MODELAGEM NUMÉRICA E SOFTWARE PARA DETERMINAR OS PARÂMETROS ESTÁTICOS E DE LIGAÇÃO DOS ORGANISMOS EM CRESCIMENTO NO PROCESSO DE TRANSFERÊNCIA ADITIVA NÃO ESTACIONÁRIA DE CALOR E MASSA**NUMERICAL MODELING AND SOFTWARE FOR DETERMINING THE STATIC AND LINKAGE PARAMETERS OF GROWING BODIES IN THE PROCESS OF NON-STATIONARY ADDITIVE HEAT AND MASS TRANSFER****ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ И ПРОГРАММНОЕ ОБЕСПЕЧЕНИЕ ДЛЯ ОПРЕДЕЛЕНИЯ СТАТИЧЕСКИХ И КИНЕМАТИЧЕСКИХ ПАРАМЕТРОВ РАСТУЩИХ ТЕЛ В ПРОЦЕССЕ НЕСТАЦИОНАРНОГО АДДИТИВНОГО ТЕПЛОМАССОПЕРЕНОСА**KUZNETSOVA, Ekaterina L.^{1*}; RABINSKIY, Lev N.²;¹ Moscow Aviation Institute (National Research University), Faculty of Applied Mechanics, Moscow – Russian Federation² Moscow Aviation Institute (National Research University), Department of Engineering Graphics, Moscow – Russian Federation

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Received 03 September 2019; received in revised form 20 October 2019; accepted 26 October 2019

RESUMO

Atualmente, os métodos de impressão tridimensional de produtos a partir de polímeros, metais e materiais cerâmicos são amplamente utilizados. As tecnologias de síntese camada a camada possibilitam a obtenção de produtos de alta qualidade com características mecânicas suficientemente altas, próximas às realizadas com os processos tecnológicos tradicionais. Um problema relacionado foi resolvido, incluindo o cálculo da temperatura no produto e da área de operação em torno dele em uma configuração plana com base em duas abordagens diferentes. Um corpo extensível camada por camada apresenta o problema instável de condução de calor. A cada passo, a altura da região computacional aumenta devido ao preenchimento de uma nova camada de pó. Uma etapa do cálculo é determinada pelo intervalo entre duas passagens consecutivas do laser. A distribuição de temperatura encontrada em cada etapa é usada como condições iniciais para os cálculos na próxima etapa. O campo de temperatura obtido como resultado da solução do problema implementado no produto em questão com uma etapa de 1000 (após a aplicação e a fusão de 1000 camadas) é ainda mais comparado com a solução do problema quase-estacionário para o produto de dimensões finitas. Usando o exemplo da geometria simples, é mostrado que uma solução quase estacionária pode fornecer uma estimativa satisfatória do estado térmico macroscópico do produto em crescimento.

Palavras-chave: *crescimento de produtos em camadas, aquecimento a laser, modelagem, condutividade térmica não estacionária, corpo em crescimento, tecnologias aditivas.*

ABSTRACT

Currently, methods of three-dimensional printing of products from polymer, metal and ceramic materials are widely used. Layer-by-layer synthesis technologies make it possible to obtain high-quality products with sufficiently high mechanical characteristics close to those realized using traditional technological processes. A related problem is solved, including calculating the temperature in the product and the operation area surrounding it in a flat setting based on two different approaches. For a layer-by-layer extensible body, the unsteady heat conduction problem is stated. At each step, the height of the computational region increases due to the filling of a new layer of powder. One time step of the calculation is determined by the interval between two consecutive passes of the laser. The temperature distribution found at each step is used as the initial conditions for the calculations at the next step. The temperature field obtained as a result of solving the problem that is implemented in the product in question with a step of 1000 (after applying and melting 1000 layers) is further compared with the solution of the quasi-stationary problem for the finite dimensions product. Using the example of the simple geometry taken, it is shown that a quasi-stationary solution can provide a satisfactory estimate of the macroscopic thermal state of the growing product.

Keywords: *layer-by-layer product growth, laser heating, modeling, non-stationary thermal conductivity, growing body, additive technologies.*

АННОТАЦИЯ

В настоящее время широко распространены методы трехмерной печати изделий из полимерных, металлических и керамических материалов. Технологии послойного синтеза позволяют получать изделия высокого качества, обладающие достаточно высокими механическими характеристиками, близкими к тем, которые реализуются при использовании традиционных технологических процессов. Решается сопряженная задача, включающая расчет температуры в изделии и окружающей его рабочей области в плоской постановке на основе двух различных подходов. Для послойно наращиваемого тела ставится нестационарная задача теплопроводности. На каждом шаге увеличивается высота расчетной области вследствие засыпки нового слоя порошка. Один временной шаг расчета определяется интервалом между двумя последовательными проходами лазера. Найденное на каждом шаге распределение температуры используется в качестве начальных условий для проведения расчетов на последующем шаге. Поле температур, полученное в результате решения задачи которое реализуется в рассматриваемом изделии с шагом 1000 (после нанесения и проплавления 1000 слоев) и в дальнейшем сравнивается с решением квазистационарной задачи для изделия конечных размеров. На примере рассмотренной простой геометрии показано, что квазистационарное решение может дать удовлетворительную оценку макроскопического теплового состояния выращиваемого изделия.

