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# METHOD FOR MODELING THE THERMAL STATE OF TURBINE BLADES OF AIRCRAFT ENGINES DURING THERMAL CYCLING TESTS

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## ABSTRACT

Test method for turbine cooled blades of gas turbine engines is developed. The new approaches during development of inductor structures, induction heating devices, cooling systems, hydraulic force loading system and methods for their design to provide the prescribed nonuniform heating the turbine cooled blades and to carry out more effective the thermocyclic tests are presented taking into account the developed test method. Study of effect of the clearances between inductor and blade surface and change of inductor efficiency on the thermal state of blade is presented. The test rig and improved systems of induction heating and mechanical loading are used to improve accuracy and simulate more complete the operating thermomechanical loading the full-scale cooled and uncooled blades at the thermocyclic tests. The results of rig testing the turbine cooled monocrystalline blades of gas turbine engine are received according to the developed test method.

## INTRODUCTION

The cooled and uncooled turbine blades are the most critical parts of aircraft gas turbine engines and they operate under high mechanical stresses from centrifugal forces and thermal stresses at high temperatures. The designs of cooled blades [Remchukov et al, 2020; Li et al, 2017] are being improved taking into account the increase in the gas temperature in front of the turbine in advanced aircraft engines. The temperature difference over the blade surface in the studied section can be 200–400 °C and more between the more heated elements of feather – edges and less heated middle. Such temperature drops occur during the non-stationary period of the gas turbine engine operation. When the gas temperature is increased suddenly, for example, at starting, acceleration trying, the rapid rise of temperature on the blade edges with heating rate of 100–200 K/s occurs. Sometimes the rates of heating can be more high. Arising in this case high thermostresses have the cyclic nature (repeat at each flight cycle), can change their sign during one flight cycle and can lead to the thermal fatigue of blade material.

Such conditions can be created with using the gas-dynamic rigs [Grinkrug et al, 2020] in which blades are flowed over by the gas flow of combustion products of aviation fuel or rigs of induction heating [Grinkrug et al, 2020; Wang et al, 2016; Bonnand and Pacou, 2016; Kuvaldin and Lepeshkin, 2019], taking into account axial loading (from the action of centrifugal forces). The rigs [Beghinia et al, 2017; Kukla et al, 2021; Geng et al, 2017] are designed to study high-temperature fatigue of turbine blades and their models using radiation heating and induction heating. Tests on gas-dynamic rigs simulate well the corrosion failure of blade surface. However, when using the existing gas dynamic rigs there is obtained relatively uniform temperature field along the height and over the sections of blade, therefore, under mechanical loading by the axial force through the bandage flange (that is necessary during testing the models of rotor blades) the failure will occur in the most thin section i.e. in the upper portion of blade while under the real conditions there is dangerous the middle section in which the active temperature and thermal stresses are maximal.

In comparison with sets where induction heating is used the tests of full-scale blades at the gas-dynamic rigs are very expensive. Set for blade-fatigue tests with induction heating allows to simulate their temperature field more precise.

Rigs with induction heating make it possible to more accurately simulate the heating rates and temperature field of turbine blades under the conditions of thermomechanical fatigue tests. The rigs [Wang, 2016; Bonnand and Pacou, 2016; Kukla et al, 2021; Geng et al, 2017] have disadvantages. On the rigs [Bonnand and Pacou, 2016 and Kukla, 2021] the

induction coils (multi-turn inductors) provide heating of the blade with small temperature differences (almost uniform heating). In addition, the rigs have one-piece designs of inductors [Wang et al, 2016; Bonnand and Pacou, 2016; Kukla et al, 2021; Geng et al, 2017] and have large gaps between the inductor and the part surface. This significantly reduces the efficiency of inductors [Wang et al, 2016; Bonnand and Pacou, 2016; Kukla et al, 2021; Geng et al, 2017].

