AN EXPLORATION OF STRUCTURE DESIGN IN 3D BRAIDED CERAMIC MATRIX COMPOSITES TURBINE BLADE DOVETAIL ATTACHMENT

Zhen Cheng, Duoqi Shi*, Xin Jing, Xiaoguang Yang

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China,
towng6@buaa.edu.cn
[2] School of Energy and Power Engineering, Beihang University, Beijing 100191, China,
shdq@buaa.edu.cn
[3] School of Power and Energy, Northwestern Polytechical University, Xi'an 710072, China,
jingxin@nwpu.edu.cn
[4] School of Energy and Power Engineering, Beihang University, Beijing 100191, China,
yxg@buaa.edu.cn

Keywords: 3D braided, Ceramic-matrix composites, Turbine blade, Dovetail attachment, Structure design

ABSTRACT

For braided composites, the direction of yarns and its braided density could vary with the parts' shape, the braided method of the composites could be designed according to the structure actual shape. In order to research the local mechanical properties variation of braided composites causing by geometric change of the structure, explore the method to design 3D braided ceramic matrix composites (CMCs) parts with complex geometrical shape. Choosing the 3D braided CMCs turbine blade dovetail attachment as the background, selected its two-dimensional section as the research object. Firstly assumed the CMCs' properties are transversely isotropic along the section plane, analyzed the structural stress distribution. Considering the requirement of CMCs forming process and its strength data, the preliminary structure design could be established. Then, in view of the local mechanical properties variation of CMCs happening in the transition of structures shape, several microcosmic cell model was established to obtain the elastic properties respectively in different areas using the finite element method. Substituting these properties into the corresponding area of the section, the result of the stress level of the structure section would be closer to the practical situation. The structure design method and the obtained key structure parameters can be used as a reference in the future work.

1 INTRODUCTION

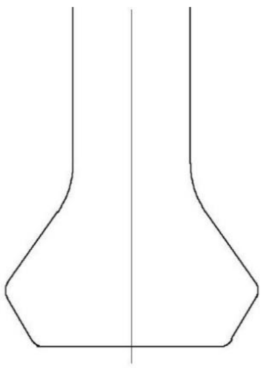
Ceramic matrix composites (CMCs) have a huge potential use in hot end components of aeronautics and astronautics. Recent years, CMCs are gradually replacing traditional superalloy in some hot end parts of gas turbine engine to satisfy more rigorous design requirements, reduced the structural weight and save costs of full life usage [1]. GE Aviation® had applied CMCs low-pressure turbine vanes in its newest generation of 30,000 pounds thrust grade turbine engine LEAP-X. Furthermore in 2015.2, GE Aviation® successfully verified the world's first CMCs low-pressure turbine blades on F414 engine, showed that these composites could satisfy well with high mechanical loads in rotating parts.

When use CMCs to replace the traditional superalloys in blades, several new requirements should be put forward to the blades' geometric structure in order to meet the feasibility of the composite process. One typical example is in the tenon/mortise. The firtree tenon attachment which usually used in superalloys blades is too complex for CMCs to manufacture. It is difficult to ensure the continuity of SiC fibers in every tenon tooth and its carrying capacity. Using dovetail attachment as alternative is a mainstream approach. This attachment had widely used in compressor blades, the stress analysis and structure design method is comparatively mature. Conventional analytical methods and finite element simulation could relatively accurately obtain the stress and guide for structure design. Recent years, researchers are concentrating on several delicate questions. Sinclair et al. paid attention to the contact inequalities in dovetails [2-4], Nakahara et al. approached fatigue and life of the dovetail [5], Anandavel et al. focus on the fretting variables at dovetail interface [6].

