PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

VALIDAÇÃO DE METODOLOGIA PARA MODELAR EFEITOS DE PERDA DE ESTABILIDADE EM PEÇAS DE PAREDES FINAIS FABRICADAS USANDO A TECNOLOGIA SLM

VALIDATION OF METHODOLOGY FOR MODELING EFFECTS OF LOSS OF STABILITY IN THIN-WALLED PARTS MANUFACTURED USING SLM TECHNOLOGY

ВАЛИДАЦИЯ МЕТОДИКИ МОДЕЛИРОВАНИЯ ЭФФЕКТОВ ПОТЕРИ УСТОЙЧИВОСТИ ТОНКОСТЕННЫХ ДЕТАЛЕЙ, ИЗГОТАВЛИВАЕМЫХ С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИИ SLM

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RESUMO

As tecnologias de manufatura aditiva possibilitam fabricar qualquer produto em camadas com base no modelo de computador 3D, mas esse problema não é bem conhecido. Portanto, o artigo considera o problema de descrever os efeitos da perda de estabilidade decorrente da impressão tridimensional de produtos que contenham elementos cujo comprimento exceda significativamente a espessura ou o tamanho característico da seção transversal. O comportamento de tais elementos, do ponto de vista da mecânica dos materiais, pode ser descrito usando modelos de placas ou vigas. Foram comparados os resultados dos cálculos obtidos usando o modelo de condutividade térmica e termoelasticidade não estacionária com dados experimentais para o elemento específico do produto impresso no qual ocorre perda de estabilidade. Foi constatado que, nos momentos iniciais, é realizado o menor coeficiente de impacto crítico, o que, por sua vez, o torna o fenômeno mais perigoso. A possibilidade de alterar os parâmetros de impressão e a geometria do produto para excluir esses efeitos foi investigada. O elemento estrutural considerado pode perder estabilidade durante o processo de construção. Os resultados da solução do problema espectral mostraram que, com o tempo, o valor do efeito crítico diminui e tende assintoticamente a um valor mínimo fixo.

Palavras-chave: *fusão seletiva a laser, estado termomecânico, estruturas de paredes finas, tensão residual, validação.*

ABSTRACT

Additive manufacturing technologies make it possible to manufacture any product in layers based on a 3D computer model, but this issue is understudied. Therefore, this paper considers the problem of describing the effects of buckling arising in the three-dimensional printing of products containing elements whose length significantly exceeds their thickness or the characteristic size of the cross section. The behavior of these elements, from the point of view of material mechanics, can be described using models of plates or beams. In this study, we compare the results of calculations obtained using the model of non-stationary thermal conductivity and thermos-elasticity with experimental data for a specific element of printed product in which stability loss occurs. It was concluded that, at the initial moments of time, the lowest critical impact coefficient is realized, which in turn makes it the most dangerous phenomenon. The possibility of changing print parameters and product geometry to exclude the mentioned effects has been investigated. The considered structural element may lose stability during the building process. The results of solving the spectral problem indicated that over time the value of the critical effect decreases and asymptotically tends to a fixed minimum value.

Keywords: *selective laser melting, thermomechanical state, thin-walled structures, residual stress, validation.*

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АННОТАЦИЯ

Аддитивные технологии производства позволяют изготавливать любое изделие послойно на основе компьютерной 3D-модели, но данный вопрос не является хорошо изученным. Поэтому в работе рассматривается проблема описания эффектов потери устойчивости, возникающих при трехмерной печати изделий, содержащих элементы, длина которых значительно превышает их толщину или характерный размер поперечного сечения. Поведение таких элементов, с точки зрения механики материалов, может быть описано с использованием моделей пластин или балок. В настоящей работе проводится сопоставление результатов расчетов, полученных с использованием модели нестационарной теплопроводности и термоупругости, с экспериментальными данными для конкретного элемента напечатанного изделия, в котором произошла потеря устойчивости. Одним из выводов, которые авторы представляют в статье, является то, что в начальных моментах времени реализуется наименьший коэффициент критического воздействия, что в свою очередь делает его наиболее опасными явлением. Исследована возможность изменения параметров печати и геометрии изделия для исключения данных эффектов. Рассмотренный элемент конструкции может терять устойчивость в процессе наращивания. Результаты решения спектральной задачи показали, что с течением времени значение критического воздействия уменьшается и асимптотически стремится к фиксированному минимальному значению.

