Stress-Strain State and Loss of Stability of Anisotropic Thermal Coating under Thermal Shock

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Abstract. The deformation behavior of thermal barrier coatings has been investigated. The mechanism of occurring instabilities in such coatings based on their representation in the form of a plate located on an elastic foundation has been studied. Loss of stability manifests itself in the form of a doubly periodic system of intrusion and extrusion zones that is qualitatively consistent with the well-known experimental results. Typical features of stability loss and its dependence on the properties of conjugated materials have been investigated by the example of the thermal loading simulation of the copper specimen with a protective ceramic coating. The influence of the thermo-mechanical properties anisotropy of the coating material on the character of the emerging instability has been estimated.

Keywords: thermal barrier coating, anisotropy, heat impact, effective mechanical properties, thermal characteristics, loss of stability

INTRODUCTION

Relevance of the research on the problem of thermal barrier coatings [1–5] is connected not only with the intensive use of thermal barrier coatings in the equipment of engineering and engine power. There is a continuous search for new materials, the use of which will raise the operating temperature of gas flows and increase the equipment life-time. The main problem of thermal barrier coatings is related to the difference in thermal characteristics, primarily the linear thermal expansion coefficient of brittle ceramic coating and plastic substrate. Research of thermal barrier coatings including simulation of their deformation behavior under operating loads has the purpose to identify the reasons for its failure and improve their design.

In this paper, using the classical approaches of the deformable solid mechanics by the example of thermal loading simulation of the copper specimen with a protective ceramic coating, the possibility of occurring instabilities that are periodic in nature is demonstrated, and their study depending on the properties of conjugated materials including the anisotropy of deformation and strength properties of the coating has been conducted.

Overall, the study includes the following stages of the analysis: solving the problem of the temperature distribution in the coating and the substrate in the transient state condition under the action of heat shock; estimating the parameters of the stress-strain state of the coating under the influence of thermal loads; simulating the stability loss process with examples of calculations for different geometrical and stiffness parameters of the coating and the substrate; evaluating stresses in the coating when instability.

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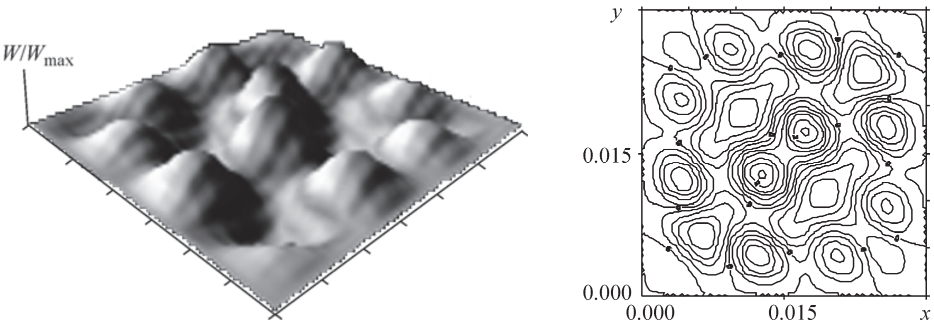

$\sigma_{11} = \sigma_{22} = 0.434 \times 10^9$ Pa $\quad h/a = h/b = 1/200$, $\alpha = -\pi/4$

FIGURE 1. Critical stresses and stability loss shapes of the orthotropic plate on an elastic foundation with rigid clamping edges. Orthotropic axes are rotated relative to the global axes at an angle α

COMPUTER AIDED DESIGN OF THE BEHAVIOR OF ANISOTROPIC THERMAL BARRIER COATING IN TRANSIENT STATE UNDER THERMAL SHOCK BEFORE THE LOSS OF STABILITY

In the plane formulation a computational area including the substrate and the thermal coating that undergo intense heat (thermal shock) directed from the coating surface is analyzed. In the calculations, the following characteristics have been used: aluminum oxide Al_2O_3—for thermal coating material, and copper Cu—for the substrate one. Specific heat of alumina C = 1106 J/kg·deg, density ρ = 3970 kg/m^3, coefficients of thermal conductivity in the direction of x and y axes are equal to $K_{xx} = K_{yy}$ = 40 W/m·deg. For the copper, specific heat C = 380 J/kg×deg density ρ = 8900 kg/m^3, thermal conductivity coefficients $K_{xx} = K_{yy}$ = 385 W/m·deg.

