SOLUÇÃO DO PROBLEMA DE ESTABILIDADE TÉRMICA DE UMA CONSTRUÇÃO DE MADEIRA DE PAREDE FINA SOB EXPOSIÇÃO A CALOR INSTÁVEL QUE SURGE NO PROCESSO DE CRIAÇÃO DE PRODUTOS PELO MÉTODO DE SINTERIZAÇÃO LASER SELETIVA

SOLUTION OF THE PROBLEM OF THERMAL STABILITY OF A THIN-WALLED STRUCTURE UNDER NON-STATIONARY THERMAL ACTION ARISING IN THE PROCESS OF CREATING ARTICLES BY THE METHOD OF SELECTIVE LASER SINTERING

РЕШЕНИЕ ЗАДАЧИ ТЕРМОУСТОЙЧИВОСТИ ТОНКОСТЕННОЙ КОНСТРУКЦИИ ПРИ НЕСТАЦИОНАРНОМ ТЕПЛОВОМ ВОЗДЕЙСТВИИ, ВОЗНИКАЮЩЕМ В ПРОЦЕССЕ СОЗДАНИЯ ИЗДЕЛИЙ МЕТОДОМ СЕЛЕКТИВНОГО ЛАЗЕРНОГО СПЕКАНИЯ

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RESUMO

A estabilidade de temperatura de um elemento de estrutura de parede fina é estudada sob efeitos térmicos locais instáveis especificados em um lado do contorno. Um modelo bidimensional de elementos finitos de uma placa quadrangular presa ao longo de um lado do contorno é construído. O lado oposto do contorno da placa é influenciado por um fluxo de calor com uma fonte móvel, que simula o movimento do feixe de laser durante a formação aditiva de um elemento de parede fina. Foi obtida a solução numérica da tarefa dinâmica não estacionária de condução de calor, as dependências espaciotemporais da temperatura e as soluções do problema quase-estático de perda de estabilidade da forma plana do estado de equilíbrio da placa em diferentes pontos no tempo devido à ocorrência de tensões compressivas locais com aquecimento intenso. As dependências da potência crítica do fluxo de calor, correspondentes à perda de estabilidade da forma plana de equilíbrio, da espessura da placa são obtidas. Os resultados podem ser considerados mais tarde como uma primeira aproximação no estudo da possibilidade de uma deformação tecnológica para elementos estruturais de paredes finas fabricados com base em tecnologias aditivas da classe Laser Melting.

Palavras-chave: *síntese de camada por camada, estabilidade térmica, corpo crescente, tecnologias aditivas.*

ABSTRACT

The temperature stability of an element of a thin-walled structure under non-stationary local thermal action, given on one side of the contour, is studied. A two-dimensional finite-element model of a quadrangular plate clamped along one side of the contour is constructed. On the opposite side of the plate contour, there is a heat flow with a movable source simulating the motion of the laser beam in the course of the additive formation of the thin-walled element. Numerical solutions of the non-stationary dynamic heat conduction problem are obtained, spatiotemporal temperature dependences are obtained, and solutions are obtained for the quasistatic problem of the loss of stability of the plane form of the balanced condition of the plate at different points of time due to the appearance of local compressive stresses under intensive heating. Dependences of the critical power of the heat flow corresponding to the loss of stability of the plain form of equilibrium are obtained from the thickness of the plate. The given results can be considered subsequently as the first approximation when

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researching the possibility of technological deformations of thin-walled elements of the structures made on the basis of additive technologies of Laser Melting class.

Keywords: *layered synthesis, thermal stability, growing body, additive technologies.*

АННОТАЦИЯ

Исследуется температурная устойчивость элемента тонкостенной конструкции при нестационарном локальном тепловом воздействии, заданном на одной из сторон контура. Построена двумерная конечно-элементная модель четырехугольной пластины, защемленной по одной стороне контура. На противоположную сторону контура пластины действует тепловой поток с подвижным источником, моделирующим движение лазерного луча при аддитивном формировании тонкостенного элемента. Получены численные решения нестационарной динамической задачи теплопроводности, получены пространственно-временные зависимости температуры и получены решения квазистатической задачи о потере устойчивости плоской формы равновесного состояния пластины в различные моменты времени вследствие возникновения локальных сжимающих напряжений при интенсивном нагреве. Получены зависимости критической мощности теплового потока, соответствующие потере устойчивости плоской формы равновесия, от толщины пластины. Приведенные результаты могут рассматриваться впоследствии как первое приближение при исследовании возможности технологических поводок тонкостенных элементов конструкций, изготовляемых на базе аддитивных технологий класса Laser Melting.

