Stress and Displacement Distribution of the Thermal Barrier Coatings in the Turbine Engine Combustion Chamber

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Abstract: A thermal barrier coating forms a high temperature resistant metal by the spraying of ceramics or other materials. Thermal barrier coatings are mainly used in the aviation field because they can significantly improve the thermal resistance of the aircraft engine turbine blades, combustion chamber and the other hot parts. In this paper, a thermal barrier coating model of the combustion chamber is established by using the finite element method. The stress field and displacement field of thermal barrier coatings under different thicknesses of the thermally grown oxide layer and thermal barrier coating layer, and the maximum operating temperature were studied. The results show that stress and deformation under the three thermal cycles increase with the increase in operating temperature and the thickness of thermally grown oxide (TGO) and thermal barrier coat (TBC), except for the case of TGO thickness of 2 μm.

Keywords: combustion chamber; thermal barrier coatings; finite element model; fatigue analysis

1. Introduction

Thermal barrier coating systems are widely used in the combustion chamber, the turbine blade and etc., due to their advantages of improving the durability of the hot parts.

The thermal barrier coating system is composed of the bond coat (BC), the thermally grown oxide (TGO), the thermal barrier coat (TBC) and the substrate as shown in Figure 1 [1–3]. The thermal barrier coating systems can decrease the temperature from the ceramic layer to the underlying superalloy substrate due to the thermally grown oxide which is formed via oxidation. In current research, the nickel alloy was widely used to form an underlying superalloy substrate, and the BC is composed of MCrAlY alloy.

During service, however, a substantial level of stress is generated within the TGO layer, as the TBC system is subjected to thermal cycling. The induced stress can cause the TGO layer to separate, buckle and even crack [4,5].

Failure of the TBC system is due to the following several factors: (a) Thermal expansion coefficients mismatch between the different layers of the TBC system; (b) Growth stress of the TGO which is formed on the underlying superalloy substrate due to porous material of the top ceramic coating layer [4–12].
Initial geometric imperfections on the interface with BC may cause the TBC failure. At the imperfections, the TGO that forms between the TBC and BC at high temperature displaces into the BC with each thermal cycle. These displacements induce strain in the superposed TBC that cause it to crack. The cracks extend laterally as the TGO displaces, until those from neighboring sites coalesce. Once this happens, the system fails by large scale buckling [12].

Rebollo [13] has performed experiments with a single groove on the surface, the edges of the groove displace upward while the base displaces downward upon each thermal cycle. Overlaying a zirconia top coat has an effect to suppress somewhat the distortions under thermal cycle. Even in such case, however, damage in the form of TGO cracking and interfacial separation near the groove edges occur in the latter.

For more a systematic analysis Karlsson et al. [14,15] performed a series of finite element simulations, which revealed that the TGO displacement is diminished by increasing high temperature strength of the underlying BC, but is increased with the strength of TGO and the curvature of the groove edge.

Although interest in the TBC failure is growing in the related communities, to the authors knowledge, many studies mainly focus on the failure of TBC on the turbine blade, and the research on the TBC in the combustion chamber has never been reported—yet. Although the stress produced by the TBC system on the combustion chamber is not enough to directly affect the efficiency of the turbine, the various properties of the material vary with the temperature. For example, when the turbine engine works for a long time at high temperature, the combustion chamber will also produce deformations such as creep, which will affect its lifetime. Therefore, it is necessary to carry out thermodynamic analysis of the TBC in a multi-turbine engine combustion chamber.

Recently, Li et al. [16] studied the deformation of the cooling hole in under 20 thermal cycles by using 2D axisymmetric model, and compared this with experimental results which measured under high temperature for 20 thermal cycles. The results of this experiment and finite element analysis (FEA) are in agreement, which proves the feasibility of 2D axisymmetric finite element calculation.

In this paper, the thickness of the TBC layer and the TGO were discussed, and the stress and displacement distributions in the different layers were investigated for upgrading the performance of the TBC system. The analytical results can provide the research basis and design reference for fatigue life and creep research.

2. Finite Element Analysis Method of TBC System

In this paper, Ansys Workbench was used to evaluate the performance of the TBC system.

Using Design Modeler of Ansys Workbench, the analysis model of the TBC system was constructed. The principle for the analysis method is calculating the stress and displacement
distribution coupled with the temperature distribution due to heat conduction theory. As shown in Figure 2, the combustion chamber of the gas turbine engines was simplified as a thin-walled cylinder having the outer diameter of 109 mm, and the thickness of the cylinder was assumed as 1 mm.