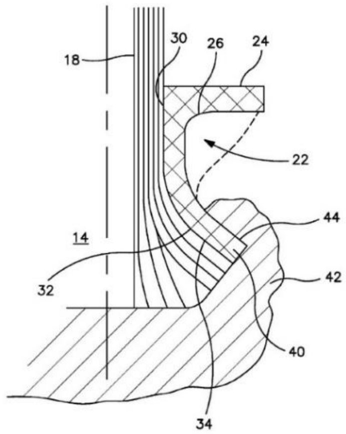
However, experimental and numerical analyses for composites dovetail attachment are still devoid. Kogo et al. explored the feasibility of dovetail attachment made by braided C/C composites [7]. Several experiments and finite element analyses were made, showed that the fracturing of their specimens was controlled by the average shear stress. But their finite element model did not consider the yarns' direction and its braided density was varied with the dovetail' shape. This paper gives a method to describe those two variations in finite element models, focus on the dovetail's stress distribution change influenced by those facts. The simulation result indicated that the direction of yarns and its braided density varied with the shape could affect the stress distribution. It is necessary to introduce these changes to simulation model when taking structure design.

2 STRUCTURE AND MATERIAL STIFFNESS PREDICTION METHOD

In this paper, we use one typical 2-D dovetail attachment showed in Fig. 1(a) as an example. This design based on the CMCs' properties are transversely isotropic along the section plane. The requirement of CMCs forming process and its strength data are also considered to determine the preliminary structure design. Fig.1 (b) showed the possible yarns' direction distribution in the dovetail.



(a)

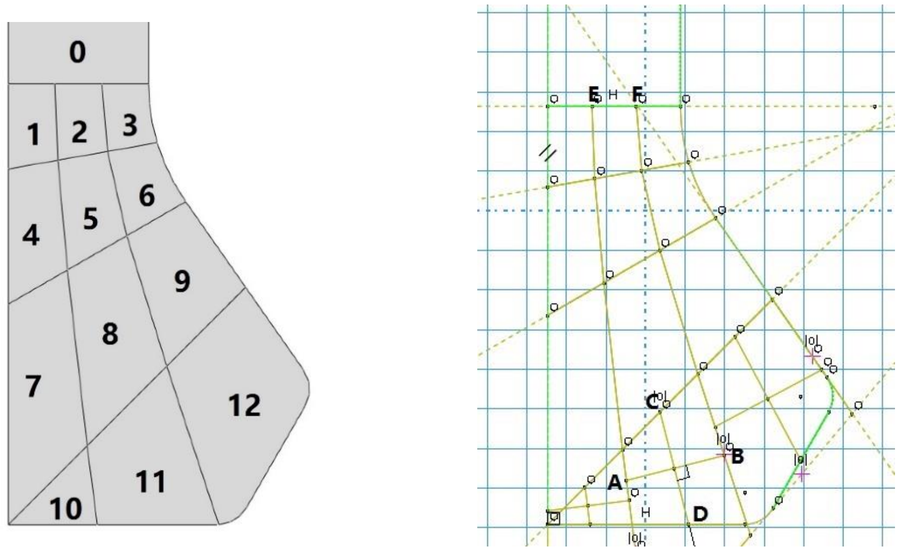


(b)

Figure 1 (a) One typical 2-D dovetail attachment (b) Yarns' direction distribution in dovetail [8]

2.1 Structure partitioned method

Because of the symmetry, one half of the dovetail structure was modeled. Considering the yarns' direction and density distribution varies in this dovetail section, comprehensively considered the computational accuracy and model complexity, the half of the dovetail was divided into thirteen subzones to identify these variations. Every subzones had its own composites direction and fiber volume fraction. In this paper, the composites direction and fiber volume fraction in one subzone regarded as no longer changing. The subzones partitioned method and its regional code No.0-12 were showed in Fig. 2(a).



(a) (b)

Figure 2 (a) The subzones partitioned method and regional code (b) The stats methods of composites directions and fiber volume fractions in every subzone

Every subzone had its own composites direction and fiber volume fraction. This paper gives a convenient method to calculate these data, use the auxiliary lines displayed in Fig. 2(b). The composites direction is more directly to obtain. For example, in subzone No.11, take the midpoint between top and bottom edges as point C and D. Line segment CD represents the composites direction of this subzone.

