HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

INVESTIGATIONS OF THE THERMAL STATE OF THE GTE BLADES USING A THERMAL VISION SYSTEM FOR TESTS WITH THERMAL MANAGEMENT

Lepeshkin A.R.*, Bychkov N.G. and Lepeshkin S.A.
*Author for correspondence
Central Institute of Aviation Motors,
Moscow, 111116, aviamotornaja, 2
Russia,
E-mail: lepeshkin.ar@gmail.com

ABSTRACT

Induction heating is the most effective heating method for thermocyclic tests and investigations of turbine blades and parts with a thermal barrier ceramic coatings. A new method is proposed for high-frequency induction heating of turbine blades and parts of gas turbine engines with thermal barrier ceramic coatings. The proposed method has been developed taking into account the electrophysical and thermophysical properties of materials in thermal cycling tests. There have been carried out thermophysical measurements, obtained the results of investigations of the nonstationary thermal state of the turbine blades and parts GTE with coatings using a thermal vision system for thermocyclic tests with thermal management. Also there have been carried investigations of the thermal state of the fan blade with the use of a thermal vision system and blade releasing method with thermal management for fan casing containment tests.

INTRODUCTION

At present, the cyclic fatigue life of thermal barrier coatings in the course of their development has been studied using radiant heating with a low rate (less than 20 K/s), which does not correspond to actual operating conditions. At such low heating rates, thermal stresses are almost completely absent and the main damage factor is the oxidation of a sublayer, which leads to spalling of the coating. Actually, these processes are heat resistance tests at variable temperatures. Under real conditions, the rate of change in the temperature of parts lies in the range 100-200 K/s. In this case, there arise cyclic thermal stresses and deformations of the base material, which are accompanied by the appearance of alternating stresses. The results of tests for thermal fatigue of parts with thermal barrier coatings can differ significantly from the results of tests for cyclic heat resistance, which have been obtained by developers at a low rate of change in temperature. Therefore, in the design of thermal barrier coatings, it is necessary to investigate their heat resistance together with a protected material under the conditions providing high rates of heating and cooling. The tests performed in a gas-dynamic flow are expansive and require a long time. The high-frequency induction heating is significantly lower in cost and requires a shorter time. The process of high-frequency heating involves not only induction heating of conductive materials but also heating of dielectrics, including ceramic materials. The dynamics of heating of the coating and the base material depends on the electrophysical and thermophysical properties of the material, its volume, the cooling conditions, the rate of heating of the object, the dielectric properties of the ceramic coating, and the frequency of the electric current used for heating. The calculated simulation of the heating conditions for parts with thermal barrier ceramic coatings has not been adequately developed as compared to thermal calculations of the parts operating in a gas dynamic flow. More reliable data on the temperature state of parts with thermal barrier ceramic coatings during their heating in a high-frequency electromagnetic field and on their heat resistance can be obtained from experimental investigations. In order to create prerequisites that are necessary for the development of computational methods used for determining the thermal and thermostressed states of parts with thermal barrier coatings in the course of their heating in a high-frequency electromagnetic field and for the experimental evaluation of the thermal cyclic fatigue life of these parts, in this work we set the problem of the development of a technique for high-frequency heating and thermophysical measurements in tests of blades and models of other parts with thermal barrier coatings based on zirconia. The purpose of this work is to develop a design-experiment method for high-frequency induction heating and determination of fatigue and thermophysical measurements in thermal cycling tests of blades of gas turbine engines, to perform experimental investigations on the determination of the temperature state of blades and models with zirconia thermal barrier coatings with the use of a thermal vision system during high-frequency heating of parts with ceramic coatings, to determine the ratio between the processes of high-frequency and dielectric heatings and to compare the thermal cyclic fatigue lives of parts with a thermal barrier coating and without it.

The investigations of the thermal state of the fan blade with the use of a thermal vision system and blade releasing method with thermal management for fan casing containment tests have been carried.

