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Original Article

# Effect of geometric parameter on thermal stress generation in fabrication process of double-ceramic-layers thermal barrier coating system

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ABSTRACT

In this work, quenching stress generated during the deposition process and the Coefficient of Thermal Expansion (CTE) thermal mismatch stress produced during the cooling down process of Double-Ceramic-Layers Thermal Barrier Coating System (DCL-TBCs) have been intensively examined. The thickness ratio of Lanthanum Zirconate (LZ, $La_2Zr_2O_7$) coating to stabilized Zirconia (YSZ, $ZrO_2$-8%$Y_2O_3$) coating, have been theoretically analyzed. In addition, DCL-TBCs specimens with different thickness ratio of LZ to YSZ coatings were fabricated, to study the effect of this thickness ratio by specimen curvature and crack density analysis. Meanwhile, Finite Element Method (FEM) has been carried out to validate results obtained theoretically. The results reveal that by comparison to CTE thermal mismatch stress, quenching stress has remarkable effect on total thermal stress. By increasing thickness ratio of YSZ to LZ coatings, average thermal stress and crack densities in YSZ and LZ coatings increased. Nevertheless, the curvature ratio of DCL-TBCs specimen decreases.

## 1. Introduction

Thermal barrier coatings (TBCs) are being widely applied in modern gas turbines and jet engines to protect metal components from the hot gas stream inside the turbine and to boost engine efficiency by increasing the operating temperature. A typical as-sprayed TBCs is composed of three components: (1) a top coating of yttria partially stabilized zirconia ceramic (YSZ coating, $ZrO_2$-8%$Y_2O_3$), which is used to provide thermal insulation from the hot gas stream to metal components, (2) a thick super-alloy substrate (such as Inconel 617) used to reduce the surface temperature of the top coating through internal hollow channels method and (3) a bond coating (NiCrA1Y), which is applied to pair the mechanical and thermal properties of the substrate and the YSZ coating [1–7]. By the increase of the demand for greater efficiency and performance, the requirement for higher operating temperature of a gas turbine is a critical parameter. However, the traditional single YSZ coating TBCs fail to meet this demand due to phase transformations and sintering occurring at operating temperatures higher than 1200 °C. A possible solution to overcome this limitation could be the use of a Double-Ceramic-Layers Thermal Barrier Coating system (DCL-TBCs). The as-sprayed DCL-TBCs consist of 4 different coatings, as shown in Fig. 1.

By comparison to the traditional single YSZ TBCs, besides the thick superalloy substrate and the bond coating, the traditional single YSZ coating is replaced by two different ceramic coatings. These include: (i) an external ceramic coating (TC1), which is made by a novel ceramic material (such as LZ, $La_2Zr_2O_7$) that provides effective thermal insulation and satisfactory sintering resistance under high temperature and (ii) an internal ceramic coating (TC2), made by (YSZ, $ZrO_2$-8%$Y_2O_3$), is used to reduce high magnitude CTE thermal mismatch stress between LZ coating and the combination of "BC + Substrate", caused by the low thermal expansion coefficient of the LZ coating [8–11]. Experimental results indicated that these DCL-TBCs presented improved thermal cycling performance than the traditional TBCs [8–10,12–14].

BC, LZ and YSZ coatings of DCL-TBCs are usually fabricated by the Air Plasma Spray (APS) technique [15]. Generally speaking, during air plasma spraying process, most of the BC, YSZ and LZ particles could be melted completely, whereby, the melting points of BC, YSZ and LZ particles are 1680 °C, 2680 °C and 2300 °C, respectively. The rapid cooling temperatures may lead to a series of remarkable thermal stresses during the fabrication of DCL-TBCs. Therefore, Thermal stress generated during the fabrication process of DCL-TBCs is a significant parameter in DCL-TBCs' performance and service life evaluation [16–18]. It's responsible for many failure mechanisms such as cracking in ceramic coating and the debonding of the coating/substrate [19–21].

Estimating thermal stress generation in the fabrication process is a

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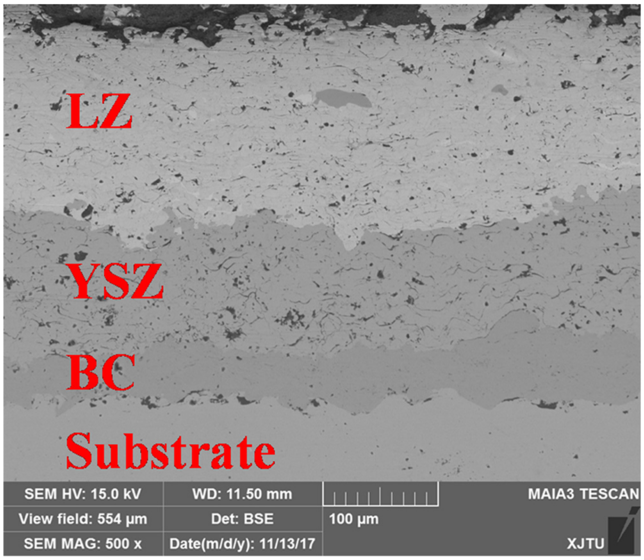


**Fig. 1.** SEM picture of cross section of DCL-TBCs.

topic that has been intensively and analytically studied in the past, such as the Stoney's equation, double-layers beam theory and the multilayer coating models [22]. However, much of the past research has focused on thermal stress investigation that arises due to the CTE thermal mismatch between different coatings of TBCs during the cooling down process. This part of thermal stress is widely reported in literature [20,23,24] and is usually investigated by adopting a) beam bending theory (Theoretical Method) or b) the birth and death element method (Finite Element Method FEM). However, recent research [25] indicated that thermal stresses generated in a plasma sprayed coating system mainly originate from three sources:

(i) Thermal stress arises by CTE thermal mismatch between different coatings.
(ii) Phase transformation stress due to the solidification of liquid particles and solid state transformation during the deposition process [25].
(iii) Quenching stress arises due to rapid contraction of molten particles during the coating deposition process [26].