In [5], the computer aided design of the deformation behavior of isotropic thermal barrier coatings is presented. The possibility of occurring instability that is periodic in nature is shown. The research of the characteristic period dependence on the properties of conjugated materials has been conducted using the example of thermal loading copper specimen with a ceramic coating. For anisotropic thermal barrier coatings, the procedure for determining the temperature field and the calculation of stress-strain state is not changed fundamentally.

When calculating the orthotropic plate stability, the aluminum oxide layer on the copper substrate is modelled as a plate on Winkler elastic foundation. The question of finding the critical load for the plate lying on an elastic foundation is a matter of finding the differential equations eigenvalues in the partial derivatives. In this paper, the problem has been solved using the finite difference method. Stability equations digitization of the anisotropic plate by the finite difference method results in a system of the algebraic equations with a non-symmetric matrix should be noted.

For the calculations, the following characteristics have been used: elastic moduli E_1 = 380 ГПа, E_2 = 190 ГПа, G =80 ГПа, Poisson's ratios ν_1 = 0.30, ν_2 = 0.15. Coefficient of subgrade $k = 1\times10^{10}$ Н/м^3, coefficients of linear thermal expansion $\alpha_1 = 6\times10^{-6}$ K^{-1}, $\alpha_2 = 9\times10^{-6}$ K^{-1}. The ratio of the plate thickness to the side length along the x or y axes equals to $h/a = h/b = 1/200$.

It is shown that thermal shock causes loss of thermal coating stability. The stability loss shape is chessboard-like, but its "cells" are elongated in one direction. When rotate the axes of the orthotropy by 90° respectively, the picture of wave making at the loss of stability is rotated.

Figure 1 shows critical stresses and stability loss shapes when the orthotropic axes are rotated about the global axis at –45°, coefficient of subgrade $k = 1\times10^{10}$ N/m^3. In this case, the anisotropy is observed, the matrix of the elastic properties is full filled. From Fig. 1, one can easily see that the wave making picture is symmetrical about the orthotropy axes.

STRESS-STRAIN STATE OF THE ANISOTROPIC PLATE AFTER LOSS OF STABILITY DUE TO THERMAL SHOCK

As an example, the parameters of stress-strain state of the orthotropic plate on an elastic foundation after loss of stability are shown in Fig. 2.

Reducing the thickness of the coating (plate) and increasing in stiffness of the substrate lead to the increase in the number of half-waves for the fixed computational area and the decrease in their amplitudes. Magnitude of the stresses arising due to loss of stability depends not only on the absolute values of the deflection as the curvature of the coating surface occurs after the loss of stability, i.e. the second derivative value of the deflection surface along the axis. Furthermore, the stresses depend on the plate thickness. In this sense, the thickness affects the maximum stress values in two ways: on the one hand, with a decrease in coating thickness the number of waves increases as loss of stability leads to increased curvature, on the other hand—couple stresses are reduced as the so-called flexural rigidity of the plate reduces.

