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# Technical Notes

## Thermal Analysis in a Film Cooling Hole with Thermal Barrier Coating

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### I. Introduction

FILM cooling and thermal barrier coatings (TBC) are widely used cooling techniques, especially in a gas turbine, which are used to protect a material surface exposed to a high-temperature environment. Increasing the turbine inlet temperature causes the thermal expansion mismatch between the TBC and the substrate, which generates high thermal stresses and thereby TBC delamination as noted in previous reports [1,2]. In addition, TBC delamination has caused thermal cracks on the sides of film cooling holes because temperature difference between regions with and without TBC increased, as reported by the Electric Power Research Institute [3]. Furthermore, the flow temperature on the TBC surface is varied by introducing secondary cooling flow from film cooling holes. Thus, the local thermal loads on the TBC surface with film cooling holes are different from convectional cooling system. However, most previous studies [4–11] of TBC delamination have mainly focused on a convectional cooling system without a film cooling hole, and have also investigated the effects of thermal cycles and thermally grown oxide (TGO) on TBC delamination.

To design hot components such as combustors, vanes, and blades and to predict their lifetime and safety, it is necessary to estimate proper TBC thickness as well as to study the thermal cycles in a film cooling system under an appropriate thermal environment. Thin TBC results in higher metal temperature, whereas thick TBC results in higher TBC temperature, which can be the source of the TBC failure. Therefore, the objective of the present paper is to determine the tolerable TBC thickness at each main hot flow temperature with a film cooling system of normal injection. For the calculation, we conduct thermal analysis using numerical methods [12] and experimental heat transfer data in a nondimensional form (Nusselt number $Nu$) from the previous studies [13,14]. The test materials of TBC and substrate are yttria-stabilized zirconia (YSZ) coating and IN738-superalloy, respectively. As results, we present maximum temperature and maximum debonding stress values at the edge of cooling holes as a function of two variables, that is, thickness of TBC and temperature of main flow. This work helps to design actual TBC systems and to understand mechanics of interface segregation between TBC and substrate.

### II. Numerical Approach and Procedures

To calculate the temperature distributions in the film cooling system, nondimensionalized heat transfer data $Nu$ around a film cooling hole obtained from the previous studies [13,14] are converted into the surface heat transfer coefficients $h$ and adiabatic wall temperature $T_{\mathrm{aw}}$ in the scaled-down system. Because the previous experimental system was enlarged from the actual film cooling holes to measure detailed local data, we converted them to actual sizes and flow velocity such as hole diameter $D_{\mathrm{eff}}$ of 4.0 mm, total wall thickness (TBC and substrate) of $1.5D_{\mathrm{eff}}$, and main flow velocity of 65.8 m/s using dimensional analysis (scaling laws) with the same blowing rate of 0.57. Wall temperature $T_w$ and wall heat flux $q_w$ were calculated using the converted heat transfer data ($h$, $T_{\mathrm{aw}}$) and the following heat transfer equations:

$$q_w = h(T_w - T_{\mathrm{aw}}) \tag{1}$$

$$\eta_{\mathrm{aw}} = \frac{T_{\mathrm{aw}} - T_\infty}{T_2 - T_\infty} \tag{2}$$

where the operating and material conditions were considered as follows: coolant flow temperature $T_2$ of 700 K, main hot gas flow temperature $T_\infty$ from 1100 to 1800 K, TBC thickness of 250∼1500 $\mu$m, and substrate thickness of $5.75 \sim 4.5$ mm to keep the total thickness of 6 mm; the materials of the substrate and the TBC are based on IN738 superalloy and YSZ coating, respectively. The material properties are presented in Tables 1 and 2.

Analysis was performed using a commercial code, ANSYS Workbench-11 to calculate the thermal stress. The finite element model and boundary conditions in ANSYS of the film cooling hole are illustrated in Fig. 1. The mapped grid is selected for the mesh construction and the geometry consists of approximately 30,000 elements. The least-mean-square method is used to impose the heat transfer coefficients $h$ and wall adjective flow temperature $T_{\mathrm{aw}}$ on the external nodes. As for the boundary conditions (BCs) for constraints, symmetric BCs and BCs for uniform deformation in the $x$-axis direction due to the existence of additional materials were imposed as shown in Fig. 1. In calculation, the constraints are important because the most stresses are caused by settlements of constraints and thermal effects (arising from temperature changes and differences). After imposing these boundary conditions, stress analysis was conducted to determine the thermal damage in the film cooling system. We have analyzed the thermal stresses, which are proportional to the thermal expansion coefficient $\alpha$ and temperature difference $\Delta t$ as noted in Eq. (3):

$$\sigma = E\alpha\Delta T \tag{3}$$

For the calculated results, the equivalent or von Mises stress, which is used to predict yielding in ductile materials, for the overall materials is presented. In addition, debonding stress, which acts direction normal to the interface between two materials, is also obtained. The finite element thermal analysis in the present work was conducted as follows:

Step 1) Create a test model using finite elements.

Step 2) Define and impose boundary conditions and the material properties.

Step 3) Calculate temperature distributions induced by conduction in the 3-D test model.

Step 4) Calculate thermal stresses using the temperature distributions and constraint conditions.

Also, to determine the minimum TBC thickness for various main hot gas flow temperatures, we make correlations upon TBC thickness and main hot gas temperature using the response surface method [15]. The maximum material temperature of TBC and substrate as well as the maximum debonding stress are obtained from the correlations at any TBC thickness and main hot gas flow temperature.

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