Ключевые слова: *селективное лазерное сплавление, термомеханическое состояние, тонкостенные конструкции, остаточное напряжение, валидация.*

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1. INTRODUCTION

The problem of predicting the residual stress-strain state of products obtained by methods of additive technologies is not completely resolved yet (Luo and Zhao, 2018; Yan *et al.*, 2018). This problem is in many respects similar to the known effects arising in the process of welding metal products (Dong and Brust, 2000), which were thoroughly researched and largely solved in the 1970-1990s. In three-dimensional product printing, the volume of added material is much more significant than in welding, and description of these processes requires development of new algorithms that take into account the increase of the part, the multiscale nature of the processes that are being implemented, and the thermal and thermomechanical state of various parts of the product under local intense heating from moving source (Kim *et al.*, 2004; Kakhramanov *et al.*, 2017; Ngo *et al.*, 2018; Bandyopadhyay and Traxel, 2018).

In this study, we consider the problem of describing unusual defects that may occur during three-dimensional printing of thin-walled parts, and which are associated with the phenomenon of loss of stability through the action of macroscopic fields of compressive stresses that arise in some versions of the product geometry when they are unevenly heated (Santos *et al.*, 2018). A specific example of a core element was considered, during printing of which these effects appeared and led to its curvature, which is unacceptable from the point of view of using the construction (Fig. 1). The product was created from 316 l steel and manufactured using standard printing settings on a Renishaw laser fusion system.

2. MATERIALS AND METHODS

The problem of modeling the thermomechanical state of synthesized product in three-dimensional quasi-static formulation of the problem of thermo-elasticity was considered. External influence follows from solutions of problem of unsteady heat conduction. Equations of the static equilibrium have the form (Equation 1). Kinematic relations correspond to geometrically linear theory of elasticity for plane elements (Equation 2). The defining equations of linear thermos-elastic medium have the form (Equation 3), where temperature field follows from solution of the heat conduction problem described below. Boundary conditions correspond to rigid termination of one of the side surfaces, the remaining side surfaces were free from bonds. Front surfaces were also free (Equation 4). The heat conduction problem was considered in unsteady setting for plane elements (Equation 5). At boundary conditions corresponding to absence of heat exchange with the external environment (Equation 6) and in homogeneous initial conditions (Equation 7). On one of the lateral surfaces, the field of heat flux vector with finite carrier was set, directed normally to the given surface and decreasing exponentially. The position of non-zero flux is defined by the point modeling center of the spot of the laser beam (Equation 8).

The accepted law of distribution of amplitude of heat flux over time is presented in Figure 2. The solution to heat conduction problem has general form $T = T(x, y, z, t)$.

The problem was being solved using the finite element method. Since the geometric areas of calculation were parameterized, then for each set of parameters its own finite element mesh was used for each types of analysis. The grid was formed by volumetric tetrahedral four-node elements. Thermomechanical state of parts at various stages of the synthesis was simulated (Fig. 3). The model was fixed by the end surfaces. In the heat conduction problem, initial and boundary conditions (Equations 6–7) are applied to all surfaces. A laser source impacts the model in the center of the upper plane (Equation 8). The problem can be solved in an unsteady setting. The solution of the problem of thermal conductivity will be the temperature field specified in the table at the points corresponding to nodes of the finite element grid $T = T_{i,k}$ (*i* – is the node number, *k* – is the moment of time).The linear thermos-elasticity problem can be solved numerically in three-dimensional formulation. Lower side surface is rigidly pinched (Equation 4). The temperature field is used as a load at a fixed moment of time in accordance with the solution of previous problem. In this calculation, the allowable exposure time in one zone and the critical impact value at which the “deformation” of the structural element occurs were analyzed.

3. RESULTS AND DISCUSSION:

The obtained solution of thermos-elasticity problem corresponds to the subcritical state of simulated system. The problem of stability of the equilibrium state for discrete analogue of original problem is considered in the bifurcation formulation, that is, it can be reduced to the eigenvalue problem for the operator of homogeneous initial-boundary value problem of bending deformation under strains corresponding to the thermos-elasticity problem. Then, the temperature field generated by source and causing subcritical stress state acts as one-parameter loading of the system. The load parameter will be the coefficient at the amplitude of heat flux, i.e. (Equation 9).