NOMENCLATURE

T	[°C]	Temperature
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction
σ	[MPa]	Stress
ε		Blackness degree
τ	[s]	Time
K		Safety factor
S	[m^2]	Cross-section area
σ_b	[MPa]	Ultimate strength

NUMERICAL SIMULATION

The computational part of the method consists in sequentially solving the following problems: the electromagnetic problem based on the Maxwell equations, the transient heat problem based on the solution of the heat conduction equation, and the problem of determination of the thermostressed state. The first problem was solved with due regard for the recommendations proposed in [1]. By solving this problem (taking into account the gap between the inductor and the part and the electric current frequency of 440 kHz), we determined the distribution of internal heat sources (specific heat power) over the thickness of the base metal (the refractory nickel alloy of the blade model with an intermediate refractory metal coating NiCoCrAlY, as well as in the ceramic coating due to the induction heating (as a result of the change in the electrical resistivity of zirconium oxide with an increase in temperature) and dielectric heating (as a result of the change in the permittivity and the dielectric loss tangent with an increase in temperature). The obtained distributions of internal heat sources are nonstationary; i.e., they depend on the heating time. During the solution of the coupled electromagnetic and heat problems at each computational step, the value of the current temperature was transferred from the module of the solution of the heat problem to the module of the solution of the electromagnetic problem in order to correct the electrophysical properties of the materials. The computational investigations allow one to refine the thermal and thermostressed states of thermal barrier ceramic coatings on cooled blades and models during high-frequency induction heating with the inclusion of dielectric heating. The initial data used in the performed calculations were electrophysical, thermophysical, and strength properties of the ceramic coatings and the material of cooled parts, the characteristics of bench conditions for heating and cooling, and the parameters of the test thermal cycle. The electrophysical and dielectric properties of the ceramic (zirconia) coating were taken from [2], and the electrophysical, thermophysical, and strength properties of the ceramic coatings were taken from [3]. The parameters of the permittivity and dielectric loss tangent of a zirconium oxide depending on temperature are shown in [2]. Electrical resistivity of a zirconium oxide makes at the temperatures: 100 °C - 10^{11} Ohm·cm, 1000 °C - 10 Ohm·cm.

The calculations performed by author using the finite element method implemented in the ANSYS program and the distribution of the heat flux from the inductor between the zirconia coating and the metal of the cooled part at an induction current frequency of 440 kHz made it possible to investigate the nonstationary thermal state of the coating and the cooled part with the inclusion of the parameters of the test thermal cycle. The boundary conditions for the solution to the heat problem were as follows: the temperature of the ambient air was 20 °C, the heat-transfer coefficients of the ambient air were equal to 20-30W/(m^2 K), the heat-transfer coefficients of the cooled air inside the blade model were equal to 1800-2000 W/(m^2 K) (according to the experimental data), the specific heating power on the surface of the refractory metal coating was 9×10^5 W/cm^2, and the specific heating power in the ceramic coating was 1.8×10^5 W/cm^2 (these specific heating powers were obtained from the solution of the electromagnetic problem). The minimum and maximum heating temperatures of the metal surface of the part in the thermal cycle were equal to 350 and 900 °C, respectively. The mathematical simulation of the thermal state of the ceramic coatings takes into account the specific features of the electrophysical properties of zirconia. In particular, an increase in the temperature results in an increase in the permittivity, the dielectric loss tangent, and the electrical conductivity [1]. On the whole, the ceramic coating in the course of the test thermal cycle was heated by means of both the heat transfer from the metal of the part and the dielectric heating. The computational scheme for a fragment of the cooled part with the thermal barrier coating is shown in Fig. 1.

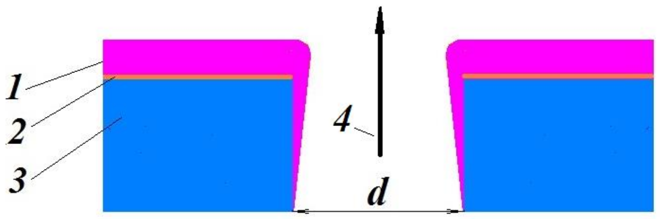


Figure 1 Schematic diagram of a fragment of the cooled part with the thermal barrier ceramic coating: *(1)* ceramic coating, *(2)* metal of the workpiece, *(3)* refractory metal layer, and *(4)* direction of the flow of cooling air in the hole. Designation: *d* is the hole diameter

The performed calculations of the nonstationary thermal and thermostressed states of the models of cooled parts with thermal barrier ceramiccoatings (Fig. 2 and Fig. 3) have demonstrated that, at the maximum temperature of the thermal cycle, the temperature of the outer surface of the ceramic coating at the end of heating is higher than the temperature of the metal and, consequently, there arise temperature gradients across the ceramic coating thickness.