![Figure 2. Turbine engine combustion chamber.](image1)

For simplicity, a 2D, one to four cylindrical model was used as shown in Figure 3. In the cylinder the stress is caused by the difference of thermal expansion coefficient between TBC, TGO and substrate during thermal cycling. And the stress is mainly composed of radial and tangential parts. Therefore, the thin-walled cylinder can be simplified as a 2D plane strain problem.

![Figure 3. FEA model for the TBC system.](image2)

The model was composed of TBC, TGO, substrate and BC, with initial thickness of 150, 3 and 1000 μm, respectively. The substrate and BC layer were combined to one block, because the material properties are similar. The maximum mesh size of TBC is 50 μm, that of TGO is 1.5 μm, and that of substrate and BC is 200 μm. The total number of the elements was 36,126.

The initial thickness of the TBC layer and TGO layer were set as 150 and 3 μm. The substrate and BC layer were combined to one block having the thickness of 1000 μm because the material properties are similar.

Using the Mechanical Model of Ansys, mesh formation was performed for the global analysis region, and the TBC layer and TGO layer were refined and modified. Figure 4 shows the generated mesh.

For the boundary conditions, the two sides of the analysis model were set as symmetry conditions because the model is a 2D, one to four model. In this analysis, three cycles composed of a heating time of 30 s, maintaining time of 180s and cooling time of 30 s were applied for the inner boundary as shown in Figure 5.
The material properties of each layers of the TBC system are listed in Table 1.

| Properties                              | TBC          | TGO          | BC           |
|-----------------------------------------|--------------|--------------|--------------|
| Temperatures Range (°C)                 | 20–1100      | 20–1100      | 20–1100      |
| Young’s Modulus (GPa)                   | 48–22        | 400–325      | 200–110      |
| Poisson’s Ratio                         | 0.1–0.12     | 0.23–0.25    | 0.3–0.33     |
| Thermal Expansion Coefficient \( \times 10^{-6\cdot°C^{-1}} \) | 9.0–12.2     | 8.0–9.3      | 13.6–17.6    |
| Thermal Conductivity (W·(m·°C)^{-1})   | 2.0–1.7      | 10–4        | 2.0–0.17     |
| Yield Strength (Gpa)                    | –            | 10–1        | 0.426–0.114  |
| Creep Exponent \( n \)                  | 1            | 1            | 3            |
| Creep Prefactor (MPa·s^{-1})            | \( 1.8 \times 10^{-11} \) | \( 7.3 \times 10^{-12} \) | \( 1.39 \times 10^{-7} \) |
| Density (kg·m^{-3})                     | 3610         | 3984         | 7380         |
| Specific Heat (J·(kg·°C)^{-1})         | 505          | 755          | 450          |

3. Analysis Results and Discussions

In the heating process the temperature will be heated from the room temperature of 22 °C to the operating temperature of 1000 °C in 30 s. After maintaining the operating temperature for 180 s, the temperature will be cooled from the operating temperature to the room temperature in 30 s. Three cycles will be applied to the analysis model. Then, we can obtain temperature and stress distributions for the TBC system.

Figures 6 and 7 show the displacement distributions of the TBC and TGO. As shown in Figures 6 and 7, the maximum displacements for the TBC and TGO were 0.69632 and 0.69515 μm. We also found out that the BC layer is the significantly affected region in view of the displacement.
Figures 8 and 9 show the stress distributions for the TBC system and the TGO layer. As shown in Figures 8 and 9, the TGO layer is the significantly affected region in the view of stress with a maximum stress of 2.5089 MPa.

Figure 6. Displacement field of TBC’s after 3 cycles at 1000 °C with the TGO thickness of 3 μm.

Figure 7. Displacement field of TGO after 3 cycles at 1000 °C with the TGO thickness of 3 μm.

Figure 8. Stress distribution of TBC’s after 3 cycles at 1000 °C with the TGO thickness of 3 μm.
4. Parameter Study

In this chapter, the maximum operating temperature, the thickness of TGO layer and thickness of the TBC layers were investigated for upgrading the performance of the TBC systems.