The purpose of this work is to develop a computational and experimental method for tests of the cooled and uncooled turbine blades on a special rig with induction heating, which does not have the above disadvantages. In this method the relation $\Delta \leq 0.1 \cdot h$ (where $\Delta$ is the depth of current penetration, h is the minimum wall thickness of the cooled blade) must be satisfied to select the current frequency. Under high enough frequency (more than 400 kHz) the induction heating allows to simulate quite satisfactorily the gas heating and because of contouring the inductor the nonuniform temperature field is obtained in accordance with preset one. The advantages of the proposed method lie in the increased accuracy and more complete reproduction of the thermal state and thermomechanical loading of turbine blades during cyclic tests for thermomechanical fatigue. New approaches are used in the development of inductor designs that reduce the gaps between the inductor and the part, make the inductor split (from two plates) and increase the efficiency of inductors and induction heating.

## TEST RIG

For thermomechanical-fatigue tests of turbine cooled blades the original rig is presented on the figure 1.
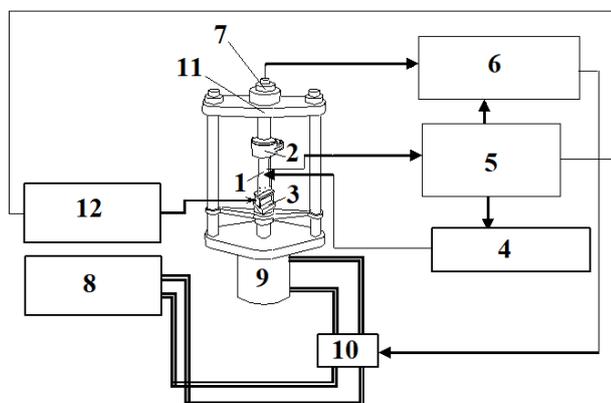


**Figure 1 Schema of the test rig: 1 – blade and inductor, 2 – top grip, 3 – bottom grip, 4 – high-frequency generator, 5 – temperature control unit, 6 – load control unit, 7 – strain gauge (tensor resistor), 8 – oil system, 9 – hydraulic cylinder, 10 – electric pneumatic valve, 11 – axial-tensile-force loading system, 12 – system of cooling-air supply into blade**

Above mentioned rig includes as follows: inductor, high-frequency generator, hydraulic system (oil system, hydraulic cylinder, electric pneumatic valve, axial-tensile-force loading system, temperature and load control units, strain gauge, system of cooling-air supply into blade, computer systems of temperature measuring and another systems.

In figure 2 the photograph of blade with inductor under thermal cyclic tests on the specified rig is presented.
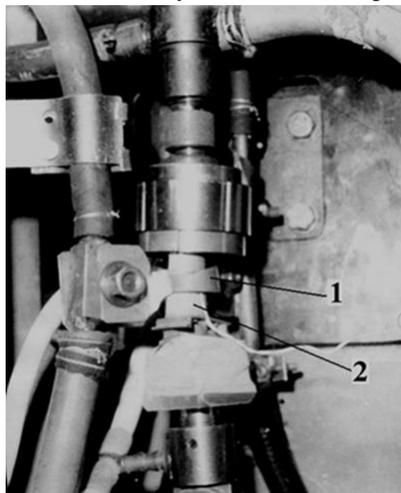


**Figure 2 Thermal cyclic tests of cooled blade at rig: 1 – inductor; 2 – blade**

Such inductor for nonuniform heating the blades is presented in figure 3 and has the inducting wire with varying width consisting of the following: two plates 1 with lead-outs (passing over the blade).
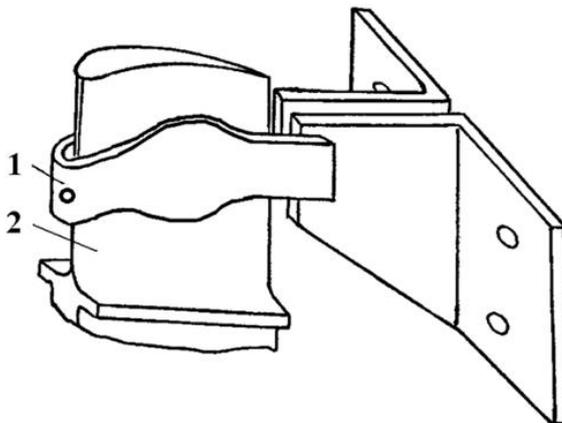