The temperature gradients depend on the thermal conductivity coefficient, the coating thickness, and the heat loss due to the environment on the surface of the coating. The heat losses were calculated taking into account the convective heat exchange, the radiative heat exchange, and the maximum experimental temperature of uncooled plates of the inductor (300 °C) at the end of heating in the first stage of the thermal cycle.

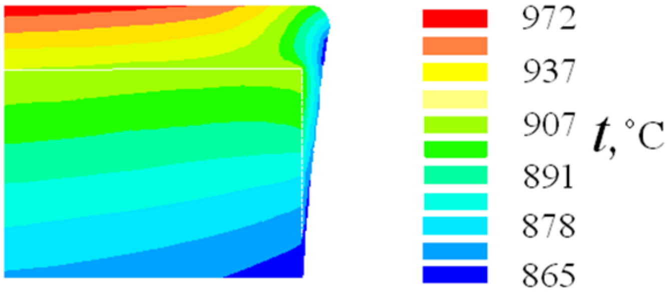


Figure 2 Calculated temperature distribution of the fragment of the cooled part with the thermal barrier ceramic coating in the region of the cooling hole

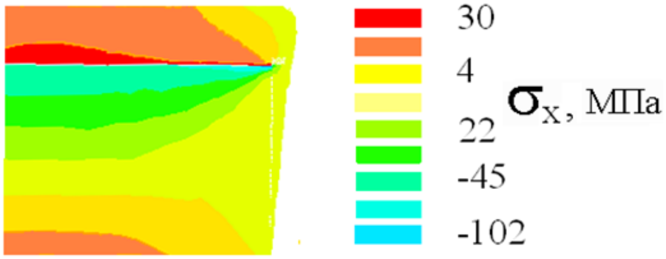


Figure 3 Calculated thermostress distribution of the fragment of the cooled part with the thermal barrier ceramic coating in the region of the cooling hole

At an induction current frequency of 440 kHz and taking into account the ratios between the heated masses of the base material from the refractory alloy and the coating, as well as their electrophysical and thermophysical properties and cooling conditions, the calculated distribution of the high-frequency electromagnetic energy over the sample from the nickel-based alloy with the zirconia thermal barrier coating approximately corresponds to 80 % for the metal (the high-frequency energy is released in the metal of the sample) and 20 % for the coating (the high-frequency energy is released in the zirconia ceramic coating due to the induction heating (10 %) and the dielectric losses (10 %)). According to the results of the numerical calculations under the aforementioned conditions at a heating rate of 100 K/s, the temperature on the outer surface of the model of the part with the thermal barrier coating in contact with the environment is approximately 60-80 °C higher than that at the "metal-thermal barrier coating" interface; i.e., the temperature state of the part is simulated in operation. In this case, compressive thermal stresses of 100 MPa on the metal surface and tensile thermal stresses of 30-35 MPa on the side of the thermal barrier ceramic coating are observed.

