Computer simulation of a small gas turbine ceramic blade

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Abstract. A new level of small gas turbines operating temperatures may be introduced by application of composite ceramic materials for specific turbine elements, especially blades, combustors, generators. This requires new design technology that takes into account element high temperatures, specific mechanical and physical performance and the composite ceramic materials compatibility with adjusting engine elements. This paper presents results of computer parametric studies of blade fir tree coupling for small gas turbines.

1. Introduction
Small gas turbine (SGT) engines operate in especially difficult conditions that are short typical missions, large endurance of highly loaded regimes, non-uniform inlet air flow, location at poorly equipped sites, poor qualification of service staff, etc. These specific SGT features determine the development trends that are possible simplifying gas turbine structures, reduction of rotor stages number and total number of engine parts. The simple structures also improve the engine reliability and reduce manufacturing and operation costs. One of the main conceptual solutions is the transition from multi-stage controllable axial or axi-centrifugal compressors to highly loaded centrifugal ones with one or two stages without flow path control, or variable elements.

The optimal combination of high performance, good operation characteristics, low manufacturing, maintenance and repair expenses, long life and high reliability may be provided by the following structural scheme and the main assemblies’ layouts:

- Two-stage highly loaded single circuit centrifugal compressor without variable flowpath elements.
- Short annular inclined combustor.
- Compressor drive by one or two stage non-cooled axial turbine.

The main problem for introduction of this concept is development of the non-cooled turbine blades [1]. There are results of computer parametric studies of the non-cooled ceramic blade fir tree coupling presented in the paper. The blade is mounted in a metal turbine disc.
2. Choice of blade material
The currently used turbine inlet temperatures require the application of ceramic blade materials, first of all composite ceramic materials (CCM) reinforced with high strength carbide and oxide fibers [2–7].

The CCMs reinforced with solid silicon carbide SiC fibers provide the best prospects for the non-cooled blade development. Experimental and technology investigations carried out by foreign companies show that this material is ready for introduction. Domestic companies do not manufacture SiC fibers and this does not allow the material introduction.

Foreign materials may be replaced with a dispersion reinforced SiC material Skeleton-D with artificial diamond particles developed by Central Research Institute of Materials (Saint-Petersburg, Russia). The main material performances are given in table 1. The material has high heat conductivity, low thermal expansion and sufficient strength. This allows its application to the non-cooled turbine blades manufacturing. Its young modulus is almost two and a half time higher than that of heat—resistant alloys. The CCM Skeleton strength is practically unchanged at operating SGT gas temperatures up to 1360 K (figure 1) [8].

| Parameter                        | Value          |
|----------------------------------|----------------|
| Maximal temperature, °C          | 1500           |
| Specific mass, kg/m³              | 3200           |
| Young module, GPa                | 500            |
| Shear module, GPa                | 300            |
| Poisson coefficient              | 0.15           |
| Linear expansion coefficient, K⁻¹ | (2.0–2.3)·10⁻⁶ |
| Ultimate tensile strength on axes, MPa | 250           |
| Compressive strength along axes, MPa* | 1790           |

* at room temperature

Figure 1. Bending strength of the CCM Skeleton.

The material advantage is its better manufacturability than that of the reinforced ceramic materials. The chemical reaction of the carbide-silicon matrix formation is carried out in the blank volume. The material formation process goes at pressures not higher than atmospheric which provides the shrink free technology.
Special tests show that the final product formation from diamond powder changes linear dimensions not more than 0.2% and this allows manufacturing complicated and large parts [9]. The technology allows blade manufacturing with fir tree or dovetail couplings.

3. Computer studies results

Traditional turbine blades have fir tree couplings with the teeth inclination angles about 35° (figure 2). This configuration is acceptable for metal blades but cannot be applied to CCM because the smaller is the inclination angle the higher are tensile stresses. Parametric studies show that the optimal CCM angle is 60° to 85° depending upon the material parameters. The teeth number should be reduced down to two.