**Figure 3 Thermal cyclic tests of cooled blade at rig: 1 – inductor; 2 – blade**

## RESULTS AND DISCUSSION

Mathematical simulating the high-speed mode of high-frequency heating (at a frequency of 400 kHz) the cooled blade of gas turbine engine was carried out by developed finite-element program. The computational algorithm of the program is based on solving the coupled task of the electromagnetic field and the unsteady thermal state and thermostress state of the blade section in a two-dimensional setting taking into account complex boundary conditions [Kuvaldin and Lepeshkin, 2019]. In the computational algorithm the transient temperature of the turbine blade is determined based on the solution of the unsteady heat conduction equation. The transient temperature depends on the heating and cooling modes and on the time parameters of the thermal cycle during testing. In order to provide the specified thermal state of blade there were calculated the high-frequency generator [Kuvaldin and Lepeshkin, 2019] operating mode and varying profile of inductor over the contour of blade back and pan including the cooling-air flow in internal channels of blade. In this paper, the parameters presented in the figures have the following values: $\alpha$ – heat-emission coefficient, W/(m²K); L – blade section relative length; F – force, N; $\tau$ – time, s; P – power, kW; t – temperature, °C; $\sigma$ - thermal stress, MPa; h – inductor width, mm; $\eta$ – inductor efficiency; $\delta$ – clearance, mm. The calculated analysis of heat-emission coefficients (figure 4) in internal channels of blade showed that under rig conditions they are in average one-third as many as under operating conditions. The heat-emission coefficients in the internal air cooling channels of the blade was used in the computational analysis of the thermal state of the blade. The indicated heat-emission coefficients correspond to the rig conditions.

The value of maximal hydraulic force loading of 15000 N for simulation of axial tension of blade was obtained from the calculation of centrifugal load reduced to the dangerous section of blade and checked during static strain gauging. The maximum total stresses (thermal stresses and stresses from the action of centrifugal forces) are observed in the dangerous section of the turbine blade under operating conditions. The ambient-air temperature at all the modes of high-speed induction heating was taken as 20 °C.

Obtained results were used to conduct the tests of monocrystalline cooled turbine blades of gas turbine engines and turbine blades of turbopump units of liquid rocket engines. Cyclograms of hydraulic force loading, high-frequency generator operating mode and experimental changes of temperature and thermostresses at the portion of blade lip are given in figures 4 and 5.



(a)                                           (b)
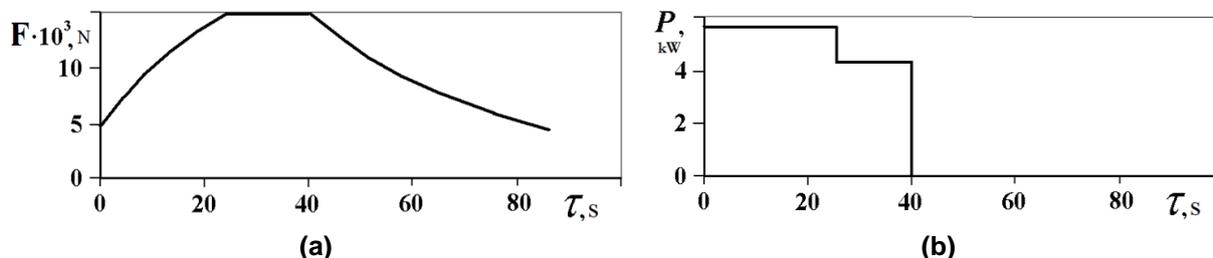
**Figure 4 Thermocyclic and mechanical loading the cooled blade of turbine at thermocyclic tests: (a) – cyclogram of axial-force F($\tau$) loading the blade; (b) – cyclic operating power mode P($\tau$) of high-frequency generator**