Ключевые слова: *послойный синтез, термо-устойчивость, растущее тело, аддитивные технологии.*

INTRODUCTION

Additive Layer Manufacturing technologies for thin-walled elements of various purpose structures, including aerospace engineering products, are widely used methods of three-dimensional printing from polymeric, metallic and ceramic materials (Nazmeeva, 2013). Exhaustive information on the use of additive technologies in the aerospace industry is given in the review (Uriondo *et al.*, 2015; Bazhenov and Solovey, 2012). Additive technologies provide the possibility of forming structural elements of almost arbitrarily complex shape, moreover, they have sufficiently high mechanical characteristics close to those that are realized with the use of traditional technological processes, as shown by the authors of the work (Kablov, 2015; Formalev *et al.*, 2014; Grachev and Sokolov, 2012).

The use of layered laser synthesis methods for the manufacture of aerospace structure elements, among other things, makes it possible to obtain products with high mass efficiency (Uriondo *et al.*, 2015; Kakhramanov *et al.*, 2017; Afanasyev *et al.*, 2010). However, despite significant achievements, this technology is characterized by problems associated with a distortion of the original shape of the product after its molding, so-called technological "deformation" that is difficult to predict. On the other hand, finished products of complex configuration often have a pronounced residual stress state, the presence of which leads to a decrease in design loads on the product (Lapshin and Zhdanova, 2012; Galvão *et al.*, 2016).

There is a need for a preliminary prediction of the expected properties of products, both residual deformations and stresses (Buchbinder *et al.*, 2015; Bazhenov *et al.*, 2013); at the same time, a full-scale simulation based on the classical models of the mechanics of a deforming solid body is impossible or poorly accurate 9 (Gorodetski and Evzerov, 2007).

Nevertheless, consideration of high-gradient temperature stresses associated with the inhomogeneity of the temperature fields in the process of product synthesis is also possible on the basis of relatively simple models (Zhumarin, 2012; Kurazhova and Nazmeeva, 2011). In particular, the presence of local areas of compressive stresses can lead to stability loss by thin-walled products. Below we consider the linearized problem of the stability loss of a plain plate with edge local heating by a high-intensity radiation source simulating the action of a laser beam, and the critical source powers for its different positions on the contour are calculated.

METHODOLOGY

The dynamical heat conduction problem is solved with a further quasistationary calculation of the stability of a square plate under the action of a gradient temperature field (Pogorelov, 2005). The plate is a body in three-dimensional space bounded by the planes x=0, y=0, x=L, y=L, z=-h/2, z=h/2. The median surface is given by the plane z=0. The plate material is considered isotropic, and its properties are assumed to be independent of temperature. The homogeneous equation of heat conduction has the following formula (Equation 1).

As the boundary conditions on the face y=L, a flow moving with constant speed in the direction from x=0 to x=L, simulating the motion of the laser beam, is given. The flow rate is determined on the grounds of the known relation (Goldak *et al.*, 1984) (Equation 2), where P – the power of the laser used, r_0 – radius of the laser beam, r – radial distance from the central point of the heating spot, η – coefficient of efficiency of the heat input (absorption efficiency). On the other faces, the condition of thermal insulation is given in Equation (3). The temperature field obtained as a result of solving the heat conduction problem is a load in the problem of stability loss.

The problem of the stability of plates reduces to the integration of two joint partial differential equations of the fourth order (Ogibalov and Gribanov, 1968; Egorova *et al.*, 2014) (Equation 4), where $K=\frac{Eh^3}{12(1-\nu^2)}$, Δ - Laplace operator, E - modulus of elasticity, ν - Poisson's ratio, α - coefficient of linear thermal expansion, w - deflection of the plate (Equation 5). Φ – stress function satisfying the following conditions (Equation 6). Here N_x, N_y, N_{xy} - internal forces in the plate. As boundary conditions, hard fixations of the plate along the faces x=0, x=L, y=0 are considered in the following form (Equation 7).

RESULTS AND DISCUSSION:

In order to solve the problem, it is expedient to resort to the finite element method (Goryunov *et al.*, 2013). Figure 1 shows the finite element model of the plate. The problem was solved in dimensionless quantities. The power of the laser beam, the length of the plate and the time of passage of the laser beam along the length of the square is taken to be equal to 1. The thickness of the plate is a parameter and it varies from 0.005 to 0.03.

When solving the heat conduction problem, a heat flow is set on the upper face of the plate, moving at a constant speed. The remaining surfaces are thermally insulated. Figure 2 shows the solution of the problem at different points of time. For each time point in the quasi-static formulation, the problem of stability loss under the influence of an inhomogeneous temperature field was solved from the previous calculation. The solution showed that the "worst", from the point of view of stability, is the time point 0.5, which corresponds to the smallest eigenvalue equal to 64.8 and the first form of stability loss is close to symmetric (Figure 3).

