

MULTIDISCIPLINARY ANALYSIS OF THE OPERATIONAL TEMPERATURE INCREASE OF TURBINE BLADES FOR AIRCRAFT ENGINE BY APPLICATION OF THE CERAMIC THERMAL BARRIER COATINGS $ZrO_2/20\%Y_2O_3$

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Abstract: *The improvement of the temperature resistance of the aircraft engine elements can be obtained by application of a ceramic coating, single layer (TBC) or several composite layers. Turbine blades are made of a super alloy that has a maximum operating temperature of close to 1000°C, the idea of using ceramic materials was foreseen. To increase thermal resistance of engine the elements requires, apart from laboratory investigations, also numerical study of the different aero-engine parts. For aircraft engine the most important are turbine blades, where high temperatures and stress concentrations during thermal shocks or thermal fatigue can be observed during engine exploitation.*

The present paper deals with the solution of the transient temperature transfer problem in bare and thermal barrier coated alloy Inconel 625 for the temperature range up to 1000 °C. The computational fluid dynamics (CFD) part of analysis was performed by application of ANSYS Fluent code receiving the temperature field of combustion gas.

Key words: TBC, ANSYS, Finite element

1. Introduction

Thermal barrier coating (TBCs) on the blades which are used to isolate components of gas turbines are subjected to severe temperature regimes thus ensuring their proper functioning [1]

The achievement ceramic coating for the aircraft gas turbo engines blades is now a

usual method for increasing strength and durability of blades.

The goal is to extend the lifetime of turbine blades by using a common, cheap and easily processed material, which coated with a thermal barrier by modern methods lead to improved thermo mechanical behaviour of the blades, increasing their high temperature

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performance and prevents peeling.

The paper analysis the temperature distribution onto a layer of ceramic material deposited by atmospheric plasma spraying composed of ZrO₂/20% Y₂O₃, on super alloy Inconel 625 blades of the aircraft turbo engine Tumanski R13, which equips the MIG 21 (Figure 1.).

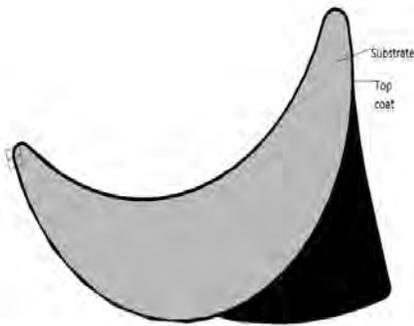


Fig. 1. Turbine blade and the TBC coating structure.

2. Analytical formulas of flow parameters through the turbine blades network

Determination of the temperature field in the blade of rotor with analytic method is a fairly difficult, because of complex shapes and boundary conditions of heat exchange. In order to define the temperature fields in aircraft engine, one should formulate boundary conditions of the third kind, it is necessary to know the temperature distribution of gas flowing over the turbine blade surface T_g , and the convective heat transfer coefficients α .

2.1. Temperature of the exhaust gas T_g

The temperature T_g in the turbine blades rotor depends on the operating temperature of the exhaust gas T_0 :

$$T_g = T_0 - \frac{c_1^2 - r_t w_1^2}{2c_{pg}} \quad (1)$$

Where: T_0 is the temperature of the exhaust gas, c_1 is absolute speed of the outflow of the exhaust gas (m/s), w_1 relative speed of the inflow of the exhaust gas on the blades of rotor (m/s), r_t is coefficient of the temperature recovery, and C_{pg} is the specific heat of the exhaust gas at the constant pressure (J / kg C).

2.2. Heat transfer coefficients

The convective heat transfer occurs between a solid surface and a moving or stationary fluid found at different temperatures. The convective heat transfer coefficient, α [W/m²K], is not a property of the fluid it is a parameter experimentally determined or with empirical relations. The value depend on the surface geometry, nature of fluid flow, temperature, speed of flow.