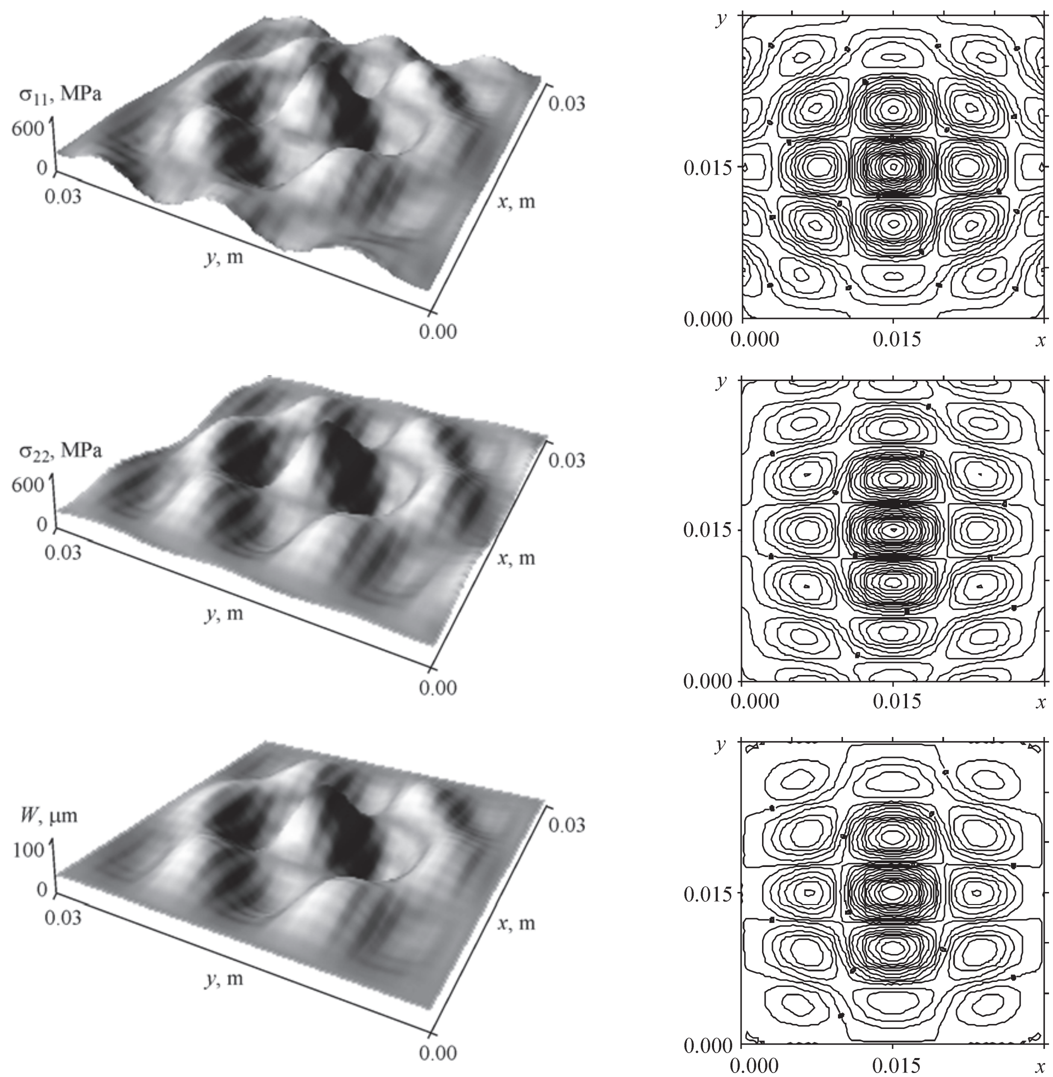

FIGURE 2. Stresses along the axes x, y in the orthotropic plate on an elastic foundation with loss of stability during heating. Deflection plate after the loss of stability. Relation $h/a = h/b = 1/200$. Coefficient of subgrade $K = 1\times10^{10}$ Н/м^3

This fact can be used for the parametric studies and the determination of the rational values of the coating thickness depending on the thermo-mechanical and thermal characteristics of the coating and substrate materials.

CONCLUSIONS

Under thermal shock in the initial moments of time when the substrate is still in its original cold state, a thermal coating experiences significant compressive stresses which can cause loss of stability of the thin-walled plate simulating this coating located on an elastic foundation (substrate).

When the loss of stability, the extreme stress values are arranged in the chessboard-like shape. If the physical and mechanical properties of the coating are anisotropic, the overall picture of stability loss is changing compared with the isotropic coating. Cells of "chessboard" are elongated along the axis which corresponds to a greater modulus.

When the loss of stability of the plate based on the elastic substrate occurs, the number of waves on the coating surface increases with the increase in rigidity of the elastic base and reduction of the ratio plate thickness to its width and length. In the calculations for the particular orthotropic coating it is shown that, in terms of square plates, there is a minimal number of half-waves along the axis with a large elastic modulus rather than along the axis of the orthotropy with a lower modulus of elasticity.

There is loss of stability of the anisotropic plate which orthotropy axis rotates relative to the global axes at 45° bulges and the dents are arranged symmetrically about the axes of orthotropy.

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