A parametric analysis was also performed to determine the value of the first eigenvalue at time point 0.5, which corresponds to the most dangerous location of the source, depending on the thickness of the plate. The resulting diagram is shown in Figure 4. Based on the dependence obtained, a correspondence is made between the permissible plate thicknesses and the critical powers of the heat source for the most dangerous source locations. For a given thickness, the maximum permissible power is selected according to the formula (2), in which the flow value must be increased to the proper number of times corresponding to (Figure 4).

The most dangerous zone for the passage of a heat source is the central point of the edge of the plate since in this case, the greatest number of areas with a high-temperature gradient arises. When solving the corresponding problem of stability loss, the first eigenvalue becomes the smallest.

CONCLUSIONS:

The problem of thermal stability of a thin-walled structure under the action of a movable heat source is formulated. The finite element model of the plate is constructed, one side of which is effected by a movable heat flow simulating the motion of the laser beam. Numerical solutions of the dynamic heat conduction problem and a quasistatic problem of stability loss at different points of time are obtained. Parametrization is carried out and the dependence of the critical flow power on the thickness of the plate is obtained.

The results obtained make it possible to create a technique for selecting the thicknesses of parts and the optimal operating conditions for laser heat sources used in additive layer manufacturing. Also, the constructed mathematical model can be implemented in standard software systems supporting user behavior models of material such as Ansys, Abaqus, Comsol and it can be a criterion for the design of a product performed by selective laser sintering method.

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$$\frac{\partial T}{\partial t} - a^2 \Delta T = 0, \quad t > 0 \tag{1}$$

$$q_0 = \frac{2\eta P}{\pi r_0^2} e^{\frac{-2r^2}{r_0^2}} \tag{2}$$

$$-n \cdot q = 0\,. \tag{3}$$

$$\begin{aligned} \Delta\Delta\Phi &= -E\left(\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - \left(\frac{\partial^2 w}{\partial x \partial y}\right)^2\right) - E\alpha \Delta T_N, \\ K\Delta\Delta w &= h\left(\frac{\partial^2 \Phi}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial x^2}\frac{\partial^2 \Phi}{\partial y^2} - 2\frac{\partial^2 w}{\partial x \partial y}\frac{\partial^2 \Phi}{\partial x \partial y}\right) - \frac{E\alpha h^2}{1-\nu}\Delta T_M \end{aligned} \tag{4}$$

$$T_N = \frac{1}{h}\int_{-\frac{h}{2}}^{\frac{h}{2}} T dz, \quad T_M = \frac{1}{h^2}\int_{-\frac{h}{2}}^{\frac{h}{2}} Tz dz. \tag{5}$$

$$N_x = h\frac{\partial^2 \Phi}{\partial y^2}, N_y = h\frac{\partial^2 \Phi}{\partial x^2}, N_{xy} = h\frac{\partial^2 \Phi}{\partial x \partial y}. \tag{6}$$

$$\begin{aligned} &u = v = w = 0 \\ &\frac{\partial u}{\partial x} = \frac{\partial u}{\partial y} = \frac{\partial v}{\partial x} = \frac{\partial v}{\partial y} = \frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = 0 \end{aligned} \tag{7}$$

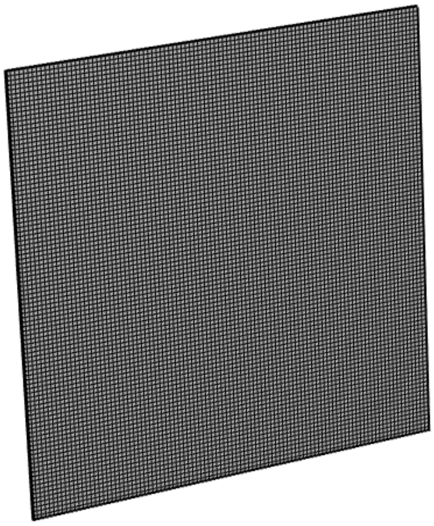
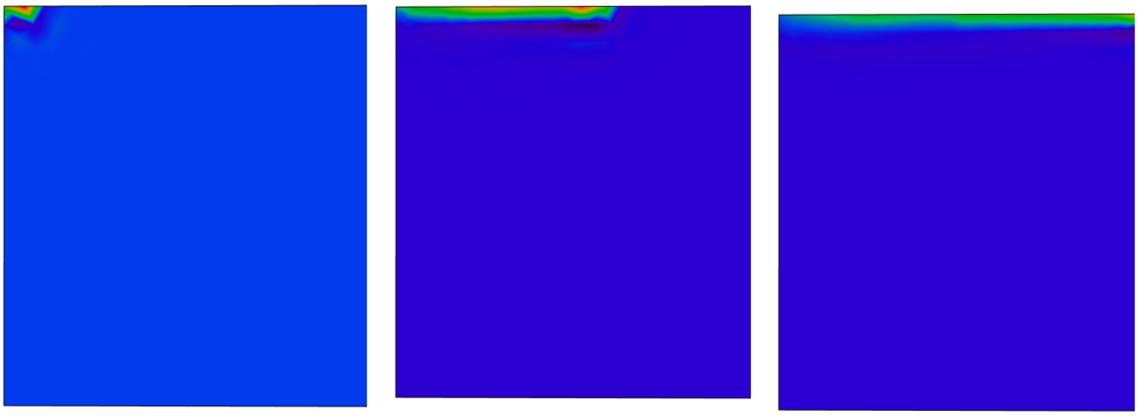


