BC interface, failure normally occurs if the strain energy density in TGO and TBCs exceeds the interfacial toughness [2,10,12]. Moreover, great danger also exists in the fine sand particles ingested by the engines. These particles not only removes the coating by erosion but also deposit on the hot coating surface as the molten calcium-magnesia-alumina-silica (CMAS) glass, which penetrates and interacts with the ceramic layers to degrade their overall properties [4,5,13]. However, the failure of TBCs can hardly be predicted due to the multilayered ceramic structures and harsh operating conditions.

Impedance spectroscopy (IS) is a non-destructive evaluation (NDE) tool of correlating the electrical properties of TBCs with their microstructure features, thus contributing to the prediction of coating failure. Ogawa et al. [14] ascertained the IS characteristic of the TGO layer and meanwhile estimated its thickness together with each layer of TBCs using IS method. Xiao et al. [2,11,15,16] made a great contribution to dry IS evaluation of TBCs, such as the morphology and growth of TGO layer, microstructure evolution and phase transformation of ceramic coatings. Sohn et al. [9,10,17] studied the TGO thickness, YSZ porosity, and cracks in TBCs using electrochemical IS techniques. Gong et al. [18,19] adopted IS to examine the microstructure evolution of TBCs under high temperature and CMAS corrosion.

Generally, the IS measurement is carried out by testing the ratio of the applied alternating current (AC) voltage to the response current of a material. Electrical response varies with the frequency

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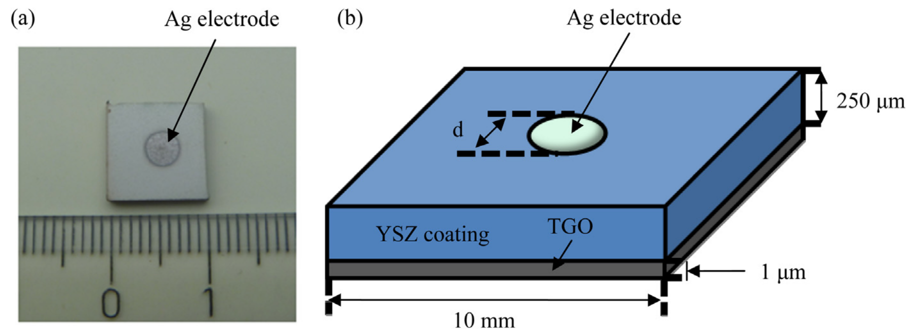

Fig. 1. Specimen of TBCs coated with silver electrode (a) and three-dimensional model of TBCs for FEM calculation of impedance spectra (b).