The value of the convective heat transfer coefficient for many gases and liquids overflowing any engine part, is expressed by several characteristic numbers: Nusselt (Nu), Prandtl (Pr), Reynolds (Re). α (W/(m² °C)) is calculated from the following formula:

$$\alpha = Nu \frac{\lambda_m}{d_h} \quad (2)$$

Where: α is the coefficient of convection, λ_m is thermal conductivity of the heat transfer, d_h hydraulic diameter

3. Thermo physical properties of materials analysis

This study describes the experimental results of thermal diffusivity, specific heat at constant pressure, and thermal

conductivity of the top coat $ZrO_2-20\%Y_2O_3$.

Three curves can be observed in these graphics: the first is made with the detector positioned on the layer side and the laser on the substrate side, the second with the detector on the substrate side and the laser on the layer side and the third only with the substrate. In the third case, when layer was removed, thermal diffusion coefficient and the conductivity coefficient increases continuously, maintained at inferior values to those obtained from the samples with deposits. Diffusivity coefficient is maintained relatively constant up to $400^\circ C$ ($3mm^2/s$), after that it increases up to $4,8 mm^2/s$ at $1000^\circ C$ (Figure 2).

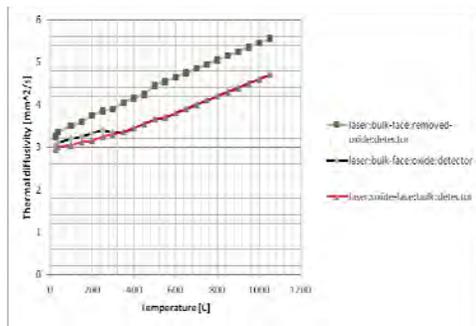


Fig. 2. Thermo physical properties thermal diffusivity

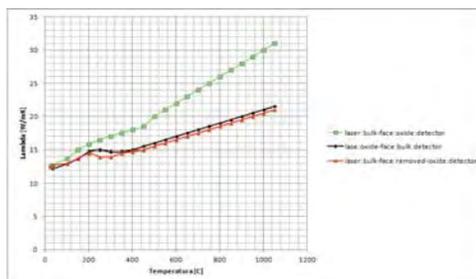


Fig. 3. Thermo physical properties thermal conductivity

Also, the coefficient of conductivity λ (figure 6.b) for both samples with deposits increased up to $200^\circ C$ at the value of 15

($W/m \cdot K$), it is maintained relatively constant until $500^\circ C$ after that increases continuously reaching 21 ($W/m \cdot K$) at $1000^\circ C$.

In conclusion, the temperature propagates with much more difficulty to the material of the turbine blades when the detector is positioned on the substrate side and the laser on the layer side. This demonstrates that the layer reduces thermal conductivity and diffusivity, protecting turbine blades in the high temperature in which it operates, around $1000^\circ C$.

4. Numeric method of calculating temperature distribution in blades of the turbine

4.1. CAD model

The first step was to create a CAD model of the mobile blade of first stage, the layers and of the model for CFD analysis. This includes defining the geometry of the blade in different sections, establishing a structural assembly between the blade and the layer and defining the material for both the components.

The CAD model for the turbine blade and ceramic layer was done using the software CATIA V5 R19. For the base material from the turbine blade, we defined the properties of the Inconel 625 material and for the ceramic layer the properties of $ZrO_2/20\% Y_2O_3$.

The assembly of the two component parts, namely the ceramic layer and the base material, was made using a rigid connection condition between them.

4.2. Finite element method model

To obtain the temperature of the exhaust gas flowing around the blade surface the ANSYS Fluent 13 [3] commercial code was applied.

Pre-processing in numerical modelling

was divided in two steps:

a) Importing the turbine blade and the ceramic layer from CATIA in the steady-state thermal module from ANSYS and the CFD analysis model from CATIA in ANSYS Fluent 13.

b) For the designing of the mesh it can be mentioned that were used only tetrahedral finite elements. The mesh for the CFD model contains 1107410 elements with 205137 nodes (Figure 4), for the uncoated blade the mesh contains 900 elements with 4851 nodes (Figure 5) and for the blade with ceramic coating the mesh contains 6000 elements with 14880 nodes (Figure 6)

As boundary condition for the CFD analyses model all the exterior and interior surfaces are regarded as a wall condition, less than the inlet surface which has a velocity inlet condition and the outlet surface witch has a pressure outlet condition.

