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Investigations of thermomechanical fatigue for optimization of design and production process solutions for gas-turbine engine parts

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Abstract

A technique for thermomechanical fatigue of gas-turbine engine parts is discussed. It is shown that induction heating at a frequency of about 400 kHz is suitable for tests of parts with thermal barrier coatings (TBC). For thermocyclic tests at conditions when the radiant component of total thermal flow is significant, a rig with gas-flame heating has been developed. Some results of the tests are presented.
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Keywords: Thermomechanical fatigue; Thermocyclic tests; Gas-turbine engine part; TBC; Gasdynamic heating; High-frequency heating; Gas-flame heating

1. Introduction

Progress in aero-engine and gas-turbine manufacturing is continuously linked with a rise of operating temperature and stresses of engine gas path elements, especially the combustor and turbine parts. More advanced cooling systems, structural materials and coatings provide the required life and strength reliability of these components.

While engines are in use, the necessity arises to repair combustion liners, turbine blade and vanes. At the same time, it is difficult to estimate the durability of the combustor components, the turbine blades and vanes because of the complexity of simulation of the damaging factors acting under service conditions and also because of problems in obtaining the input data required for making such estimations [1].

Therefore, the development of methods for the experimental investigation of thermomechanical fatigue of engine parts is of great importance. While conducting these investigations, the main tasks are the comparative estimation of the design and production (or repair) process solutions and verification of the methods of calculation of the durability of engine parts. To provide simulation of loading conditions for the hot engine parts under service conditions, the test procedure shall ensure the possibility of cyclic surface heating of the object under testing (simulating its heating in hot gas flow) up to temperatures of 1150 °C and more (for parts with a TBC) at heating rates of 150–200 °C/s and subsequent cooling. Also it is desirable to have the possibility for mechanical loading of parts with a required phase shift between mechanical load and temperature.

2. Methods of heating under thermomechanical fatigue test

For providing the above-indicated heating conditions, there are various ways of heating such as gasdynamic heating and radiant heating, for example, in a reflective furnace electrical current (AC or DC) or induction heating with the use of high-frequency currents [2].

Gasdynamic (flowing hot gas) heating has been used for more than 50 years [2–10]. When using this method, a more accurate simulation of the heat exchange conditions from gas flow to the part is realized relevant to the gas-turbine engine. The rigs with gasdynamic heating enable a high heating rate to be provided to the part, to investigate the influence of oxidation in gas flow, but at the same time it

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is difficult to provide mechanical loading of parts [2–10]. The cost of tests using such rigs is very high and the bench equipment needs to be frequently repaired or replaced.

Alternating current (AC) or direct current (DC) resistance heating is effective for testing solid and tubular specimens. In accordance with this method, there is no need to use expensive and complex equipment. It enables tests to be conducted both at in-phase and at out-of-phase change of temperatures and mechanical loads. This method provides ease for inspection of the specimen surface. At the same time, this method cannot be used for tests of gas-turbine engine parts. The direct passing of electrical current can influence on the mechanical properties of the specimen material [3]. In addition, this method does not enable the actual conditions for part heating in gas flow to be simulated. When a specimen with a thermal barrier coating (TBC) is heated by direct passing of electrical current, the coating temperature is lower than the base material temperature.

Radiant heating of parts is of certain use when conducting the thermocyclic tests for specimens with TBC. In so doing the surface is heated at a high rate, however, because of radiation focusing during test of a part (or a part model) it is difficult to simulate the required temperature field. Additionally, the heaters have a low cyclic lifetime.

Evidently, induction heating with the use of high-frequency currents in the surface of a part is of greatest use to heat parts and models of parts when conducting tests for thermomechanical fatigue. Such a method may be used to test both standard specimens and engine parts. When it is used, the surface part heating realized under service conditions is well simulated. In so doing, heat releases directly in the part. There is no need to use expensive heating equipment, and the equipment used features of high durability. The mechanical loading device can be used in the rig with inductor heating. It provides the possibility of conducting thermomechanical fatigue tests of turbine blades. In so doing, with the use of a special inductor the temperature field is simulated for the blade section under the service conditions of which the strength margin is minimum and with the use of a suitable loading device, the centrifugal load is simulated in this section.

It is worth noting that induction heating is only effective for testing of metallic alloys. For tests of parts made of ceramic materials, it is recommended in a number of papers to use dielectric heating (in Mega Hertz frequency range) or heating with the use of a susceptor [2]. In the latter case, it is not possible to provide suitable heat-up rates for the temperature of the part.

As our investigations showed that when using currents of more than 440 kHz to heat a metallic part with a TBC, both heating of metal located under the external layer coating and the effective heating of the dielectric (TBC) take place. Correlation of heat shared depends on the thermophysical properties of the base and coating materials and the frequency at which heating is performed, and a number of other factors. The experiments showed that the ceramic ZrO_2 – based thermal barrier coatings on specimens and parts made of high-temperature nickel-based alloys are effectively heated at frequencies between 0.4 and 2 MHz. Use of a higher frequency requires a complicated rig design.

Consequently, it seems that in spite of a lack of data concerning the absence of a knowledge of the influence of induction heating on mechanical properties of the materials under investigation, this method of heating can be successfully used for tests of specimens and engine parts (primarily for comparative tests for selection of materials, design solution, manufacture and repair of engine parts production processes). The cost of the tests conducted with the use of high-frequency heating is by an order lower than the cost of the tests conducted on a gasdynamic rig.

3. Rig for thermomechanical fatigue tests with induction heating

As noted above, induction heating is the most effective heating method to be used when conducting thermocyclic tests and TMF investigations of engine turbine blades and combustion liner components.

The block diagram of the test rig developed and used at the Central Institute of Aviation Motors (CIAM) successfully for many years for conducting the thermomechanical fatigue tests of engine parts is shown in Fig. 1 [1].

For example, in Fig. 2 are shown the turbine blade (a) and the model specimen of combustion liner with TBC (b) that are mounted in the test rig.

The rig consists of a high-frequency generator (25 kW power, 440 kHz operating frequency), servo hydraulic loading devices, hydro pump, water and air provision system, control system, to provide the required phase shift between mechanical load and temperature, and a fixture for the object under test.

The rig enables heating (on part surfaces) up to 1600 °C to be performed, and loading with a tensile force up to 50 kN. The inductor design method developed at CIAM [11] allows the required thermal state of the part under test (for example, a turbine blade) to be obtained. The air cooling system has two contours. The internal contour provides continuous cooling of the inner cavity of the object under test. The external contour provides part blowing around a semi-cycle of cooling. The maximum flow of cooling air is 30 g/s. The cooling system allows nonisothermal thermomechanical part loading.

During tests of the specimens made of nickel-based alloys, the thickness of surface layer, in which at a frequency of 440 kHz 80% of energy releases in the form of heat, is less than 0.1 mm. This means that the blade surface heat-up taking place under service conditions is well simulated. It also releases about 15% of thermal energy in the TBC with a thickness of about 200 μm.

For testing a shroudless blade for thermomechanical fatigue, a technological shroud is welded to the blade. To