The result of solving the spectral problem can be a set of eigenvalues and eigenvectors of a discrete analogue of the original problem, while the smallest positive value is taken as critical. Similar problems with the study of temperature effects were considered in works (Knyazeva et al., 2007; Riedlbauer et al., 2012; Keller et al., 2013; Lurie *et al*., 2015; Formalev and Kolesnik, 2018; Rabinsky and Tushavina, 2019a; Rabinskiy and Tushavina, 2019b; Formalev and Kolesnik, 2019).

The result of integrating the equations of unsteady heat conduction was a solution in form of isothermal contours similar to concentric circles, while the density decreased with increasing time (temperature gradients decreased). When calculating the linear thermos-elasticity problem, the obtained stress fields had high gradients at the initial time instants, which quickly decreased over time. Figure 4 shows kinds of the first form of buckling for various degrees of body growth.

The results of solving the spectral problem have demonstrated that over time the value of critical effect decreases and asymptotically tends to a fixed minimum value. Figure 5 shows graphs of the dependence of logarithm of coefficient of critical impact on time.

4. CONCLUSIONS:

Based on the results obtained, the following conclusions can be made. The considered structural element may lose stability during the growing process. The most dangerous are initial moments of time, since the smallest critical impact coefficient is realized in them. To ensure a stable growth process, we should implement the following measures:

– to provide maximum number of supporting elements, since an increase in the number of bonds will raise the value of critical impact coefficient;

– to realize a high speed of the laser beam, in order to prevent overheating of a local zone, which will lead to "deformation";

– to reduce the thermal effect, if possible, minimize the power of the laser beam at the initial stages of element formation, if this is permissible in terms of working process.

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$$\begin{aligned}
&\frac{\partial \sigma_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}=0,\\
&\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \sigma_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}=0,\\
&\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \sigma_{zz}}{\partial z}=0.
\end{aligned} \qquad \text{(Eq. 1)}$$

$$\begin{aligned}
&\varepsilon_{xx}=\frac{\partial u_x}{\partial x},\ \varepsilon_{yy}=\frac{\partial u_y}{\partial y},\ \varepsilon_{zz}=\frac{\partial u_z}{\partial z},\\
&\varepsilon_{xy}=\frac{1}{2}\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right),\\
&\varepsilon_{yz}=\frac{1}{2}\left(\frac{\partial u_y}{\partial z}+\frac{\partial u_z}{\partial y}\right),\\
&\varepsilon_{xz}=\frac{1}{2}\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right),
\end{aligned} \qquad \text{(Eq. 2)}$$

$$\begin{aligned}
\sigma_{xx} &= \lambda(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})+2\mu\varepsilon_{xx}-(3\lambda+2\mu)\alpha T,\\
\sigma_{yy} &= \lambda(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})+2\mu\varepsilon_{yy}-(3\lambda+2\mu)\alpha T,\\
\sigma_{zz} &= \lambda(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})+2\mu\varepsilon_{zz}-(3\lambda+2\mu)\alpha T,\\
\sigma_{xy} &= 2\mu\varepsilon_{xy}, \sigma_{yz} = 2\mu\varepsilon_{yz}, \sigma_{xz} = 2\mu\varepsilon_{xz}.
\end{aligned} \qquad \text{(Eq. 3)}$$

$$u_x = u_y = u_z = 0,\ z = 0, \qquad \text{(Eq. 4)}$$

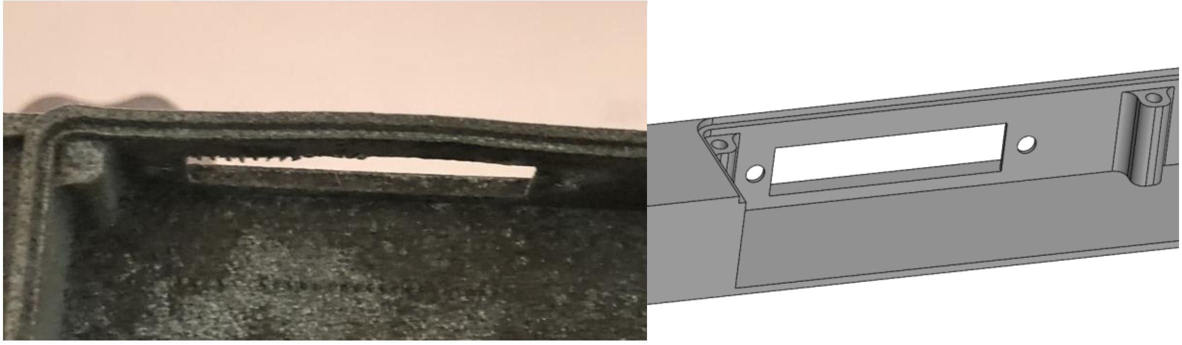
$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{Q}{\rho c}, \qquad \text{(Eq. 5)}$$