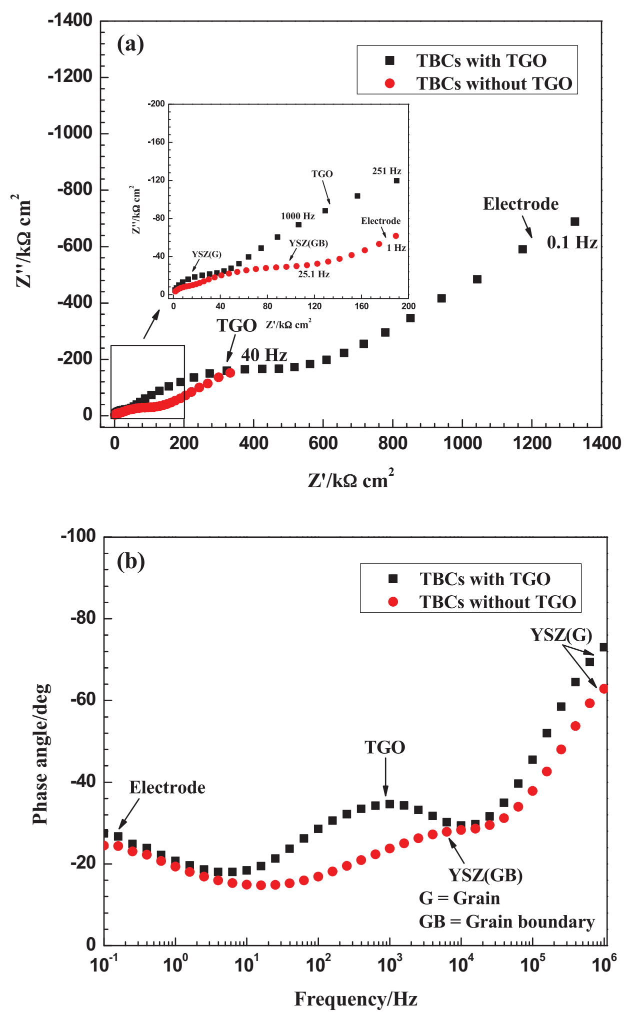

Fig. 2. Measured impedance spectra (IS) of TBCs with and without TGO in (a) Nyquist plots and (b) Bode plots. The temperature is 400 °C, the AC voltage amplitude is 0.5 V, and the area of silver electrode is 7.1 mm^2.

of AC voltage owing to the physical characteristics of the studied material. For example, the IS corresponding to different components of TBCs (e.g., YSZ coating, TGO layer, and defects) commonly reflect in different frequency domains [6,20]. Therefore, these components can be resolved via IS and their microstructure features are related to the impedance parameters. Changes in microstructures of TBCs due to oxidation, corrosion, and phase transformation lead to variation in electrical properties, which can be reflected from the impedance response. Consequently, the microstructure evolution of TBCs is monitored via IS measurement.

For conventional impedance measurement, the metal side of substrate is polished to remove the oxide for acting as one electrode. A platinum or silver paint coated on the ceramic side with an area smaller than the TBCs serves as the other electrode. Hence, a couple of asymmetric electrodes are adopted, resulting in the divergence of electrical field that has been experimentally discovered [6]. During the measurement, a small amplitude of voltage is imposed on the TBCs specimen over a range of frequencies. The IS in both Bode and Nyquist plots are then recorded based on a certain measuring condition. Generally, it is believed that the IS are naturally determined by the physical characteristics or microstructure features of TBCs. In addition, the measuring conditions, e.g., AC voltage amplitude, temperature, and size of silver or platinum electrode, also significantly affect the corresponding IS, especially the spectra resolution. However, up to now, there are a lot of reports about the effect of microstructure features on the impedance behaviour of TBCs [10,16,21], whereas less attention has been paid on the IS measuring conditions [6,22,23].

Since the IS of TBCs are controlled by both physical characteristics and measuring environments, the mechanism of one measuring parameter on the impedance response can hardly be well understood just via experimental testing owing to the interaction of several factors. In addition, the measured IS are normally fitted using an equivalent circuit to obtain the electrical parameters of each component in TBCs (e.g., YSZ grains, YSZ grain boundaries, and TGO layer). However, the response caused by YSZ grain boundaries and TGO layer usually overlaps and thus cannot be clearly resolved [22,23]. Furthermore, there are more than one equivalent circuit suitable to fit the IS of TBCs, hence causing problems in interpretation of the spectra. As a consequence, models of TBCs are constructed and finite element method (FEM) is used to calculate the IS for better clarifying the impedance behaviour [24,25]. Deng et al. [24] developed a two-dimensional finite element model to examine the effect of TGO growth and conductivity change on the IS of TBCs prepared by electron beam physical vapour deposition (EB-PVD). Fleig and Maier [25] used finite element simulations to treat the influence of point contacts as the constituents of imperfect contacts on the total impedance. However, until recently, FEM have not been widely used to study the IS of TBCs, especially simulate the measuring environments.

In this work, the TBCs samples prepared by air plasma spray (APS) are considered, and the impact of measuring parameters (i.e., voltage amplitude, temperature, and size of silver electrode) on the impedance response is systematically analyzed by experimental testing combined with FEM calculation. Furthermore, the suitable values for these parameters are optimized based on the experimental results and calculated data. The aim of this work is to clarify the effect of measuring conditions on the IS of TBCs and hence optimize the testing parameters, thus contributing to achievement of the IS measurement with high resolution.