4.1. Effect of Maximum Temperature

In this section, the maximum operating temperatures were set as 800, 900, 1000 and 1100 °C, respectively, to investigate the variations in stress and displacement. Figure 10 shows the variation in the TGO stress and displacement after three cycles at various maximum temperatures. As shown in Figure 10, the stress and displacement have been increased with increasing the maximum operating temperature. These results tell us that the mismatch of thermal expansion coefficients of different layers in the TBC system should be decreased for upgrading the operating temperature.

4.2. Effect of TGO Thickness

Under the condition of setting the TBC thickness, the total of BC and substrate, and the maximum operating temperature of 150, 1000 μm and 1000 °C, the effect of the TGO thickness was investigated using the various values of 2, 3, 4 and 5 μm.

As shown in Figure 11, the stress variation has nonlinear characteristics with increasing the TGO thickness.
As shown in Table 2, the stress and displacement become smaller when increasing the TGO thickness, under the condition of setting the TGO thickness as the value between 2 and 3 μm, but the stress and displacement increase with increasing the TGO thickness when the value is between 4 and 5 μm.

Table 2. TGO stress and displacement after 3 cycles at various TGO thicknesses.

| Maximum Temperature (°C) | TBC Thickness (μm) | TGO Thickness (μm) | Displacement (μm) | Stress (MPa) |
|---------------------------|--------------------|--------------------|-------------------|--------------|
| 1000                      | 150                | 2                  | 0.72072           | 4.3137       |
| 1000                      | 150                | 3                  | 0.69514           | 2.5089       |
| 1000                      | 150                | 4                  | 0.71718           | 2.6429       |
| 1000                      | 150                | 5                  | 0.75993           | 3.8923       |

4.3. Effect of TBC Thickness

Under the condition of setting the TGO, the total thickness of BC and substrate and the maximum operating temperature of 3, 1000 μm, 1000 °C, respectively, the effect of the TBC thickness was investigated when having the values of 100, 150 and 200 μm.

As shown in Figure 12, the stress and displacement increase with increasing the value of the TBC thickness.
Table 3 shows the effect of the TBC thickness at different values. The results show that the stress and displacement have become larger when increasing the value of the TBC thickness.

Table 3. TGO stress and displacement after 3 cycles at various TBC thicknesses.

| Maximum Temperature (°C) | TBC Thickness (μm) | TGO Thickness (μm) | Displacement (μm) | Stress (MPa) |
|--------------------------|-------------------|-------------------|------------------|--------------|
| 1000                     | 100               | 3                 | 0.64137          | 2.2317       |
| 1000                     | 150               | 3                 | 0.69514          | 2.5089       |
| 1000                     | 200               | 3                 | 0.73462          | 2.7108       |
| 1000                     | 250               | 3                 | 0.76238          | 2.8678       |

In this paper, the effects of the maximum operating temperature, TGO thickness and TBC thickness were investigated. Compared with Figures 10–12, the stress and deformation under the three thermal cycles increase with the increase in operating temperature and the thickness of TGO and TBC, except for in the case of a TGO thickness of 2 μm. This is because the increase in operating temperature will cause greater thermal stress, and the increase of TGO and TBC thickness will also increase the resistance to the substrate during thermal expansion, and then cause the increase in stress and deformation.

5. Conclusions

TBC has been widely used as a coating material in turbine engines due to its excellent heat insulation performance. The research on TBC mainly focuses on the turbine blade, but the combustion chamber of turbine also works in a high temperature environment. Although the stress in combustion chamber is small in the thermal cycle, under cyclic high-temperature working conditions, stress accumulation and creep deformation may occur, which will affect the efficiency and lifespan of the turbine engine. The detailed descriptions are as follows:

- Setting the TBC system used for the combustion chamber of the gas turbine engines in the aircrafts as the research objective, thermal and structural finite element analysis has been performed for the TBC system;
- In this paper, the combustion chamber is simplified as a thin-walled cylinder with a thickness of 1 mm. The stress is caused by the difference of thermal expansion coefficient between TBC, TGO and substrate during thermal cycling with the stress mainly being composed of radial and tangential parts. Therefore, the thin-walled cylinder can be simplified as a two-dimensional plane strain problem;
- The effects of the maximum operating temperature, TBC thickness and TGO thickness have been investigated for improving the performance of the TBC system;
- The developed analysis model and the parameter study have yielded a standard basis for designing a high performance TBC system for use in the combustion chamber of the gas turbine engines of aircrafts.

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