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**(a)**

**(b)**
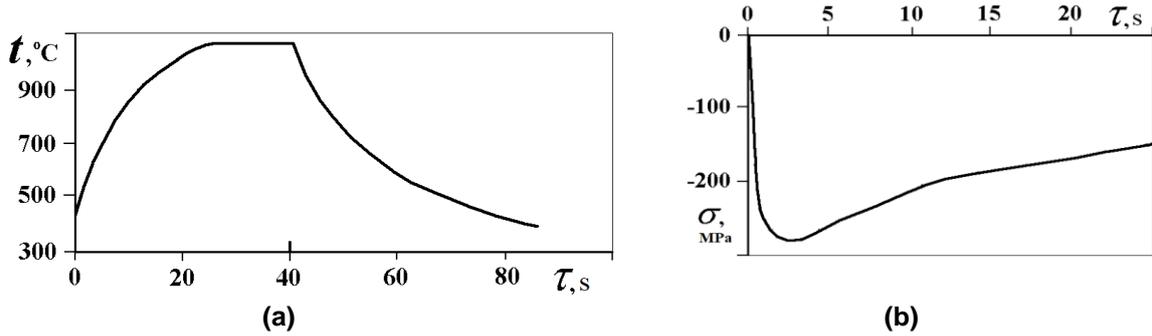
**Figure 5 Thermocyclic and mechanical loading the cooled blade of turbine at thermocyclic tests (a) – cyclic change of temperature t (τ) at portion of lip; (b) – change of thermostresses σ(τ) at portion of lip**

Figure 6 shows the preset and experimental temperature fields of blade (at the moment of time 30–40 seconds in figure 6(a) with considering varying profile of inductor (figure 7) at the thermal cyclic tests.



**(a)**

**(b)**
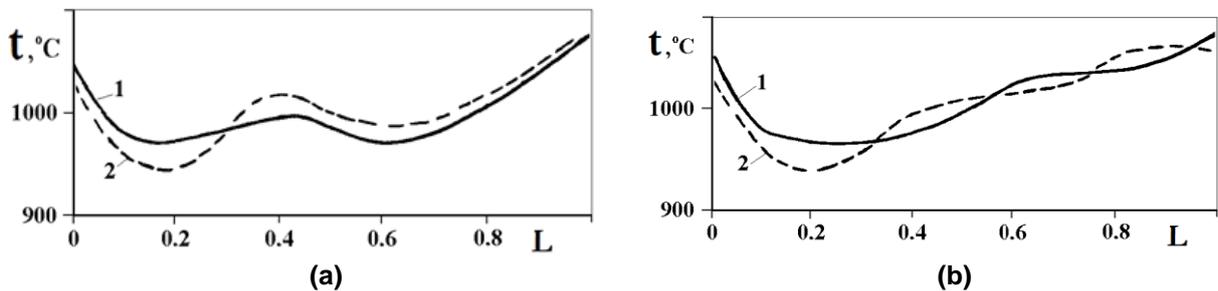
**Figure 6 Temperature distributions t(L) of cooled blade temperature at thermocyclic tests on surface of back (a) and pan (b): 1 – preset one; 2 – experimental one**



**(a)**

**(b)**
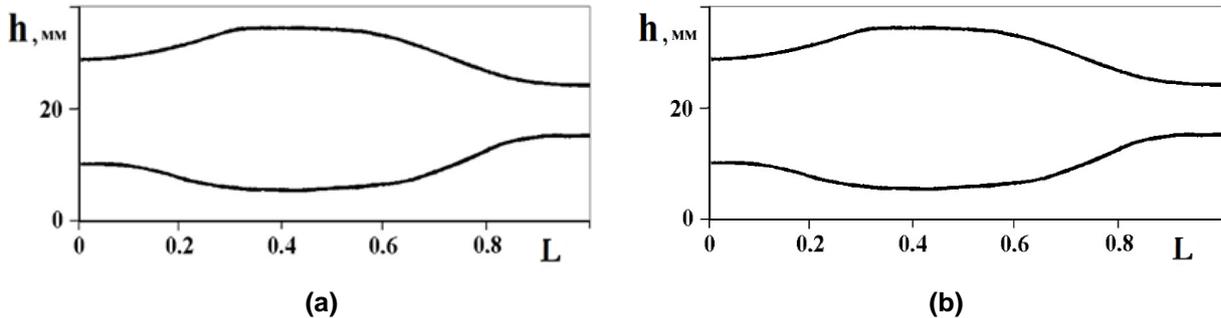
**Figure 7 Varying profile h(L) of inductor on side of blade back (a) and pan (b)**

Experimental temperature field obtained with using computer measuring system allowed more precise to maintain the experimental temperature field relative to preset one. In this case the maximal difference from preset temperature field was 20–25 °C.