The fiber volume fraction *f* in every subzone was slightly complicated to obtain. In subzone No.0, V_f is initial value. When the width of the structure begins to widen in the downward direction, no new yarn is introduced so that V_f Start to get smaller (Fig.1b). The extent to which every subzone width increase determined its V_{fn}. Count the characteristic widths of every subzone could obtain V_{fn}. This paper gives a convenient method to calculate characteristic width. In the same subzone No.11 in Fig. 2(b), the midperpendicular of CD, which AB is the characteristic width of subzone No.11. V_{fn} can use equation (1) to get.

$$V_{fn} = \frac{l_0}{l_n} V_f \tag{1}$$

For subzone No.11, l_n = AB, l_0 =EF, V_f =0.465(initial value).

The V_{fn} result was figured out in Fig. 3. It showed that as subzone No. increased, V_{fn} decreased in general. The subzone at the same height (such as No.1-3 or No. 4-6) had similar V_{fn} .

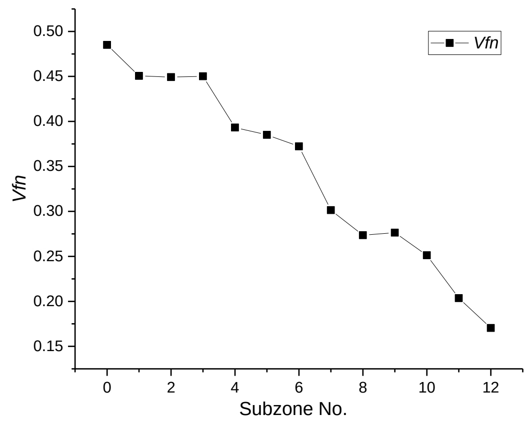


Figure 3 The V_{fn} result of every subzones

2.2 Fiber bundle stiffness

Combined with the prior research [9], the decrease of V_f causes the yarn filling factor ε_n to decrease in the fiber bundle. According to the consistency of forming process of 3D braided composites, braiding angle and meso cell approximately unchanged. The volume fraction of fiber bundle V is constant. It was set to be $V=95.8\%$ by the meso cell [9]. These parameters satisfy equation (2).

$$V_{fn} = \varepsilon_n V \tag{2}$$

After figured out ε_n, the scale between the fiber diameter and cell side length will be confirmed. We established several microcosmic fiber bundle cell (including fiber, interface and matrix). Fig. 4 shows one of these cells.

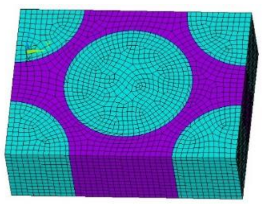


Figure 4 Microcosmic fiber bundle cell in subzone No.0

Using the finite element method, applying periodic boundary conditions could obtain the elastic properties. Table 1 showed the component properties and Table 2 showed the fiber bundle properties in subzone No.0.

	E/GPa	μ
SiC fiber	150	*0.2*
Interface	5.1	*0.3*
SiC matrix	50	*0.3*

Table 1 component properties

Engineering constants	Prediction result
E_{11}/GPa	114
E_{22}/GPa	91.2
G_{12}/GPa	38.4
G_{23}/GPa	39.3
ν_{12}	0.231
ν_{23}	0.275

Table 2 Fiber bundle properties in subzone No.0

In this paper, subscript 1 signified main direction of material. The fiber bundle and braided composites approximate transversely isotropic, so the properties along direction 2 and 3 were same. The properties of fiber bundles in other subzones was not shown here.

2.3 Braided composites stiffness

The meso cell model we use is shown in Fig. 5. Furthermore, applying periodic boundary conditions, substituting different fiber bundle stiffness into this finite element model could obtain the elastic properties of braided composites in different subzones.

