Coupled thermomechanical analysis of stress distributions in a ceramic matrix composites turbine vane considering the anisotropic properties

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Abstract. The prediction of the stress distribution plays a key role when replacing conventional metallic components with ceramic matrix composites (CMCs) ones in the turbine engine. Furthermore, the complete thermal-mechanical properties of a CMCs component cannot be obtained through experimentation. Accordingly, a numerical method to calculate the thermal-mechanical properties of a CMCs component should be established. In this work, a 3D finite element model of CMCs turbine vane was applied. Then, the stresses due to thermal and pressure loads were simulated. Based on the simulation results, the maximum thermal residual stresses are about 40MPa and occur at the surface of the vane. It can be concluded that the thermal residual stresses should not be neglected for the studied CMCs turbine vane. The load cases have significant effects on the stress distributions. The maximum spanwise stress reached the level of 300MPa and it was larger than the hoop stress and through thickness stress. The locations of maximum and minimum stresses also vary with load cases.

1. Introduction

As known, the ceramic matrix composites (CMCs) are promising structural materials for hot-section structure in the turbine engine because of the excellent thermo-mechanical properties [1][2]. Owning to the better performance under elevated temperature compared to the conventional metallic ones, the CMCs vane and blades can remarkably enhance gas turbine efficiency [3]. Therefore, the understanding of the relationship between composite behaviors and constituents’ characteristics is fundamental to optimize the properties of CMCs components [4]. To replace conventional metallic components with ceramic matrix composites (CMCs) ones in the turbine engine, issues due to different properties need to be explored. Particularly, the stress distribution within the CMCs structure will be quite different from the metallic one because of the anisotropy mechanical properties for CMCs. So, the prediction of the stress distribution is rather an important element for the engine designers [5].

The typical fiber reinforced CMCs used in the turbine engine consist of a SiC matrix and a reinforcing SiC fiber and this combination can lead to a composite with superior mechanical properties under high temperature [6]. The fiber reinforced CMCs is of particular interests in the present study because it has anisotropic thermo-mechanical properties. This results are combined action of the different thermal-mechanical properties of the constituents, the complex fibrous architectures, and the manufacturing
defects [7][8]. Therefore, the development of an analysis tool for CMCs structure is rather an important issue for the engine manufacturers to help improve the durability of their hot engine components. To this end, the stress analysis method considering the anisotropic thermal-mechanical properties of CMCs materials need to be developed.

A few previous studies have focused on modeling the effect of anisotropy properties on the response of CMCs vane using numerical technology [9]. By the macroscopic method, homogenized stress and strain fields are generally obtained from the finite element method ignoring the inhomogeneity at the microscopic scale. Shen et al. [10] applied the material mapping method to calculate the macroscopic stress and strain of a CMCs turbine vane and compared the results with experimental data measured by DIC technology. Tu et al. [11] developed a numerical approach to analyze the heat transfer of a CMCs turbine vane. They considered the anisotropic thermal conductivity and its spatial variation due to the vane’s curved surface. These studies analyzed the effect of the anisotropy mechanical or thermal properties on the behavior of CMCs components using numerical methods. This is still a difficult task to model the thermal-mechanical behavior of the CMCs component.

In a realistic service condition for turbine vane subjected to the hot gas, non-uniform pressure and temperature are induced on the vane surface in different positions such as leading edge, trailing edge, pressure surface, suction surface [12]. Because of the complexity of the vane geometry in the three-dimensional model, it’s even harder to calculate the stress field when taking the influence of spatial variation of anisotropy material properties into account [13][14].

After reviewing the main considerations for the design of CMCs vane, we aim to perform a simulation: (1) considering the complex distribution of thermal loads and aerodynamic loads, and (2) considering the anisotropy thermal and mechanical properties of CMCs. The influence mechanism between anisotropy material properties and thermal stress distribution can be discussed. A clear understanding of this mechanism is useful for the optimal designs of CMCs structure. Therefore, this paper focus on the investigation of turbine vane stress resulting from both thermal and mechanical loads. It elaborates a calculation method for the thermo-mechanical stresses in a CMCs vane under engine operating conditions. To this end, a 3D finite element model of a CMCs vane was developed to study the influence of the spatial variation of anisotropy material properties resulted from the complex shape and structure on the stress field.