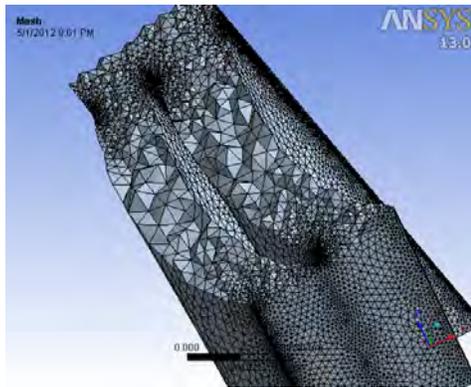


Fig.4. Finite element mesh for model CFD

For this there where defined the thermal convective coefficient and the gas temperature for the convection heat transfer and the thermal conductive coefficient for the ceramic coating and the base material for the conduction heat transfer. (Figure 5.)

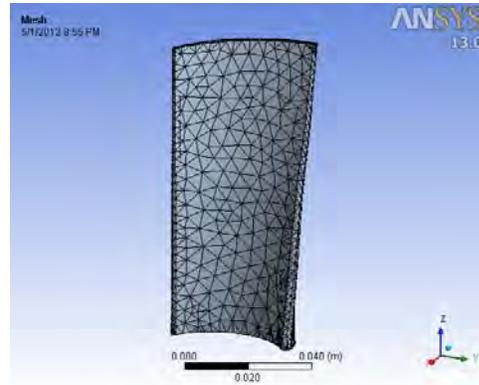


Fig.5. Finite element mesh without ceramic layer

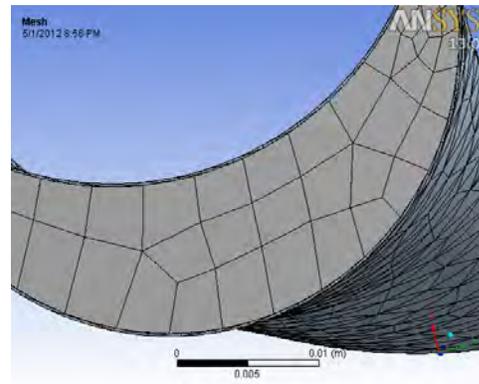


Fig.6. Finite element mesh with ceramic layer

5. Numerical results

The CFD analysis was performed with ANSYS Fluent 13. The following parameters for the exhaust gas were introduced: density, heat capacity, thermal conductivity and dynamic viscosity coefficient. A laminar flow was used for the gas.

5.1. Fluent analyses

The values obtained from the flow simulation helped to determine the parameters needed to achieve the

temperature distribution in the blade. The speed distribution helped determine the convective heat transfer coefficients and the pressure distribution the gas temperature

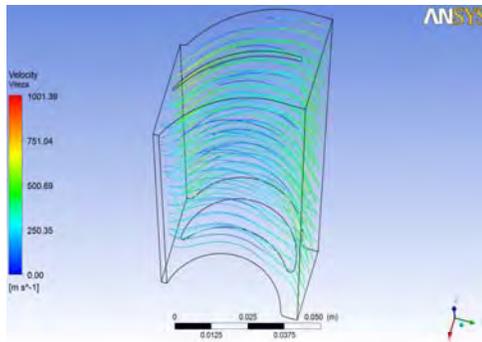


Fig.7. Flow velocity

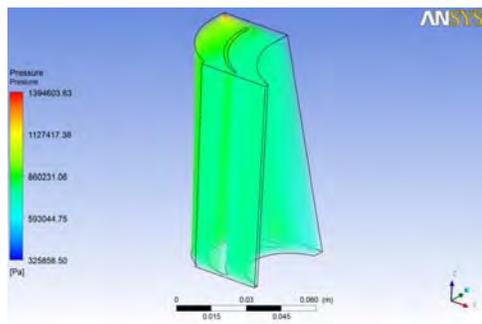


Fig.8. Pressure distribution

5.2. Temperature distribution

In Figure 9 it is presented the blade with ceramic coating. The maximum temperature is achieved in the coating and the base material is less affected by the very high temperature. In Figure 10 it is a section in the blade with the ceramic coating. It can be seen how the temperature decreases in the coating.