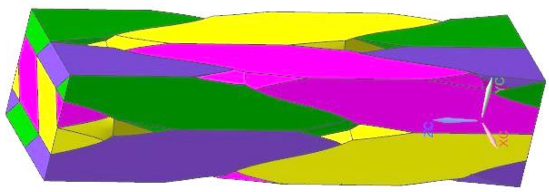
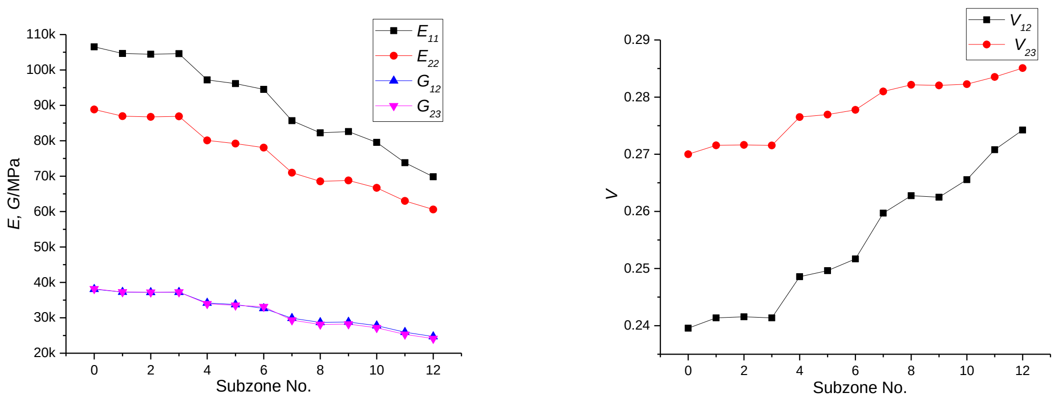


Figure 5 Meso cell for 3D braided composites

The stiffness of different subzone from No.0 to No.13 was shown in Fig. 6.



(a) (b)

Figure 6 (a) the CMCs elastic modulus *E* and shear elasticity *G* in different subzone (b) the CMCs Poisson ratio ν in different subzone

It showed that as subzone No. increased, *E* and *G* corresponding decreased in general, whereas ν increased in general. The subzone at the same height (such as No.1-3 or No. 4-6) had similar stiffness. This law of result is similar with V_{fn}. Because from the beginning we only change this parameter.

3 DOVETAIL ATTACHMENT SIMULATION

3.1 SIMULATION MODEL

Considering of the symmetry, one half of the 2D structure was modeled in Abaqus®. 38MPa tensile stress was applied on the top edge of dovetail neck section (Fig. 7). The fan disk was isotropic superalloy contact with the CMCs dovetail with finite sliding under friction μ=0.2. Because the stress level of the two is not quite high, linear elasticity is used as constitutive relation.

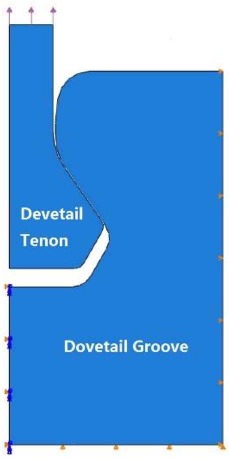


Figure 7 Finite element simulation model

3.2 RESULTS AND DISCUSSION

According to the different material properties applied to the CMCs dovetail, Three model were simulated to find out the stress distribution change affected by local mechanical properties variation.