The blade with fir tree coupling is applied to design of an experimental turbine rotor stage. The stage was initially designed of a metal and was not re-designed for the CCM specific features. The 3D rotor element model is shown in figure 2. It is worth mentioning that this report discloses a numerical evaluation of the completely new CCM possible application to the SGT blade manufacturing. The structure is analyzed irrespectively to a specific gas turbine, so the gas loads radial distribution is not considered. Nevertheless the retained metal blade structure includes the tip shoulder torque that balances the steady state bending moment. This produces stress concentration in the coupling area that is not experienced in the actual structure. So this work evaluates the coupling area stress caused by centrifugal loads. The considered mean stress values do not involve stress concentration.

![Figure 2. 3D model of the experimental turbine rotor element with the fir tree coupling.](image)

The computer studies used the ANSYS Mechanical software intended for finite element analysis of metal structures. In this study the following boundary conditions were applied:

- Central disc mounting provides zero displacements.
- The blade is fixed in the axial direction by the tooth face surface.
- The disc rotation speed 44000 rpm.
- Friction coefficient in the teeth contact surfaces 0.2.

In the first simulation model both teeth had equal angles of 60°. The calculation results shown in figure 3 show the lower teeth higher load than the upper one. This is caused by the metal disc upper contact surface centrifugal displacement and the ceramic blade coupling high stiffness allows smaller displacement. So the lower teeth carry larger parts of the centrifugal load. In the case of metal blade mounted in metal disc, this problem is absent.

The calculation results show maximal stress concentration of 461 MPa in the contact zone. In this study location of the blade airfoil center of mass was not optimal which caused the non-uniform stress
distribution. Here the investigation subject was only the coupling strength. Figure 3 shows the contact stress above 245 MPa which is not acceptable for the material. The stress was reduced by increase of the upper and lower teeth inclination angles. The upper tooth angle was 70° and it was combined with the lower tooth angles of 70°, 75° and 80° (figure 4). The calculation results are shown in figures 5–7.

![Figure 3. Radial stress in the fir tree coupling with equal upper and lower teeth angles 60°.](image3)

![Figure 4. The two teeth coupling versions.](image4)

The results for the blades with equal upper and lower teeth angles of 70° (figure 5a) show that the equal angles are not reasonable. The stress distribution shows that the lower tooth is overloaded but the upper tooth is almost free. Figures 6a and 7a also show the contact non-uniformity and strong stress concentration at the lower tooth.

The coupling calculation results for 70° upper tooth and 75–80° lower tooth angles show sufficiently uniform contact stress distributions (figures 5b and 5c, figures 6b and 6c and figures 7b and 7c). The 75° version has maximal radial stress 608 MPa but the mean contact stress is below 265 MPa, the maximal total contact stress in the lower tooth is 441 MPa. Here the contact stress is compression so this level is acceptable for the Skeleton-D material.

The last version with the lower tooth angle 80° is the most acceptable. The results in figure 5c show the maximal stress concentration of 379 MPa and the mean contact surface stress of 196 MPa, the strength margin 1.2. The contact surfaces interaction of upper and lower teeth (figure 6c) are uniform and the maximal total contact compression stress is below 343 MPa, the strength margin 5.2 (figure 7c), the upper and lower teeth are loaded equally. The stress distribution in figure 7 shows prospects for the further coupling optimization by verifying the lower tooth angle from 75° to 80° as to provide more uniform teeth loading.

![Figure 5. Fir tree coupling radial stress distribution.](image5)
a) lower tooth angle 70°  

b) lower tooth angle 75°  

c) lower tooth angle 80°  

**Figure 6.** Interaction in fir tree contact surfaces, CCM blade and metal disc.

a) lower tooth angle 70°  

b) lower tooth angle 75°  

c) lower tooth angle 80°  

**Figure 7.** Total contact stress in the CCM blade fir tree coupling.

4. Conclusion
Specific features of composite ceramic materials require combined application of mechanical and technology design. Stress simulation of the disc-blade system shows that the fir tree coupling of a ceramic material blade with the young module twice higher than the metal disc one is necessary to use the two-teeth fir tree coupling with different teeth contact angles.

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