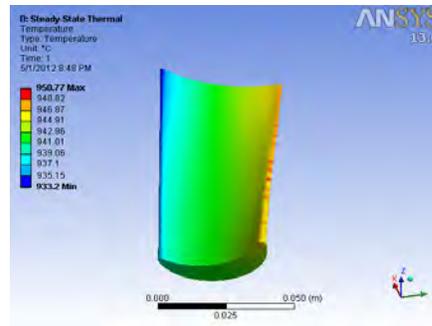


Fig.9. The temperature distribution on the turbine blade with ceramic coating on the pressure side

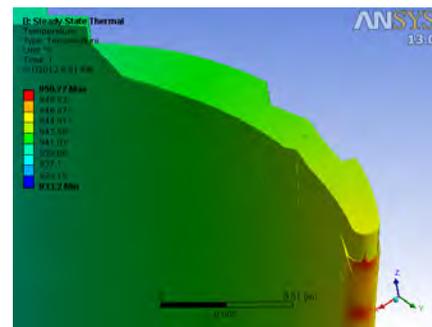


Fig.10. Section view on the blade with ceramic coating

In Figure 11 and Figure 12 it is presented the turbine blade without the thermal coating. It can be seen that the maximum temperature is achieved in the base material.

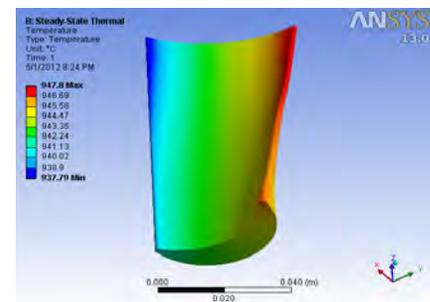


Fig.11. The temperature distribution on the turbine blade without ceramic coating on the pressure side

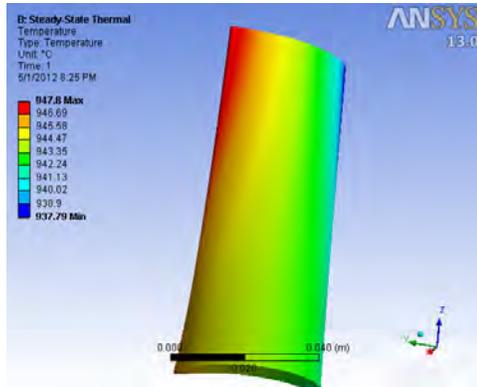


Fig.12. The temperature distribution on the turbine blade without ceramic coating on the suction side

6. Conclusions

The major conclusions are summarised as follows:

Because of the very low conductive heat transfer coefficient of the layer, the coating behaves as a thermal barrier. This fact can be easily observed from the temperature distribution in the blade with the ceramic coating and in the blade without the ceramic coating.

Application of 0.2 mm thickness YSZ thermal barrier coating significantly reduces the operation temperature

This leads to an increased life span of the blade and to the protection of the base material which is heavily subjected to mechanical stresses.

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References

1. C.C.Berndt et al: *J.Thermal Spray Tech.* 1(4) (1992).
2. N. Noda, *J. Therm. Stress.* 22 (1999) 477–512.
3. Ansys Fluent 12 *Theory Guide*, April 2009.
4. Aristotel Popescu, *Elemente fundamentale de t transfer de caldura*, Editura Eurobit Timisoara 2003.
5. T. Sadowski, Non-symmetric thermal shock in ceramic matrix composite (CMC) materials, in: R. de Borst, T. Sadowski (Eds.), *Lecture Notes on Composite Materials–Current Topics and Achievements*, Springer, 2008.
6. T. Sadowski, P. Golewski: *Multidisciplinary analysis of the operational temperature increase of turbine blades in combustion engines by application of the ceramic thermal barrier coatings* *Computational Materials Science* 50 (2011) 1326–1335
7. T. Sadowski, M. Boniecki, Z. Librant, K. Nakonieczny, *Int. J.: Heat Mass Transfer* 50 (2007) 4461–4467.