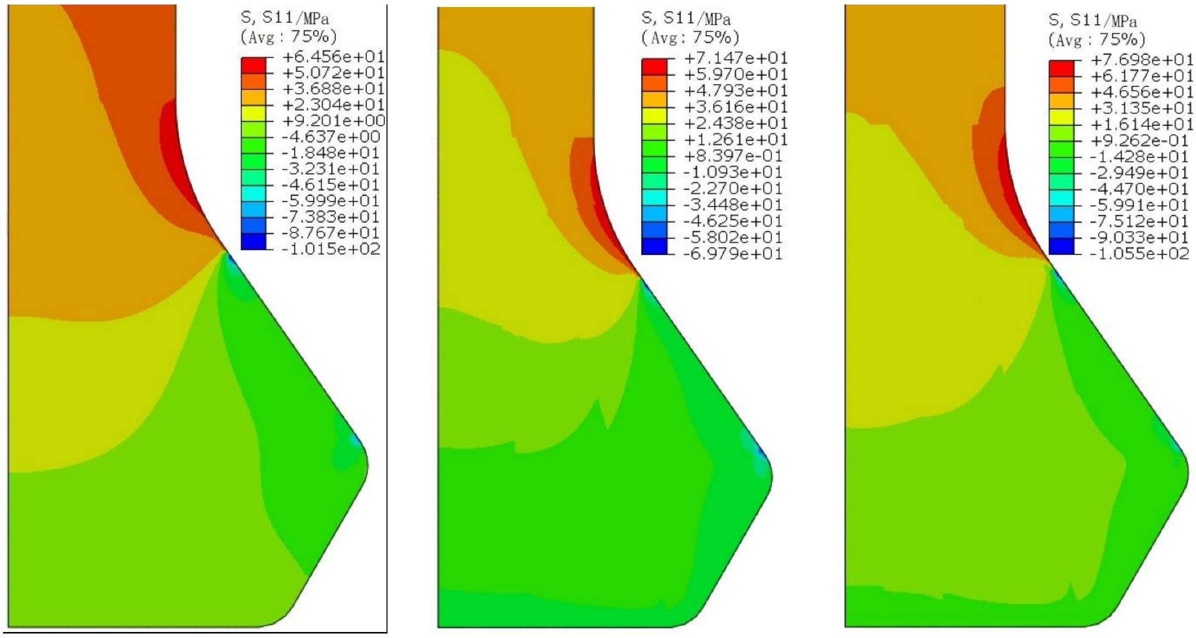
Model A assumed the whole dovetail was formed by one material with constant stiffness values (using the data from subzone No.0). In addition, the composites direction was along initial coordinate, did not change by the parts' shape.

Model B also assumed the whole dovetail was formed by one material with constant stiffness values (using the data from subzone No.0). However, the composites direction was changed by the parts' shape. There were thirteen subzones expounded in 2.1 to describe the direction changes.

Model C assumed the dovetail had different stiffness and composites directions in different areas. There were thirteen subzones expounded in 2.1 to describe the stiffness and direction changes.

The simulation results are shown below. The CMCs initial failure criterion were not clear yet. Here we use stress standard. σ_{11} (main direction of composites), σ_{22}, and τ_{12} were all under consideration.

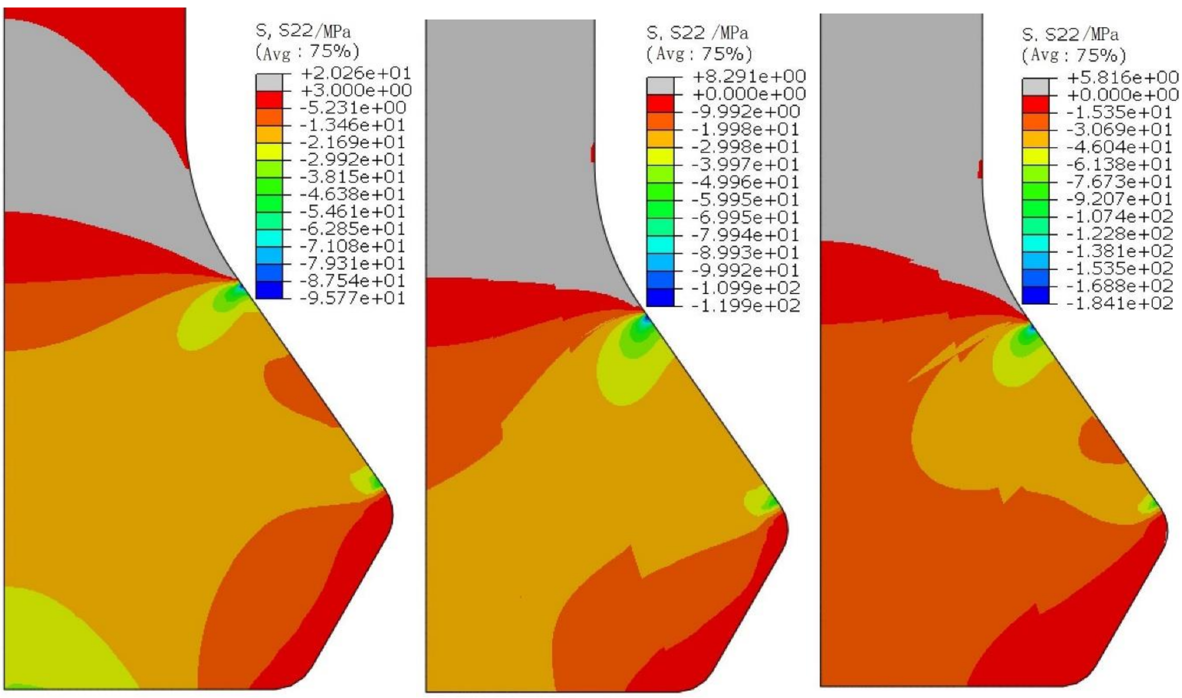
Fig. 8 indicated that considering composites direction changes and introduce stiffness changes into the model would increase the dovetail fillet transition stress concentration by simulation results. If we use only Model A to take structural design verification, the actual σ_{11} stress may be 20% larger than the simulation results.