Ключевые слова: *послойное выращивание изделий, нагрев лазером, моделирование, нестационарная теплопроводность, растущее тело, аддитивные технологии.*

1. INTRODUCTION

Currently, methods of three-dimensional printing of products from polymer, metal and ceramic materials are widely used (Guo and Leu, 2013; Uriondo *et al.*, 2015). Layer-by-layer synthesis technologies make it possible to obtain high-quality products with sufficiently high mechanical characteristics close to those realized using traditional technological processes (Skvortsov *et al.*, 2000; Murr *et al.*, 2012; Skvortsov *et al.*, 2012; Kablov, 2015; Smurov *et al.*, 2015; Bikas *et al.*, 2016; Shejko *et al.*, 2016; Skvortsov and Karizin, 2017).

A significant part of the work is devoted to modeling of physical phenomena at the micro level or only in the vicinity of a local high-energy source, leading to the melting of the powder (King *et al.*, 2015; Khairallah *et al.*, 2016) and heating is carried out using a laser or an electronic beam. Other works are related to the simultaneous or sequential modeling of macroscopic temperature fields in the process of layer-by-layer synthesis and the residual stress strain behavior of the products obtained. The main result of such calculations is an estimation of the effectiveness of the applied technological modes for obtaining high-quality products in which minimal negative effects of permanent deformations and residual stresses are implemented (Riedlbauer *et al.*, 2012). The process is accompanied by multiple laser passes on the surface of the parts. Modeling of such processes is carried out in the

framework of the unrelated problem of thermoelastic behavior: the non-stationary problem of thermal conductivity is solved, and the product stress strain behavior is determined on the basis of the solution of the quasi-static problem of thermoelastic behavior. To speed up numerical calculations, methods of creating adaptive finite element meshes are used (Keller *et al.*, 2013). When using finite element packets to accelerate numerical calculations, the finite element mesh can be enlarged so that each finite element contains several sintered layers (Orlov *et al.*, 2003; Gorchakov *et al.*, 2004; Dmitriev *et al.*, 2011).

In the study of residual stress strain behavior, it can be used an assumption about the insignificant influence of trajectory of the heating source (laser or electronic beam) on the surface of the product (Knyazev *et al.*, 2007; Formalev and Kolesnik, 2017; Kakhramanov *et al.*, 2017; Formalev *et al.*, 2018a; Rabinskiy *et al.*, 2018; Rabinsky and Tushavina, 2019b).

2. MATERIALS AND METHODS

The problem is considered in a flat setting. It is assumed that the wall is quite extended and the heat transfer at its remote faces can be neglected, then the same thermal mode is realized in each section perpendicular to the direction of motion. The process of layer-by-layer synthesis of a thin vertical wall is shown in Figure 1. As a result of the calculation, it is necessary to

determine the thermal state of the synthesis operation area, which includes the product itself, non-sintered powder surrounding it and the working platform, schematically shown in Figure 1a. For this purpose, at each step corresponding to a new poured layer, we solve the unsteady heat conduction problem. Then, for a layer-by-layer growing body, we come to periodic local heating of its surface, associated with the action of a laser. Shrinkage loss of powder is neglected at a first approximation.

The region in which the calculation is carried out is denoted by Ω_i . This region consists of a working platform (Equation 1) and from a growing region (Equation 2), which includes the growing product and non-sintered powder surrounding it. Accordingly, piecewise constant properties corresponding to the materials of the platform, the synthesized product, and the powder are set in the region Ω_i . In this example, the wall is located in the center of the computational region and has a thickness d . We will carry out the calculation for half of the region, taking into account the symmetry of the problem shown in Figure 1b, which also shows the coordinate system used in the calculations.

The generalized mathematical model should take into account unsteady heat conduction, unsteady and non-uniform mass loss, arbitrary orientation of the principal axes of the heat conductivity tensor, complex heat transfer at free boundaries, the presence of heat fluxes, the direction of which deviates significantly from the direction of the normal to the boundaries, the non-convexity of the boundaries during mass growth, as well as curvilinear coordinate systems.