With using final element method [Kuvaldin and Lepeshkin, 2019] according to experimental data of cooling-air flow and thermal state on the blade surface there were calculated the thermal and thermostress states (with taking account of axial tension) of studied blade at the mode tmax (figure 8 (a)) and change of thermostresses (figure 8 (b)) on the portion of lip within the cycle of loading.



**(a)**

**(b)**
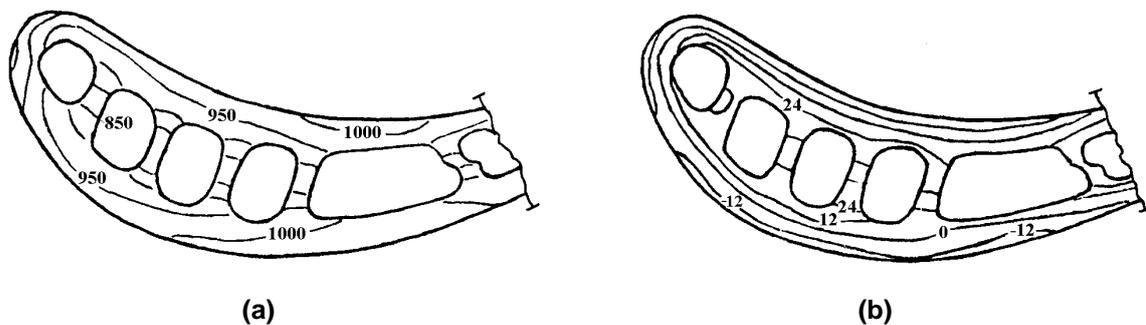
**Figure 8 Calculated thermal (a) and thermostress (b) states of blade during tests: temperature, °C; thermal stress, 10×MPa**

Results of rig testing the monocrystalline cooled blades of gas turbine engine turbine showed that the blades with [001] orientation have the average life 4 times as many as ones with [111] orientation.

The values of clearances between inductor and blade surface over its predetermined section effect on the thermal modes of blades. Experimental study of this effect on the thermal state of blade at the portion of exit edge is presented in figure 9. It follows from it that the experimental and calculated data by developed program have close agreement.
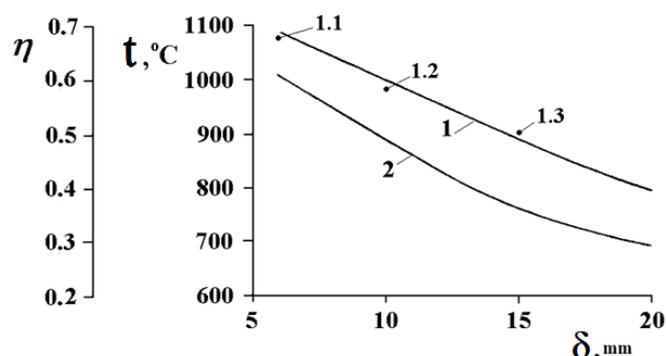


**Figure 9 Effect of clearance on blade temperature t and inductor efficiency η: 1 – calculated change of temperature at exit edge of cooled blade; 1.1, 1.2, 1.3 are experimental points of temperature values at exit edge; 2 – change of inductor efficiency**

## CONCLUSIONS

Test method for turbine cooled blades of gas turbine engines has been developed. The new approaches during development of inductor structures, induction heating devices, cooling systems, hydraulic force loading system and methods for their design to provide the prescribed nonuniform heating the full-scale cooled and uncooled blades of gas turbine engines and turbine blades of turbopump units of liquid rocket engines and to carry out more effective the thermocyclic tests have been presented taking into account the developed test method. Study of effect of the clearances between inductor and blade surface and change of inductor efficiency on the thermal state of blade was investigated. The test rig and improved systems of induction heating and mechanical loading were used to improve accuracy and simulate more complete the operating thermomechanical loading the full-scale cooled blades at the thermocyclic tests. The results of rig testing the monocrystalline turbine cooled blades of gas turbine engine showed that the blades with [001] orientation have the average life 4 times as many as ones with [111] orientation using the developed method.

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