$$-nq = 0, \qquad \text{(Eq. 6)}$$

$$T = 0,\ t = 0. \qquad \text{(Eq. 7)}$$

$$q0 = \frac{2\eta P}{\pi r_0^2} e^{\frac{-2r2}{r_0^2}} \qquad \text{(Eq. 8)}$$

$$q0 = \lambda \frac{2\eta P}{\pi r_0^2} e^{\frac{-2r2}{r_0^2}} \qquad \text{(Eq. 9)}$$



a *b*

Figure 1. *Fragment of product in which the loss of stability occurred, a: initial geometry of model, b: manufactured product containing defect*

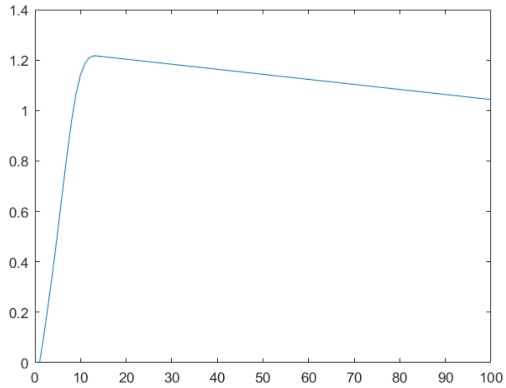
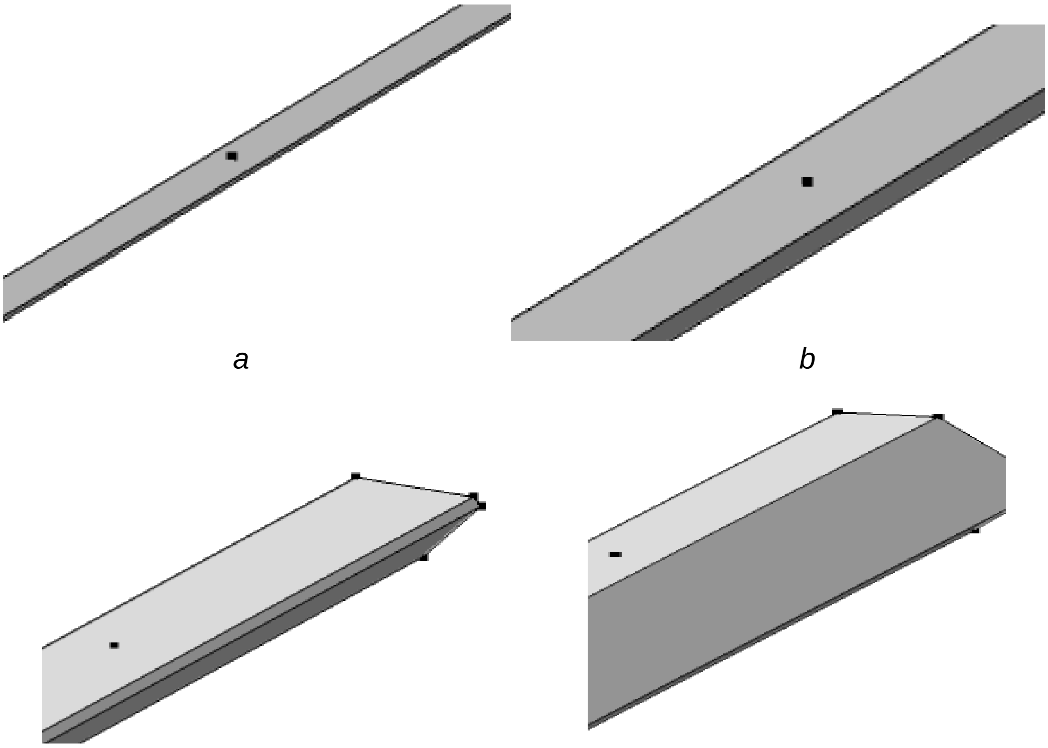