The problem is solved in an unsteady setting, taking into account the method for determining the moment of beginning and end of mass growth under substantially unsteady conditions.

3. RESULTS AND DISCUSSION:

Based on the refined software system that implements the above methods, the influence of the computational region curvature, the degree of anisotropy, the orientation of the principal axes of the thermal conductivity tensor on the two-dimensional non-stationary temperature field is explored, and it is presented the nature of the isotherms at the outer boundary during heating with mass growth (Mykhalevskiy, 2018; Mykhalevskiy, 2019).

To solve this problem, we use the one-

dimensional equation of unsteady heat conduction, taking into account the terminal velocity of propagation of the heat wave and scale effects (Lomakin *et al.*, 2018) (Equation 3).

The balance of thermal energy at the inner boundary of the layer (Equation 4).

Continuity of heat fluxes and temperatures at the boundary w_1 between the liquid film and the body (Equation 5)

In the mathematical model (3-5), the following designations are used: τ , T , λ , c , ρ – respectively, temperature, thermal conductivity, heat capacity, density; δ_T – body thickness; q – heat flux density; Indices: w_1 , w_2 – respectively, the outer and inner borders of the body; eff – effective;

At each i -th step of the calculation, the region height Ω_i is increased by the thickness of one layer h . In the resulting region in the time interval $t \in [(i-1)\Delta t, i\Delta t]$ the problem of non-stationary thermal conductivity is solved.

Where $T_i(x, y, t)$ – the temperature field, which is realized in the computational region Ω_i at the i -th calculation step, Equation 6 – the heat flux vector, $k(x, y, T_i)$, $C_p(x, y, T_i)$, $\rho(x, y)$ – the coefficients of thermal conductivity, heat capacity and density, the values of which are given piecewise constant functions of coordinates and continuous temperature functions. The solution of unsteady heat conduction problems was considered in (Babaytsev *et al.*, 2015; Lurie *et al.*, 2015; Koshoridze *et al.*, 2017; Lomakin *et al.*, 2018a; Lomakin *et al.*, 2018b; Formalev *et al.*, 2018b; Formalev *et al.*, 2018c; Formalev and Kolesnik, 2019; Rabinskiy and Tushavina, 2019a; Nikitin *et al.*, 2019; Rabinskiy *et al.*, 2019; Babaytsev *et al.*, 2019)

As the initial conditions for problem (1), we use the solution obtained in the previous calculation step, which is extrapolated to the new layer added as follows:

Here $(i-1)h$ is the maximum height of the computational region at the previous calculation step, that is, the sum of the thicknesses of the layers already applied.

In the recorded initial conditions (Equation 7), the found temperature distribution on the surface of the product at the previous calculation step is, in fact, extended by one new layer upwards for performing calculations at a new step. This assumption is based on the small thickness of the applied layers, which almost

instantly warm up to the substrate temperature after their application and, at the same time, slightly affect the macroscopic thermal state of the product.

At the first calculation step $i=i_0$, it is assumed that the region under consideration Ω_{i_0} uniformly warmed up to ambient temperature T_0 . This medium is air or an inert gas in which synthesis is carried out and which is supplied to blow and chill down the product and to prevent oxidation of its surface.

As the boundary conditions at the lower and lateral boundaries of the computational region Ω_i , the heat transfer condition is set according to Newton's law (Equation 8). Where the heat transfer coefficient α is a parameter of the model and it is determined by the arrangement of the processing chamber used for the synthesis of equipment, n is the vector of a unit external of the normal to the boundary of the region.

At the upper boundary of the region, heat transfer by radiation according to the Stefan-Boltzmann law and heat supply are additionally taken into account due to the action of the heating source (Equation 9).

Here, σ – the Stefan-Boltzmann constant, ε – the degree of blackness of the surface, $q(x,t)$ – the heat flux supplied to the surface of the product under the action of a laser. It is assumed that the temperature of the walls of the chamber, where the heat is exchanged by radiation, is equal to the ambient temperature T_0 .

In the calculations, we assume that the modeling wall is rather thin, and the velocity of the heating source v is quite large (usually from several tens of millimeters to several meters per second). Therefore, at the upper boundary of the wall in the laser operating zone, we will set a constant value with respect to the x -coordinate for the heat flux supplied simultaneously to the entire melted surface of the product. In the selected coordinate system, this is a section of the boundary with the coordinate $y=ih$ in the range $-d/2 \leq x \leq d/2$. For approximate calculations, we assume that this function $q(x,t)$ is piecewise constant in time and has the following form (Equation 10). Where $t_0=d/v$ is the operating time of heating, which is determined by the width of the wall and the velocity of the source.