(a) Model A (b) Model B (c) Model C

Figure 8 The CMCs σ_{11} field using different models

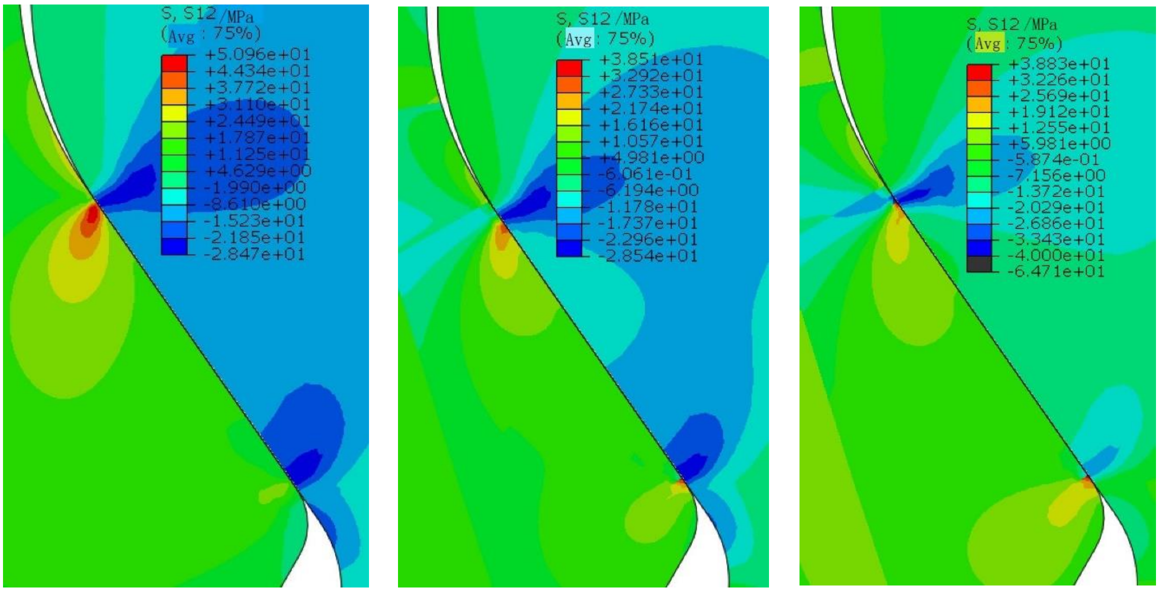
Fig. 9 showed that σ_{22} field (transverse direction of composites) would also influenced by both composites direction changes and composites stiffness changes. The maximum area of compressive stress usually happened on the upper or lower edges of the contact surface. The stiffness changes played a more pronounced role. If we use only Model A to take structural design verification, the actual σ_{22} compressive stress may be 90% larger than the simulation results.