EXPERIMENTAL INVESTIGATIONS

The experimental part of the method provides simulation of high-frequency induction heating and the performance of thermophysical measurements in the course of thermal cyclic tests of blades and other cooled parts with thermal management and takes into account the electrophysical and thermophysical properties of their materials. In the developed method, the contactless thermophysical measurements are carried out using a thermal vision system for the performance of investigations and for the confirmation of the calculated results for the nonstationary thermal state of the part with the thermal barrier ceramic coating (with the inclusion of the temperature gradient across the ceramic coating thickness) in thermal cyclic tests of rotating blades and blade models with thermal barrier ceramic coatings. The temperatures of the surfaces of the ceramic coating and the metal under the coating were measured simultaneously with a thermal imager lens through a hole in the inductor. In this method, we also proposed the design of a split uncooled plate inductor [1] with a hole for the examination of thermal and thermostressed states of the cooled and uncooled blades, including parts of gas turbine engines with coatings. The specific features of this method are as follows: the possibility of performing thermal cyclic tests of parts of gas turbine engines with retaining a guaranteed minimum constant gap between the inductor and the blade surface, which decreases the probability of distortion of the temperature field after the replacement of the parts and favors an increase in the efficiency of high-frequency induction heating; the fulfillment of the relationship $\Delta < 0.1 \cdot h$, where Δ is the depth of penetration of the electric current (the electromagnetic wave) and h is the minimum thickness of the metal wall of the part (the cooled blade) for the choice of the frequency of the electric current; etc. Two cooling circuits are used to create the required nonstationary thermal state of the cooled part and to provide the optimum parameters of the thermal cycle. The first cooling circuit ensures air supply into the inner cavity of the part, and the second circuit is responsible for supply of air passing between the inductor plates and the part for blowing the surface of the part and its cooling at the end of each thermal cycle. Preliminary, while heating the model in electric furnace there were obtained empirical data about degree of blackness for specimen with and without the thermal-protective coating which were used for thermal-imaging measurements. The values of blackness degree ε_b for specimen with the coating under temperatures, approximately, of 850÷900 °C close to peak ones in the cycle were equal to about 0.55 and for blade specimen in high-temperature-resistant alloy without the coating their value was about 0.80 (Fig. 4). The thermal cyclic tests of the blades with a thermal barrier coating and the models of cooled parts were carried out in the course of high-frequency induction heating of the object at a frequency of 440 kHz according to the developed technique on a setup [1] equipped with a VChG-10/0.44 high-frequency valve generator with thermal management. In order to perform comparative thermal cyclic tests, the working surface of the blade models produced from a refractory alloy sheet 1.0 mm thick with preliminarily perforated holes was subjected to sand blasting with synthetic corundum, followed by the deposition of two variants of the thermal barrier ceramic coating with the intermediate refractory joining NiCoCrAlY layer and without it. Fig. 1 shows a fragment of the model of a cooled part (the model with a thermal barrier coating) mounted inside the inductor connected to electric buses of the VChG-10/0.44 generator. Air with a controlled flow rate and a controlled pressure was fed inside the sample. This scheme provided the possibility of reproducing the operating fields of temperatures and thermal stresses for the model and the possibility of experimentally determining the thermal cyclic fatigue life of the blade models with different variants of thermal barrier coatings and without them.

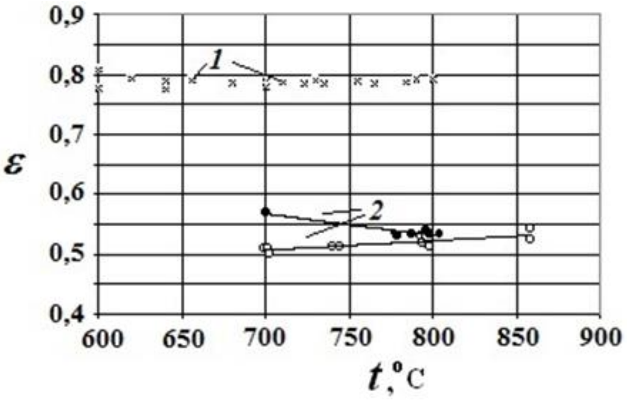


Figure 4 Blackness degree ε_b depending on temperature

The temperature was controlled by a chromel-alumel thermocouple. The temperature state of the surface of the thermal barrier coating in the working region was controlled using an Agema thermal imager. For the experimental verification of this thermal state, we carried out contactless measurements of the temperature of the surface of the model with the thermal barrier coating based on zirconia with the use of an Agema 782 SW thermal imager operating in the spectral range from 3.0 to 5.6 μm. The specific features of the technique used for measuring temperatures with thermal vision systems are described in [1]. The model of the cooled part with holes is shown in Fig. 5. The diameter of two rows of holes is equal to 1 mm. The diameters of holes of the other rows are smaller than 1 mm. The refractory joining layer (coating) has a thickness of 0.06 mm.