2. Numerical modeling

Figure 1 shows the CMCs vane used for the analysis. As illustrated, the geometric model of a CMCs turbine vane consists of three portions: a vane and two end plate. In general, it shows all the necessary characteristics of a practical vane. The external shape was developed from the vane of Moffitt et al. [4]. This vane has a uniform wall thickness of 2mm. Its chord is 5.819cm and its height is 3.81cm. The design inlet total temperature and total pressure were 2200K and 38.61atm, respectively. To simulate the typical vane installation, the following boundary conditions were applied: (1) the bottom face of the end plate under the vane is fixed in z direction; and (2) two side faces of the end plate are fixed in x and y directions, respectively.

Figure 1. Geometry model of the CMCs turbine vane.
If using CMC material replaces metal in a high pressure turbine, the differences in material properties should be considered. Directionally dependent responses needed to be calculated as the non-uniform and anisotropic features of CMC materials. Properties of the CMCs material, a representative plain woven SiC/SiC composites, were directionally dependent as listed in Table 1. As known, the in-plane properties of plain woven CMCs can be measured through experiments, while the out-plane properties were usually obtained through numerical analysis. These thermos-mechanical properties were obtained numerically in [10]. As seen, the CMCs have a modulus that is significantly lower through the thickness direction while metals are usually isotropic material. Also, the thermal conductivity and coefficient of thermal expansion of the CMCs material is lower. Unlike the metallic vane, considering the anisotropy properties in stress analysis is important and necessary during the design of a CMCs vane.

Table 1. Properties of a typical plain woven SiC/SiC composites [10].

| Properties                                  | Data          |
|---------------------------------------------|---------------|
| Elastic modulus, $E$, GPa                   | $E_1=239$     |
|                                              | $E_2=239$     |
|                                              | $E_3=81$      |
| Poisson's ratio, $\nu$                      | $\nu_{12}=0.20$ |
|                                              | $\nu_{13}=0.21$ |
|                                              | $\nu_{23}=0.21$ |
| Shear modulus, $G$, GPa                     | $G_{12}=97$   |
|                                              | $G_{13}=46$   |
|                                              | $G_{23}=46$   |
| Coefficient of thermal expansion, $\alpha$, $1\times10^{-6}/\text{C}$ | $\alpha_1=4.36$ |
|                                              | $\alpha_2=4.36$ |
|                                              | $\alpha_3=3.80$ |
| Thermal conductivity, $k$, W/(m·°C)          | $k_1=12.1$    |
|                                              | $k_2=12.1$    |
|                                              | $k_3=8.83$    |

The commercial software ABAQUS was used in the present study. The stresses distribution of a turbine vane under thermal and mechanical loading was analyzed. Coupled temperature-displacement elements were chosen for all of the simulations. As seen in Figure 2(a), there were 1203455 elements in total. It should be noted that the woven direction of the composites parallel to the vane’s curved surface. In theory, the material direction remained parallel to the local tangent of the curved surface. Therefore, the material direction varied at different positions because of the curved surface of the CMCs vane.

Figure 2. Mesh and material orientations of the representative turbine vane for finite element analysis.

Figure 2(b) shows a diagram of the fibrous architecture of the studied CMCs vane. It is manufactured using the plain woven CMCs. The geometry coordinates were denoted as $(X, Y, Z)$ while the principal axis of anisotropic material were set as $(1, 2, 3)$. It was found that the woven direction is inconsistent with the coordinate axis. Instead, it was consistent with the local tangent vane’s curved surface. The 1-axis for a particular position was parallel to the tangent of the vane surface and the 3-axis was perpendicular to the 1-axis. Besides, the 2-axis was parallel to the Z axis. The material direction depends on the woven direction of fiber yarns in the composites. As the tangential directions are continuously
changing along the curved surface of turbine vane, the material orientations of elements vary at different positions. A similar method in literatures [11][15] were applied here to determine the material orientations. First, tangential directions of each mesh node on the vane profile was calculated. Then, the material orientations of elements were determined by the closest mesh node of the vane surface profile.

3. Results and discussions

The concerned problem is a typical thermos-mechanical coupled process. There were two kinds of loads: (1) firstly, pressure loads were applied on the surfaces of vane according to the aerodynamic analysis; (2) secondly, the thermal loads were induced by the distribution of fields of temperature in the steady state after the heat transfer under the setting thermal boundary condition. This work concentrates on the stresses induced by the thermal-mechanical loads. The aerodynamic analysis was not considered. The pressure and thermal boundary conditions for the turbine vane were obtained from the literatures [4]. Then, the coupled thermo-mechanical analysis can be performed accordingly. Stress analysis was done using the couple temp-displacement step in ABAQUS code.