Figure 2.*The accepted law of distribution of amplitude of the heat flux in time*



a *b*

c *d*

Figure 3. *Element geometry for 10%, 25%, 50% and 100% of growth*

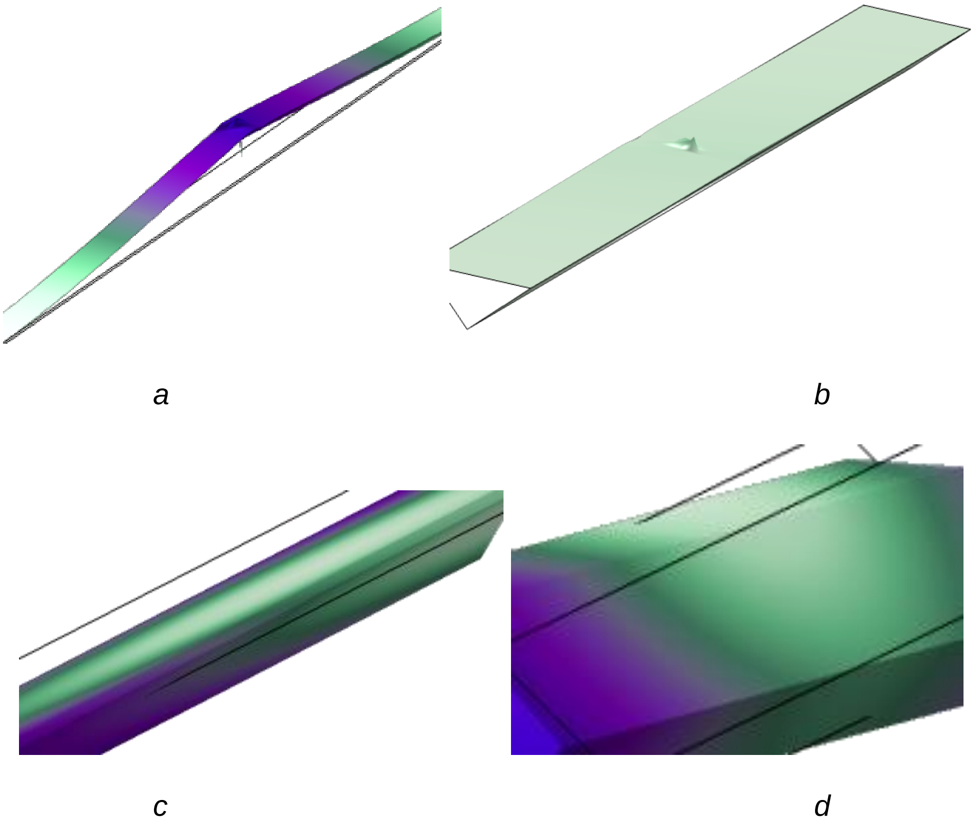


Figure 4. *The first form of stability loss (a -10%, b – 25%, c – 50 %, and d – 100% of part growth)*

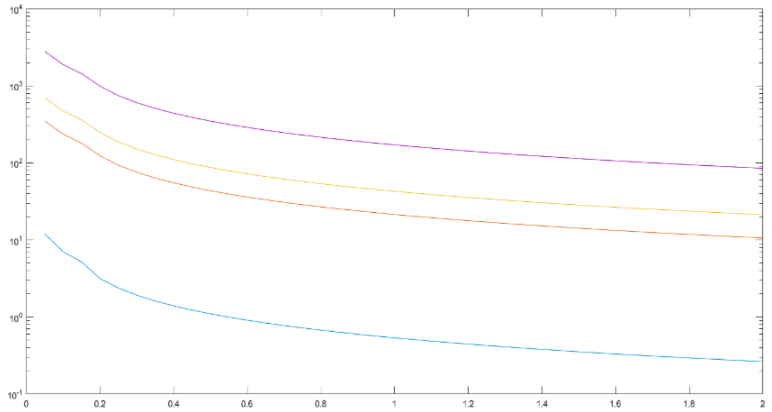


Figure 5. *The dependence of logarithm of coefficient of critical impact on time for different degrees of body growth (10%, 25%, 50%, 100%)*