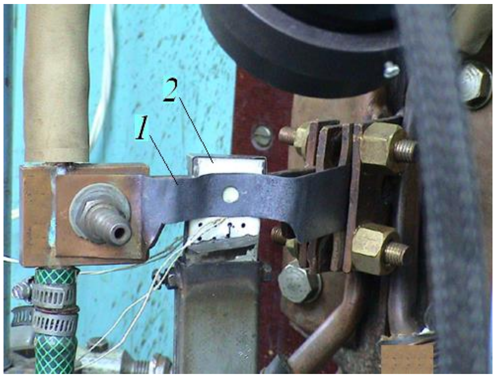


Figure 5 Tests of the cooled part with the heat_resistant ceramic coating: (*1*) inductor and (*2*) cooled part

The cooling air was fed into a box-like hollow model (with a rectangular cross section). The model had a wall thickness of 1 mm and a cross section of 10 x 25 mm. In the examination of the temperature state of the part with the ceramic coating, the optical accessibility of the object during the thermal cycle was provided by a small hole (5 mm in diameter), which was drilled in the inductor and through which the surface region was scanned (Fig. 5). Thermal images in the course of thermal cyclic tests were recorded in a personal computer with a frequency of three to five frames per second. The analog signal of the thermal imager was digitized using an L-783 analog-to-digital converter board fabricated by the L-CARD Corporation. The complete cycle (from the beginning of heating of the sample to cooling) was recorded; however, only the frames in the vicinity of the peak value of the temperature were used in the processing. The parameters of the thermal cycle with thermal management are presented in Fig. 6.

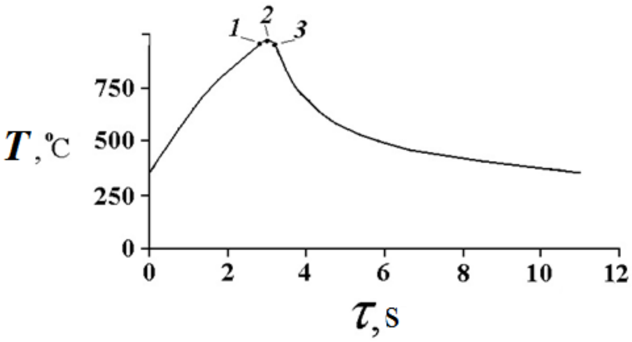


Figure 6 Parameters of the thermal cycle with thermal management

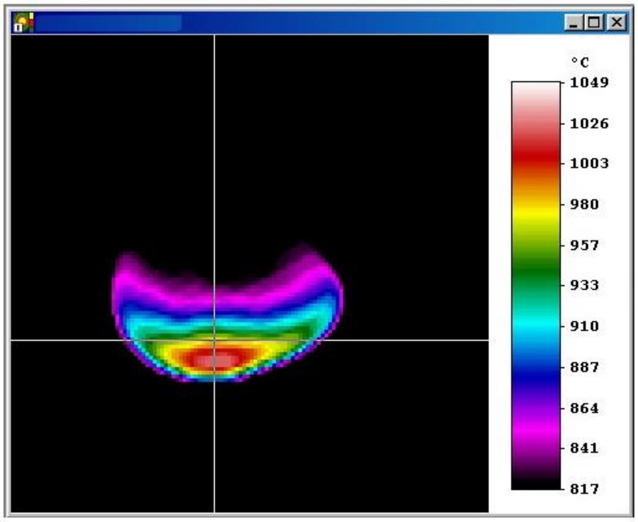


Figure 7 Thermal image of the sample with the thermal barrier ceramic barrier coating at the instant of switching off

As an example, Fig. 7 displays three thermal image of the blade model with the thermal barrier coating during induction heating. The temperatures at the surfaces of the ceramic coatings shown in the thermal image in Fig. 7 are equal to 969.4 °C (point 2). At the peak temperature, the indication of the control thermocouple on the sample (which corresponds to the lower edge of the thermal image) is approximately 60…70°C below the temperature of the outer layer of the coating (in the vicinity of the thermocouple), which is recorded by the thermal imager (Fig. 7).