3.1. Thermal residual stress

Although the thermal residual stress usually results from the mismatch of the coefficient of thermal expansion between the constituents when considering the microstructure. The engineers also need to concern the manufacturing procedure to minimize residual stress. The initial conditions of the CMCs vane defined the stress-free state, which was set to 1000°C, the manufacturing temperature of the component. The turbine vane was simulated to cool from 1000°C to room temperature (25°C) to calculate the thermal residual stress.

In order to figure out the influence of the anisotropic properties of CMCs on the thermal residual stress of turbine vane, a vane of isotropic material was analyzed as a baseline. The thermal–mechanical properties of the isotropic material were chosen as below: \( E = 239 \text{ GPa}, \nu = 0.20, \alpha = 4.36 \times 10^{-6}/^\circ\text{C}, k = 12.1 \text{ W/(m·}^\circ\text{C)}. \) Noted, these properties were comparable with the in-plane properties of the studied CMCs listed in table 1. Figure 3 shows the thermal residual stress inside the baseline vane. For reference purposes, three stress components were calculated and illustrated as hoop stress, spanwise stress and through thickness stress. As seen, the stress is of a low level with the maximum lower than 1.0 Pa. This is because that the vane of isotropic material is able to expand under uniform temperature.

![Figure 3. Stress components of the thermal residual stress of the baseline turbine vane, MPa; (a) \( \sigma_{11} \) in the vane, (b) \( \sigma_{22} \) in the vane, (c) \( \sigma_{33} \) in the vane.](image)

Figure 4 shows the thermal residual stress due to manufacture. As seen, the hoop stress \( \sigma_{11} \) and spanwise stress \( \sigma_{22} \) are much larger than the through thickness stress \( \sigma_{33} \). The maximum through thickness and hoop stresses occurs at surfaces of the vane. Almost all stresses in the vane are below 40MPa. This does not imply that thermal residual stresses could be ignored. Compared with the turbine vane of isotropic material, the thermal residual stresses increased significantly for the studied CMCs vane. These residual stresses mainly resulted from the non-uniform distribution of the anisotropy coefficient of thermal expansion due to the complex geometry of vane. For film cooling vanes, larger
thermal residual stresses can be expected resulting from the cooling holes. Analysis of film cooling rows was not considered here as they vary for particular turbine engines.

![Stress components of the thermal residual stress of the CMCs turbine vane, MPa; (a) $\sigma_{11}$ in the vane, (b) $\sigma_{22}$ in the vane, (c) $\sigma_{33}$ in the vane.](image)

**Figure 4.** Stress components of the thermal residual stress of the CMCs turbine vane, MPa; (a) $\sigma_{11}$ in the vane, (b) $\sigma_{22}$ in the vane, (c) $\sigma_{33}$ in the vane.

### 3.2. Stresses under thermal loads

The vane operating temperature is in the range of between 1000 to 1500°C depending on the composition [16]. Calculation of temperature distribution in a turbine vane is a very complex coupled problem. Both aerodynamic and thermal transfer analyses need to be considered. In present study, the influence of aerodynamic on the temperature field was not concerned. A simplified case of heat transfer was considered here. Figure 5 shows typical temperatures distribution for the turbine vane surface. These temperatures were obtained from the midspan temperatures of the surface. An $x$ value of zero correspondings to the stagnation point at the vane surface.

![Temperature distribution along the midspan path applied to the surface of the turbine vane as the boundary condition for thermal analysis.](image)

**Figure 5.** The temperature distribution along the midspan path applied to the surface of the turbine vane as the boundary condition for thermal analysis.

The shown temperature distributions were applied on the surface of the analyzed vane. Besides, the thermal boundary conditions at the inside face of the vane needs to be specified. In ABAQUS, an interaction was built to model the heat change between the cooling air and the vane. Specifically, a surface film condition was created at the inside surface of the vane. The convection heat transfer coefficient was set as 8000W/(m²·°C) and sink temperature was chosen as 600 °C [12]. After the thermal transfer analysis, the temperature field of the turbine vane was illustrated in figure 6. It should be noted that there were obviously temperature concentrations at the trailing edge region of the vane. The reason is that the trailing edge ejection cooling was not considered here. Despite this, we believe the stress results under these temperature distributions are meaningful when discuss the influences of temperature gradients.
Figure 6. The results of the temperature distribution in the CMCs vane under the typical service condition, °C.

Figure 7 shows stresses under the applied thermal loads as illustrated in figure 5. As can be seen, the distributions of the three stress components were close to each other. The maximum stresses occurred in the fork region. The maximum value of the hoop stress $\sigma_{11}$ is 197MPa and the maximum spanwise stress $\sigma_{22}$ is near 264MPa which is at a quite high level. These high stresses result from the large temperature gradients near the trailing edge region. Therefore, they can be reduced by the trailing edge ejection cooling. In another word, the proper design of a CMCs vane should take the trailing edge ejection cooling into account by thermal stress analysis.