According to previous study [25], for DCL-TBCs, stress generated by solidification of liquid particles, could be relaxed by the liquid phase particles, since there is no solid state transformation. Thus, the phase transformation stress can be ignored. Therefore, besides the CTE thermal mismatch stress, also quenching stress generated during the deposition process of DCL-TBCs should also be considered.

Quenching stress constitutes a significant parameter on thermal stress generation during the fabrication of DCL-TBCs. During thermal plasma spray process, BC, YSZ and LZ molten particles, which are deposited onto the substrate surface layer by layer, are flattened and quenched to the substrate temperature, within a very short period. Thermal contractions of the molten particles are constrained by underlying solid and result in tensile stress, also known as quenching stress [26]. Previous research [27,28] indicated that quenching stress may easily lead to the initiation of micro cracks and their propagation inside the coating system. Therefore, the magnitude of quenching stresses obtained experimentally was much lower compared to that calculated by theory, especially for brittle coatings.

The recent research on thermal stress generation in the fabrication of DCL-TBCs is relatively poor and mainly carried out by adopting the FEM. Wu et al. [29], studied thermal stress generation during the deposition process of traditional single ceramic coating TBCs, by using FEM; Nayebpashaee et al. [30], simulated thermal stress during an actual heating process of DCL-TBCs using FEM; Wang et al. [25], studied thermal stress generation in DCL-TBCs by using birth and death element method (FEM). For the theoretical method, quenching stress generated during the deposition process of DCL-TBCs is rarely considered theoretically. Tsui and Clyne [20,23,24], considered quenching stress arisen during the deposition process and calculated thermal stress in the fabrication process of traditional single ceramic coating TBCs. Current author previous work [11], included a study concerning CTE theoretically thermal mismatch stress generation during the fabrication process of DCL-TBCs. However, there is still a knowledge gab in the theoretical analysis studies for quenching stress generation during the deposition process of DCL-TBCs. Meanwhile, since DCL-TBCs represent a new advanced TBC system, related experimental research work is limited compared to that of traditional single ceramic coating TBCs. Furthermore, this research mainly focuses on the investigation of the thermal cycling and the thermal shock behavior [8–10,12,13,31]. Hence, experimental research on thermal stress generation during the fabrication of DCL-TBCs is barely carried out.

As a double ceramic coating system, parameters such as the thickness ratio of LZ to YSZ coatings, have been demonstrated to influence significantly the performance of DCL-TBCs. An FEM investigation by Han et al. [8], indicated that heat insulation behavior of DCL-TBCs is strongly dependent on this thickness ratio. By using experimental methods, Dai et al. [13], demonstrated that the thickness ratio has a significant effect on the cycling life of DCL-TBCs. However, the approach of this thickness ratio effect on quenching stress and on total thermal stress generation during the fabrication of DCL-TBCs, is barely carried out theoretically and experimentally.

In this work, quenching stress generated during the deposition process and CTE mismatch thermal stress generated during the cooling down process of DCL-TBCs have been intensively theoretically studied by developing Tsui and Clyne's model [20,23,24]. Additionally, some important geometric parameters, such as thickness ratio of LZ coating to YSZ coating, have been theoretically studied in extension. Furthermore, a series of DCL-TBCs specimens including different thickness ratio of LZ coating to YSZ coating have been fabricated and the curvature and the crack density of these specimens has been studied by the laser method and SEM, respectively. Thus, the effect of the thickness ratio of LZ to YSZ coatings was investigated experimentally. In addition, a birth and death Finite Element Method (FEM) has been carried out to validate the theoretical results. To obtain thermal stress more precisely, the temperature effects on the material properties of DCL-TBCs were also incorporated in this work.

## 2. Formulation of the method

As mentioned above, BC, YSZ and LZ coatings are fabricated by using the APS method. According to previous [20,23,24] and current research, to simulate and analyze quenching stress and CTE thermal mismatch stress generations in DCL-TBCs, the BC, YSZ coating and LZ coating are divided into several thin layers, such as $n_{BC}$, $n_{YSZ}$ and $n_{LZ}$, respectively. All the BC, YSZ and LZ particles are assumed to be melted completely in the deposition process. All components in DCL-TBCs are assumed to be isotropic, have linear elasticity and present an equal-biaxial in-plane stress state ($\sigma_x = \sigma_z$ and $\sigma_y = 0$). The Young's modulus and CTE of each of the components of DCL-TBCs are ($E^*_{\mathrm{Sub}}$, $\alpha_{\mathrm{Sub}}$), ($E^*_{\mathrm{BC}}$, $\alpha_{\mathrm{BC}}$), ($E^*_{\mathrm{YSZ}}$, $\alpha_{\mathrm{YSZ}}$) and ($E^*_{\mathrm{LZ}}$, $\alpha_{\mathrm{LZ}}$), respectively, with an effective Young's modulus of $E^* = \frac{E}{1-\nu}$. Plastic deformations and stress release mechanisms are not considered here. Thus, thermal stress (including quenching stress) obtained through these two assumptions may be overestimated.

### 2.1. Quenching stress generation in the deposition process of BC and YSZ coating

According to Tsui and Clyne [20], BC and YSZ coating were divided into $n_{BC}$ and $n_{YSZ}$ layers to simulate their layer-by layer deposition