The control thermocouple is fixed on the metal surface (locally protected against the ceramic coating) of the refractory layer. The temperatures of the thermal barrier coating and the refractory layer were recorded on the thermal imager simultaneously. The performed experimental investigations and measurements of the temperature of the part with the thermal barrier coating with the use of the thermal imager in the course of thermal cycling confirmed the calculated value of the temperature gradient across the ceramic coating thickness. Thus, the analysis of the results obtained has demonstrated that the thermostressed state observed for parts of the hot gas section of gas turbine engines (combustion chambers, turbine blades, etc.) during blowing them by a high-temperature gas flow under operating conditions can be simulated under laboratory conditions on a setup with high-frequency heating. The temperature gradient across the ceramic coating thickness can be varied over a wide range by varying the flow rate of air supplied for cooling, the power of the high-frequency generator, and the wall thickness. Thus, the analysis of the results of thermal fatigue tests of blades (Fig. 8) of gas turbine engines during thermal cycling according to the regime $t_{\min} \leftrightarrow t_{\max}$ (350 °C ↔ 900–1000 °C have shown that the thermal cyclic fatigue life of blades with a thermal-barrier ceramic coating deposited by the electron-beam method increases, on average, by a factor of 3.4 compared to the blades produced from the refractory nickel alloy without a coating. The photographs of turbine blades with a ceramic TBC and inductor under thermocyclic tests are presented in Fig. 9.

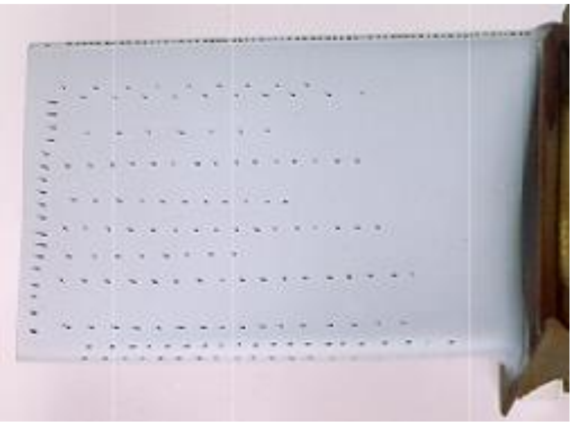


Figure 8 Blade feather with a thermal ceramic barrier coating before thermocyclic tests

The results of thermal fatigue tests of the blade models during thermal cycling according to the regime tmin ↔ tmax (350 °C ↔ 900 °C) have revealed that the service life of the models with a three-layer coating of the thickness h = 320-520 mm increases by a factor of approximately 2.7 compared to the models without a coating.

Figure 9 Thermocyclic tests of the turbine blades with thermal management

When designing aviation gas turbine engines, check for fan casing penetrability is envisaged by normative documents. Modern calculated methods of forecasting casing containment capabilities use a set of a priori limitations, and these methods can not give a reliable assessment of this event. Experimental checkup of casing containment capability of aero engines is one of the most important tasks with respect to ensuring flight safety. When the engine blade is released in the aircraft, serious damages of the frame may occur, as well as engine mount release, fire, e.t.c., which cause catastrophic effects. To decrease expenses for the engine operational development and to solve the mentioned problems it is purposeful to carry out stage-by-stage tests of the engine components on a spin rig. One of these problems, namely, localization of blade rupture inside the engine casing, is solved by carrying out fan casing containment test on the spin rig.

The blade releasing method is proposed for casing containment test on the spin rig. It's necessary to make calculations to determine conditions of the controlled blade-off under effect from centrifugal loads at a specified speed.