Figure 7. Stress components of the stress field of the CMCs turbine vane under thermal loads, MPa; (a) $\sigma_{11}$ in the vane, (b) $\sigma_{22}$ in the vane, (c) $\sigma_{33}$ in the vane.

3.3. Stresses under pressure loads

Figure 8 plots the external pressure distributions along the vane surface. They were induced by the aerodynamic analysis. The largest differential between pressure surface and suction surface occurs in the vicinity of mid-chord. The pressure was described as a ratio to the total pressure at inlet. On the other hand, the gas pressure inside the vane was chosen to equal the inlet total pressure. As mentioned previously, the total pressure at the vane inlet was chosen as 50 atm.

Figure 8. The pressure distribution along the midspan path applied to the turbine vane according to the aerodynamic analysis.
Figure 9 shows calculated stresses when subjected only to pressure loads. We analyzed the stress contours according to the stress components. The maximum hoop stress $\sigma_{11}$ is near 122MPa and occurs at the fork region similar to the case under thermal loads. The maximum spanwise stress $\sigma_{22}$ is near 303MPa and occurs at the root of the vane. This high stress resulted from the large bending moment and the stress concentration at the junction. Therefore, they can be reduced by the smooth connection between the vane and the end plate. On the other hand, the through thickness stress $\sigma_{33}$ due to pressure load is at a low level, the maximum value is less than 60MPa.

![Figure 9](image)

**Figure 9.** Stress components of the stress field of the CMCs turbine vane under pressure loads, MPa; (a) $\sigma_{11}$ in the vane, (b) $\sigma_{22}$ in the vane, (c) $\sigma_{33}$ in the vane.

3.4. Stresses under couple loads
Figure 10 illustrates the stresses resulting from the combination of pressure and thermal loads. The maximum hoop stress $\sigma_{11}$ is near 310MPa and occurs at the fork region similar to the case under thermal loads and pressure loads. Similar to the pressure load case, the maximum spanwise stress $\sigma_{22}$ is near 390MPa and occurs at the root of the vane. Different from $\sigma_{11}$ and $\sigma_{22}$, the through thickness stress $\sigma_{33}$ due to combined pressure and thermal loads retained a low level, the maximum value was less than 100MPa.

To examine the dependence of the stress distributions on the load cases, we compared the stresses field of different load cases. Comparing figures 6, 8 and 9 shows that, stress distributions significantly change. The locations of maximum and minimum stresses also vary with load cases. The maximum stress components under thermal load occur at the fork region. For the pressure cases, the maximum values occur at different positions depending on the component directions. As known, the through thickness strength of woven composites is very weak compared to the in-plane one. The results of stress distribution showed that the CMCs was very suitable material for turbine vanes.

![Figure 10](image)

**Figure 10.** Stress components of the stress field of the CMCs turbine vane under couple loads, MPa; (a) $\sigma_{11}$ in the vane, (b) $\sigma_{22}$ in the vane, (c) $\sigma_{33}$ in the vane.

4. Conclusions
In present study, a numerical simulation method was applied for predicting stress in turbine vane structures made of CMCs. The integrated simulation procedure contained the generation of the vane geometry, the descriptions of thermal and pressure loads, and the orientation method of the anisotropic thermal-mechanical properties. The present method considered anisotropic mechanical properties and
thermal conductivity. Based, several simulation cases have been conducted to examine the stress distribution in a CMCs vane. The simulation results for both mechanical and thermal loading cases demonstrated the ability of the model to analyze the stress and predict the critical regions of the vane structure. The remarks from the simulation results were listed as follows:

(1) Compared with the turbine vane of isotropic material, the thermal residual stresses should not be ignored for the studied CMCs vane. The maximum stresses are about 40MPa and occur at the surface of the vane. These residual stresses mainly resulted from the non-uniform distribution of the anisotropy coefficient of thermal expansion due to the complex geometry of vane.

(2) The load cases have significant effects on the stress distributions. For all the three load cases, the maximum spanwise stress was larger than the hoop stress and through thickness stress. The maximum spanwise stress $\sigma_{22}$ under thermal load is near 264MPa which is at a quite high level. For the case under pressure loads, the maximum spanwise stress $\sigma_{22}$ is near 303MPa. The maximum spanwise stress $\sigma_{22}$ due to coupled loads is near 390MPa. The positions of maximum and minimum stresses also vary with load cases.

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