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The influence of quantity and distribution of cooling channels of turbine elements on level of stresses in the protective layer TBC and the efficiency of cooling

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A R T I C L E   I N F O

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A B S T R A C T

The modern turbine engines are designed to operate in the temperatures of combustion gases, of order 1800–2000 K, which considerably exceed admissible values for applied metals. Therefore turbine elements should be protected against raw thermal environment to keep the acceptable lifetime and standards of safety. There are two ways of protection: (1) different cooling systems of the turbine elements and (2) thermal barrier coatings (TBC).

As an example of the turbine element a nozzle guide vane was analysed. It was protected by TBC layer of 0.1 mm thickness and several systems of cylindrical cooling channels. Different numbers of the cooling channels, their distribution as well as diameters were considered. The aim of the work was estimation of: the efficiency of cooling vanes, the level of Mises stresses in the vane and the influence of the protective layer TBC on the thermal response of the turbine element. All considered variants were compared.

In the simulation real boundary conditions were applied, i.e. the temperature of combustion gases was 1600 K and inlet velocity of cooling gas 1.23 m/s. For delimitation of temperature fields the Computational Fluid Dynamics (CFD) analysis was applied, using the programme ANSYS Fluent. The turbulence model of flow k–ε was applied in numerical calculations and the temperature distributions were established. Computational Structural Mechanics (CSM) analysis was done with ABAQUS, taking into account temperature fields. It lead to calculation of the stress distributions in the blade and in the protective layer TBC. The most important stress concentrations took place near cooling holes, which had significant influence on endurance of the turbine elements.

1. Introduction

The attempts to use an internal cooling in turbine elements of jet-propelled engines reach fiftieth years of 20th century. The main aim was to protect the jet engine parts, e.g. vanes and blades, against melting resulting from the growth of combustion gases temperature together with the Mach number growth. There were two ways of protection: (1) different cooling systems of the turbine elements and (2) thermal barrier coatings (TBC), e.g. [1–16].

There were at least three methods of internal cooling:

1. Using liquid, i.e. the vane was cooled by water or fuel, however there was no possibility to chill these substances again.
2. A mixed method with application of liquid and gas media – the heat was taken away from the vane or blade with the help of flowing liquid. Then it was given back in exchanger to surroundings.
3. An air coming from a jet engine compressor.

The first two methods were not developed due to increased degree of complexity of an engine structure (additional pumps, lines, exchangers).

The application of the internal cooling only with the use of the air allows for the increase of the temperature level in turbine elements to the range of 1400 K. The further rise of this crucial parameter for the jet-propelled engine is possible by covering of a working part of the turbine elements with a thin-films of a ceramic layer TBC (with application of electron beam physical vapour deposition – EB PVB, pulsed laser deposition or sputter deposition, etc.). Application of the TBC coatings increases not only the engine efficiency, but also contributes to the decrease of nitrogen oxides emission. The blades and vanes as well as the protective TBC are subjected to thermal shocks during operation of the jet engine and are additionally influenced by non-homogeneous temperature field resulting from the internal cooling channels system. These arguments justify significance of numeric investigations of this complex 3-D multiphysical problem, particularly for: stress concentrations, damage and failure processes, both in macro and microscale, e.g. [2–16]. The most important stress concentrations take place near the cooling channels, which have significant influence on endurance of the blade or vane.

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The aim of the paper is to investigate four different systems of cooling channels in the nozzle vanes to assess efficiency in each considered case. Additionally a new material, i.e. $MgZrO_3$, was considered for TBC, which creates better thermal shock protection, [17]. The analysis done on the nozzle vanes used in jet engine includes CFD and CSM. Obtained results are useful for optimisation in designing process of the jet engine vanes.

2. Numerical method

A numerical algorithm for the solution of the problem includes three stages:

1. The first stage, concerned the blade or vane heating by combustion gases to working temperature and reaching the steady state. This part was done with the use of the program ANSYS/Fluent. The heterogeneous fields of temperature inside of the vane were obtained.
2. The middle stage was transferring of the temperature field from CFD and simulation of a coarser mesh used in CSM analysis.
3. The last stage was calculation of the stress distributions in the vanes for all types of protection configurations. This part was done with the ABAQUS program.

In numerical examples we assumed that the vane (substrate) was made of Ni-based superalloy, whereas the thin-protective layer – from $MgZrO_3$, [17]. All materials data (including temperature dependence) were collected in Table 1.