The developed blade releasing method [4] at tests has the following stages:

1. The computational modelling performed to determine the parameters of the cropped section of the blade: the dimensions of the edges and central part of the blade for achieving of the minimal safety factor.
2. Cutting of the blade.
3. Balancing of a rotor with the undercut blade.
4. The casing with the working wheel is set on the spin rig.
5. Testing:

5.1. The specified speed of rotation of a rotor achieved.

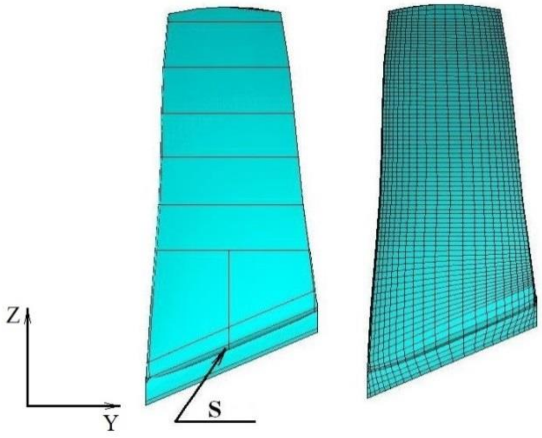
5.2. The central part of the undercut blade section heated up. The safety factor of the blade decreases when the temperature rises. The central part of the undercut blade section extended at the rise of the temperature with thermal management and centrifugal force transferred to the edges of the blade. The blade edges broke. Then centrifugal force transferred to the central part of the blade and the blade released on the specified speed.

5.3. The analysis of the test results.

The results of calculations of the rotor blade (Fig. 10) release conditions using finite element analysis and fan casing containment test are presented.

To calculate the conditions of the cut blade destruction, a temperature distribution shown in the Fig. 11 was used. At that the central cross-section will be unloaded with thermal management, and the blade will be broken due to initial rupture of the weakened cross-section zones near the edges. When computing the tensile load effecting each zone of the cross-section, with account of the temperature field formed with T_{max}= 320 °C, the results have been obtained.

Distribution of σ stresses in the cut cross-section of the blade is shown in the Fig. 12. This distribution has been obtained as a computation result of static stress-strained state in the zone of elasticity at the heater temperature of T_{max} = 320 °C. It can be seen from the figure that the cross-section zones, which are overloaded hardly, are those adjoining the blade edges.



a) b)

Figure 10 Solid model (a) and finite-element model (b) of the blade. Pressure side view. S - Specified cross-section

There are small zones with high stresses in the central cross-section. They do not influence significantly on the static strength of this cross-section as a whole. Stresses in the edge zones exceed significantly ultimate strength of the blade material.

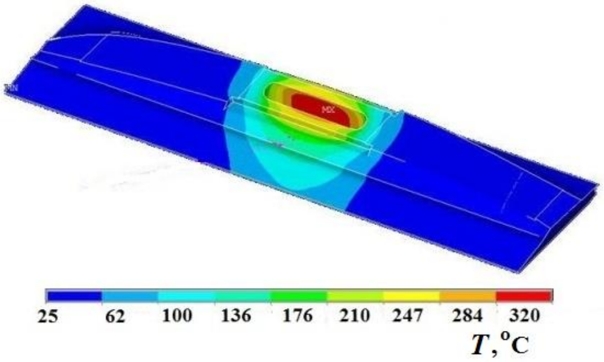


Figure 11 Temperature distribution in the cut cross-section of the blade

During breakdown of the edges the total load will be transferred to the central cross-section, which is warmed up to T_{max} = 320 °C and $T_{surface}$ = 200 °C, that will be followed by reduction of the safety factor to K < 1. Besides, the system balance will be violated and tangent stresses will appear. The load-carrying capability will be reduced approximately to 0,7 $\sigma_b \cdot S$; due to that one can expected that blade-off will occur under lower value of T_{max}.