(a) Model A (b) Model B (c) Model C

Figure 9 The CMCs σ_{22} field using different models

The simulation results of shear stress τ_{12} are still obvious (Fig. 10). Different models with different materials properties equivalent methods would affect the distribution of shear stress in the contact surface edges. When use Model A, the upper edges of the contact surface showed the biggest τ_{12}. However, when use Model B or C, considered the composites direction changes and composites stiffness changes, result are different, the lower edges may also be the maximum shear stress area.



(a) Model A (b) Model B (c) Model C

Figure 10 The CMCs τ_{12} field using different models

4 CONCLUSION

For braided composites which apply in components and parts with complex geometrical shape. The direction of yarns and its braided density variations along the shape would seriously disturbed the simulation accuracy of the traditional stress analysis methods.

In chapters 2, several method are given to quantitative descript the direction and properties changes of the composites. It is simple but direct to solve problems and can be used in structural design optimization. However, more methods needed to be establish to describe direction and properties changes with other braided or woven methods, other forming process such as increase or decrease yarns.

Because of the example dovetail structure is designed under an assumption of transversely isotropy material. According to the simulation results of chapter 3, change the direction and properties hypothesis of the original material would lead to deteriorations of stress distribution or changes in stress concentration area. But it is clear that the latter method’s deteriorated result is more close to practical situation. If the method considering both direction and properties changes is complex to use. According to Model B, the method considering only material direction changes would also take a partial correction effect. Furthermore, using transversely isotropy hypothesis to design braided composite structures with complex geometric are not recommend, the stress level and stress concentration location may differ greatly from the actual situation

ACKNOWLEDGEMENTS

The research and data was supported from the National Natural Science Foundation of China (NO. NSFC51275023). Meanwhile, Thanks to Professor R. Luo for the help of composites preparation experience and technique.

REFERENCES

[1] Katoh Y, Snead L L, Henager C H, et al. Current status and recent research achievements in SiC/SiC composites[J]. Journal of Nuclear Materials, 2014, 455(1): 387-397.

[2] Sinclair, G. B., and N. G. Cormier. "Contact stresses in dovetail attachments: alleviation via precision crowning." ASME Turbo Expo 2001: Power for Land, Sea, and Air. American Society of Mechanical Engineers, 2001.

[3] Beisheim, J. R., and G. B. Sinclair. "Three-dimensional finite element analysis of dovetail attachments with and without crowning." Journal of Turbomachinery 130.2 (2008): 021012.

[4] Beisheim, J. R., and G. B. Sinclair. "Improved three-dimensional crowning profiles for dovetail attachments." Journal of Engineering for Gas Turbines and Power 132.6 (2010): 064504.

[5] Nakahara, Tetsuya, Yusuke Ueda, and Hiroshi Nakamura. "Development of Life Prediction Method of Turbine Blade Using the Theory of Critical Distance." ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. American Society of Mechanical Engineers, 2012.

[6] Anandavel, K., and Raghu V. Prakash. "An Assessment of Centrifugal Loading Effect of Rotor Disc on Fretting Variables at a Dovetail Interface of an Aero-Engine." ASME 2012 Gas Turbine India Conference. American Society of Mechanical Engineers, 2012.

[7] Kogo, Yasuo, et al. "Application of three-dimensionally reinforced carbon–carbon composites to dovetail joint structures." Composites science and technology 62.16 (2002): 2143-2152.

[8] McCaffrey, Michael G. "CMC blade with integral 3D woven platform." U.S. Patent No. 9,212,560. 15 Dec. 2015.

[9] Zhen, Cheng, et al. "Improved model and stiffness prediction of 3D four-directional braided ceramic-matrix composites." Acta Materiae Compositae Sinica (2016).