Figure 1. *Finite element model of the plate*



A) B) C)

Figure 2. *Temperature field at different points of time. (A – time 0.1, B – time 0.5, C – time 1)*

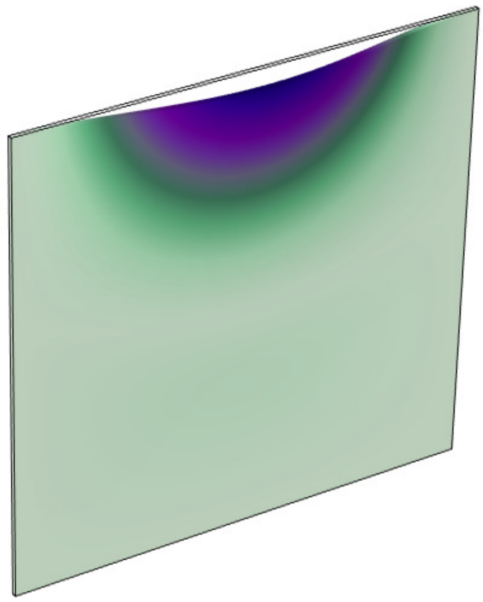


Figure 3. *The first form of stability loss at time point 0.5*

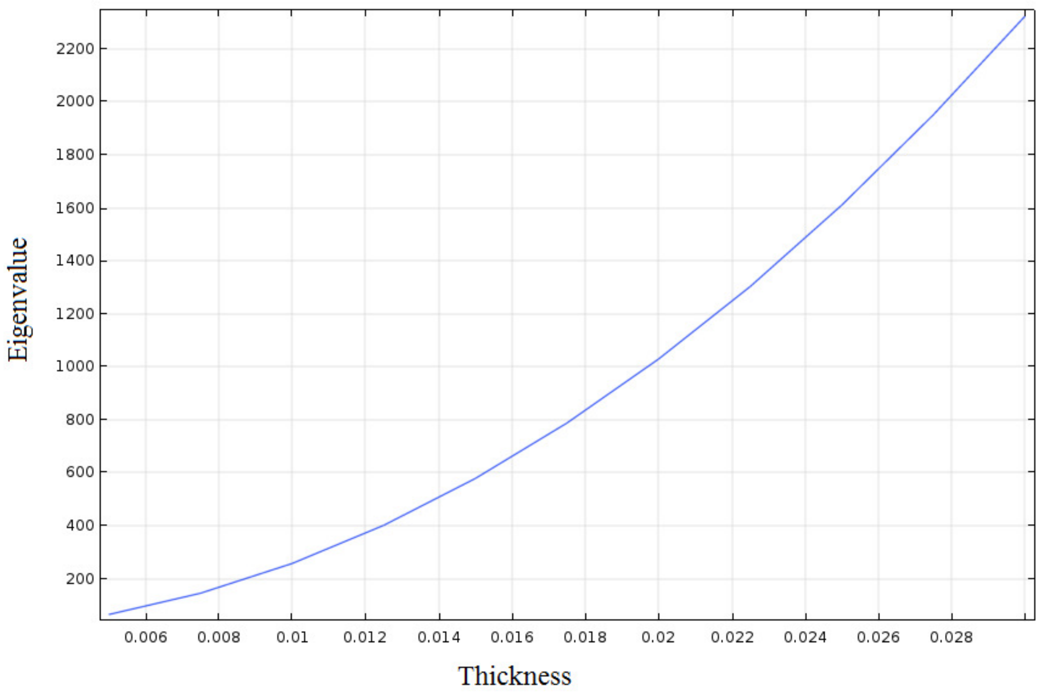


Figure 4*. Dependence of the first eigenvalue at time point 0.5 depending on thickness*