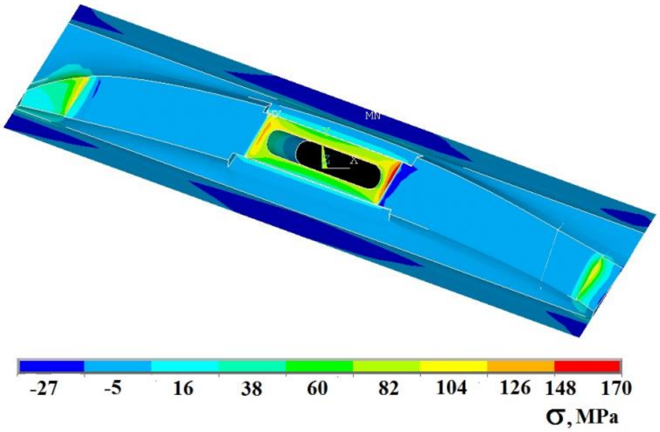


Figure 12 Distribution of stresses in the cut cross-section of the blade

The debug experimental investigations of the thermal state of the fan blade with the use of a thermal vision system (Fig 13) and blade releasing have been carried out on the special rig without rotation.

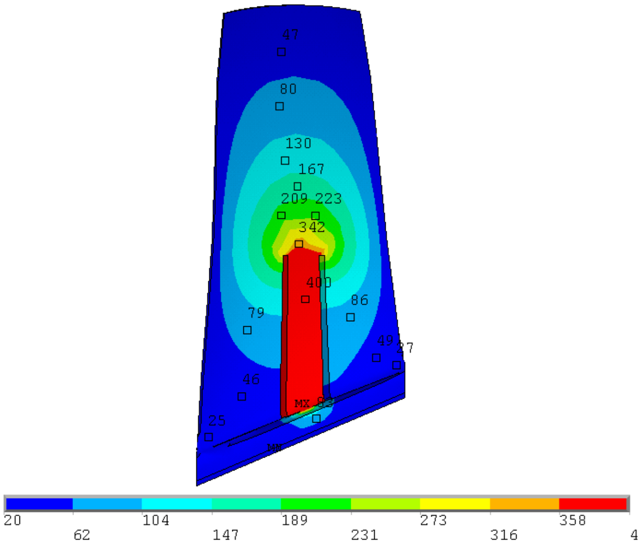


Figure 13 Temperature distribution in the cut cross-section of the blade (thermal image)

The fan casing containment test using developed release method with thermal management has been carried out on the spin rig.

CONCLUSION

The analysis of methods of heating for investigations of ceramic thermal barrier coatings of parts has been conducted. The induction heating was demonstrated to be effectively used during investigations of a thermal ceramic barrier coatings and tests for thermofatigue and thermo-mechanical fatigue of such gas-turbine engine parts with a ceramic coatings as the cooled turbine blades and vanes and combustion liner components. When using induction heating the surface heat-up of the part in the high-temperature gas flow is well modeled. It was shown that induction heating at a frequency 440 kHz may be successfully used for tests of the parts with a coatings. It was experimentally shown that when using such a heating method, the temperature of the outer ceramic coating surface exceeds the temperature of the metallic bond coat by 60…70 °C. Thus, a design-experiment method of high-frequency induction heating and thermophysical measurements in thermal cycling tests of blades with thermal management and other cooled parts with a ceramic coatings has been developed taking into account the electrophysical and thermophysical properties of their materials. The results of thermophysical measurements, design-experiment studies of the nonstationary thermal state of the parts with coatings with the use of a thermal vision system, and thermal cycling tests of blades and blade models with thermal barrier ceramic coatings are presented. Also there have been carried investigations of the thermal state of the fan blade with the use of a thermal vision system and blade releasing method with thermal management for fan casing containment tests.

REFERENCES

[1] Kuvaldin, A.B., Lepeshkin, A.R. High-speed modes of induction heating and thermostresses articles: monograpf. – *Novosibirsk: NSTU Publishing House*, 2006, 286 p.

[2] Rubashev, M.A., Presnov, V.A. Thermal dielectrics and their junction in new technologies, *Atomizdat,* Moscow, 1980.

[3] Tamarin, Yu.A., Kachanov, E.B. (2008). Properties of the Thermal Protective Coatings Rendered by Electron Beam Technology (New Technological Processes and Reliability of Gas Turbines Engines), CIAM, Moscow, №7, 2008, pp. 125-143.

[4] Lepeshkin, A.R., Bychkov, N.G., Nozhnitsky, Y.A. Method of casing containment test and device for its implementation, RU Patent 2371692, 2009.