PROCEDURE AND ANALYSIS OF THREE-DIMENSIONAL THERMAL STRESSED STATES OF TURBINE BLADES WITH COATINGS SUBJECTED TO THERMAL CYCLING

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We propose a procedure of numerical analysis of three-dimensional thermal stressed states of machine parts with multiplier heat-shielding coatings based on the use of the SPACE finite-element software package. A detailed analysis of thermal and stressed states of wedge-shaped models simulating the blades of gas-turbine engines with coatings of different thickness subjected to thermal cycling is performed. The character of the influence of the thickness of coatings on thermal and stressed states in the half-cycles of heating and cooling is studied.

Among numerous problems encountered in the analysis of high-temperature strength of materials with coatings, the problems of thermal fatigue and estimation of admissible levels of thermal influence and thermal stressed states of systems of this sort prove to be the most important.

The efficiency of application of protective coatings largely depends on the optimal selection of the compositions of coatings, the procedure of their application, the ratio of their thickness, and reliable estimates of the durability of the entire composition with regard for all damaging factors. The solution of these problems requires the development of contemporary physical and mathematical methods of simulation of thermal stressed states and the kinetics of damage of structural components subjected to thermal and mechanical cycling and corrosive action of the combustion products. General approaches to the indicated problems and their partial solutions were developed at the Institute of Problems of Strength of the National Academy of Sciences of Ukraine [1].

It is reasonable to solve the problems of optimal heat-resistant and heat-shielding coatings used to protect the base material for a broad class of structural components [such as structural members of the circulation parts of gas-turbine engines (GTE) and internal-combustion engines] under conditions simulating or reproducing the action of basic damaging factors as correctly as possible. However, the methods used for the full-scale experimental investigation of the durability of structural components are too labor-consuming and the ranges of applied testing conditions are limited and can hardly be realized in the laboratory. Therefore, the procedures used for the numerical simulation of the thermal stressed states of coating-base systems are of great importance for the solution of the problems posed above.

Since the most stressed parts of structural components are observed in the regions with sharply varying cross sections (in particular, in the edges of GTE blades), it is desirable to simulate their stressed states for quite simple objects (plates, cylinders, and wedges) [1, 2]. In the present paper, we study a wedge-shaped model of a blade with heat-resistant coating used in testing metals, alloys, and heat-resistant coatings for thermal fatigue in gas flows (Fig. 1).

A procedure for the numerical analysis of the stressed states of turbine blades and similar objects in a quasi-3D formulation was originally proposed in [3–5] and developed in [5]. However, the application of the quasi-3D algorithm requires some restrictions to be imposed on the shape of a blade and the loading mode. Moreover, axial strains must obey a linear law. For parts made of several materials whose physical and mechanical properties differ significantly, this restriction cannot be realized in the general case. Therefore, in the numerical analysis of the wedge-shaped model of a blade with coating, the problem posed should be regarded as three-dimensional. In what follows, we describe a procedure used for the three-dimensional analysis of machine parts with multiplier heat-shielding coatings based on the use of the SPACE software package designed for the finite-element analysis of thermal and elastoplastic stress-strain state of structural components. The software package works with the MS DOS 6.2 and Windows 98 operating systems and includes the following functional utilities:
Fig. 1. Schematic diagram of a wedge-shaped model.

— control over the process of computations;
— construction of a geometric model;
— specification of boundary conditions for the problems of heat conduction and thermoelastoplasticity;
— solution of stationary and nonstationary problems of heat conduction;
— solution of problems of thermoelastoplasticity;
— service functions.

The process of control over computations is carried out in the interactive mode by choosing the required item from the main menu of the software package. Selecting an item from the menu, we initiate the operation of the corresponding functional utility. In the process of operation of the utilities used for the construction of the geometric model and specification of boundary conditions, and other utilities, the user has a possibility of visual observation of the object or its parts and may realize both the input of the initial data and the output of the numerical results.

The geometric simulation of three-dimensional bodies is performed by splitting these bodies into subregions that can be modeled by simple geometric objects (hexahedral or pentahedral prisms and tetrahedra) and applying the topological transformation of elementary objects. As a result, the three-dimensional body is represented as a union of geometrically simple subregions. The faces of the subregions can be described either by the equations of canonical surfaces or parametrically. The application of the canonical equations is possible if the faces bounding a subregion are parts of canonical surfaces (elliptic cylinders or tori, ellipsoids, and derived objects). For the parametric description of the surfaces, we use the method of transfinite mapping [6] based on the transformation of a reference geometric object to a topologically similar object. As reference objects, it is customary to use unit squares and triangles mapped on the surface of a subregion. The parametric representation is also used for the lines bounding the subregion.

The procedures realized in the software package are based on the use of both methods of description. This enables us to simulate quite complicated geometric forms. The discretization of a part of the surface is carried out by using the corresponding reference object.

The boundary conditions in the problems of a heat conduction and thermoelastoplasticity are specified in the interactive mode and the input data are displayed on the screen of the monitor. This enables us to check the correctness of the procedure of input.

Problems of nonstationary heat conduction are solved by the method of splitting with adaptive choice of the step of integration over time and Richardson’s extrapolation. The thermal stressed state is determined by using the mixed scheme of the finite-element method [7] guaranteeing the possibility of evaluation of strains and stresses with accuracy higher than that ensured by the classical approach [8]. The method of conjugate gradients is used for the solution of the linear algebraic equations.

The results of the analyses of thermal and thermoelastoplastic states are represented, by using special utilities, in the form of plots, isolines, and isobands.

The numerical analysis of the three-dimensional machine parts with protective coatings is quite difficult due to the small thickness of the coating. Thus, we encounter a problem of construction of the optimal finite-element mesh for a wedge with a coating that should contain at least three layers of finite elements across the thickness of the coating. Moreover, this mesh must be sufficiently dense at the edge of the wedge and less dense far from the edge. This is attained by using transient zones (Fig. 2) guaranteeing the possibility of smooth transition from a more dense mesh to a less dense one. In addition, the transient zones enable one not only to significantly decrease the dimensionality of the problem, but also to increase the accuracy of the numerical evaluation of stresses on the interface of the coating and the base material.