2.1. Pre-processing

Fig. 1 shows an example of the nozzle guide vane used for production of the aerospace engines. For the purpose of this analysis a part of this vane was selected and numerically modelled. Fig 2 presents details of the vane cross section with characteristic dimensions. On the basis of this scheme 3-D FEA model of the vane was created. The next step of the pre-processing was introduction of several different cooling systems to the vane. Four basic configurations of cooling systems (Fig. 3) were analysed with:

1. 9 cooling channels of diameters equal to1 mm.
2. 6 cooling channels of diameters equal to 1.25 mm.
3. 4 cooling channels of diameters equal to 1.5 mm.
4. 3 cooling channels of diameters equal to 1.75 mm.

The cross sections of all considered cooling systems are approximately the same. The side surfaces of the channels in the last case are the smallest. Moreover, in this case the distance from the edges of the channels to the nozzle vane surface is the smallest. Additionally, next four configurations contained also the TBC layers with thickness of 0.1 mm were modelled to investigate the effectiveness of this thin ceramic layer protection. Introduction of the TBC to the model was done by cutting of the whole vane volume into two separate solids.

Table 1
Material properties.

Material properties	Ceramic coating		Substrate	
	$MgZrO_3$		Ni-based superalloy	
Temperature (K)	293	1273	293	1273
Elasticity modulus, E (GPa)	48	28	200	150
Poisson ratio, ν	0.23	0.23	0.33	0.33
Thermal expansion coefficient ($1/K \times 10^{-6}$)	5.6	7.8	12.6	16,8
Density (kg/m^3)	6000	6000	8500	8500
Thermal conductivity, k (W/m K)	0.9	0.7	8.9	21.6
Specific heat, Cp (J/kg K)	510	650	440	700

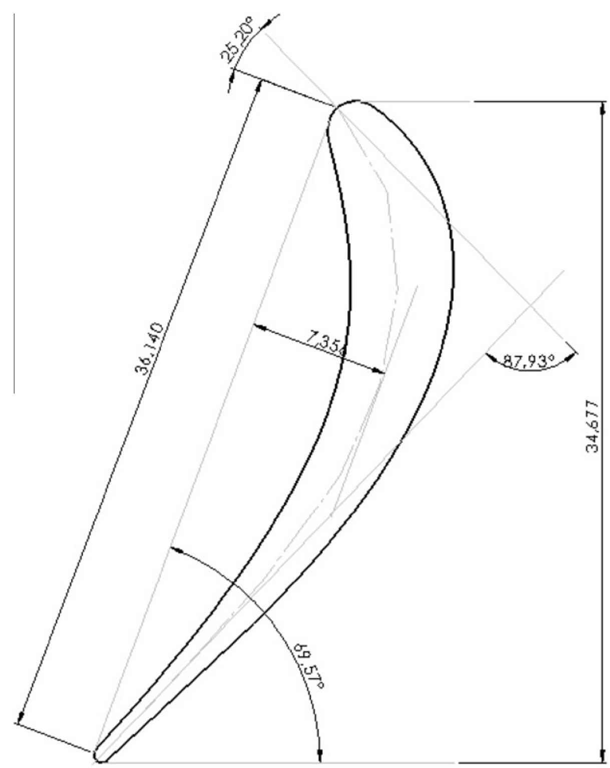

Fig. 2. Four basic configurations of cooling channel systems inside nozzle guide vanes.

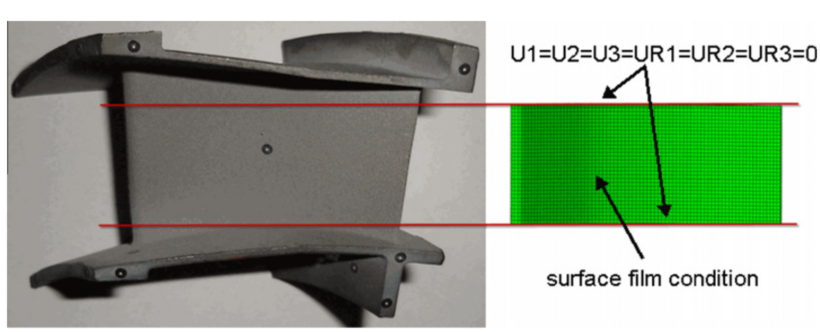

Fig. 1. The nozzle guide vane and the selected part for numerical investigations.