Let us consider the growing process, starting with step $i_0=1000$, to avoid creating too small finite element mesh. We are talking about layer-by-layer growing of a thin vertical wall made

of stainless steel. We set the parameters of the problem in the form: - the thickness of one layer $h = 20 \mu\text{m}$, the width of the considered part of the operation area $L = 3 \text{ cm}$, the wall thickness $d = 1 \text{ mm}$, the maximum height $H = 3 \text{ cm}$, the thermal conductivity of the powder is 0.01, and the density is 0.5 from the corresponding characteristics of the sintered material, the melting temperature $T_{\text{melt}} = 1400 \text{ C}$. The calculations are carried out under the assumption that the characteristics of the materials vary linearly depending on the temperature and that the working platform and the wall are made of the same material.

At above temperatures the material characteristics we consider constant. The calculation time at each step (the time between the actions of the heating source) $\Delta t = 25$ seconds. The heat transfer coefficient α on the surface will be set equal to the case of natural and forced (intense blowing) convection. The ambient temperature $T_0 = 25\text{C}$, the degree of blackness of the surface $\varepsilon = 0.5$. The velocity of the heating source $v = 2 \text{ m/s}$, the power $P = 100\text{W}$, the efficiency coefficient $\eta = 0.4$, the radius of the heating spot $r = 120 \mu\text{m}$. The calculations are carried out for the maximum number of steps $N = 1500$.

As a result of the calculations, the following results were obtained: Figure 2 shows a diagram of temperature changes along the y coordinate, throughout the height of the wall. Here, on one graph, temperature profiles are applied at different points in time in the growing product. All graphs are constructed, 10 seconds later, after exposure to the laser, that is, at the moment when the surface of the product manages to cool down after the next intense heating. With an increase in the heat transfer coefficient at the boundaries of the computational region, shown in Figure 2b, the wall warms up less, but the temperature difference throughout its height increases. For the case of low heat transfer coefficient shown in Figure 2a, the product actually overheats. Thus, according to the modeling results, we can see that the specified synthesis mode is unacceptable and requires correction.

4. CONCLUSIONS:

The problems of heat and mass transfer are one of the most important problems of mathematical physics. This is due to both their widespread distribution and the determining influence on the efficiency of thermal, diffusion

and chemical apparatuses.

The problems of thermal conductivity and diffusion have wide practical application. The ability to solve such problems allows you to get the most important information about the process. For example, for a thermal process, it is possible not only to calculate the stationary temperature field, heat fluxes and average temperatures of individual structural elements and the apparatus as a whole, but also to determine the nature of the change (profiles, differences, gradients) of temperatures at individual points of the structural elements of the apparatus, to predict possible thermal diffusion effects, find the optimal parameters and offer a control circuit for this unit or installation.

The scientific paper gives the results of a numerical solution of the plane problem of incremental growth of a thin vertical wall in the process of its layer-by-layer laser growing. In the proposed modeling method, a finite element mesh is built at each new calculation step, and solutions at different calculation steps are joined by redefining and extrapolating the initial conditions.

The approach used makes it possible to obtain, with a sufficient degree of accuracy, synthesis parameters for a specific geometry region of the growing product. The region for which the solution is framed should be large enough so that during the growing process the necessary mode can be realized in it.

5. ACKNOWLEDGMENTS:

The work was carried out with the financial support of the state project of the Ministry of Education and Science project code 2.9219.2017/8.9.

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$$\Omega_P = \{0 \leq x \leq L, -H \leq y \leq 0\} \quad (\text{Eq. 1})$$

$$\Omega_L = \{0 \leq x \leq L, 0 \leq y \leq ih\} \quad (\text{Eq. 2})$$

$$(\lambda_{yy})_{eff} \frac{d^2 T}{dy^2} - \Pi(c\rho)_f \cdot v_f \frac{dT}{dy} = \rho C_p \frac{\partial T}{\partial t} + \tau \frac{\partial^2 T}{\partial t^2} + \frac{k_v}{l_T^2} T, \quad 0 < y < \delta_T. \quad (\text{Eq. 3})$$

$$(\lambda_{yy})_{eff} \frac{dT}{dy} \Big|_{w2} = q_{w2}, \quad y = 0. \quad (\text{Eq. 4})$$

$$\lambda_f \frac{dT}{dy} \Big|_{w1} = (\lambda_{yy})_{eff} \frac{dT}{dy} \Big|_{w1}, \quad T_f \Big|_{w1} = T \Big|_{w1}, \quad y = \delta_T. \quad (\text{Eq. 5})$$

$$\mathbf{q} = -k \nabla T_i \quad (\text{Eq. 6})$$

$$T_i(x, y, 0) = \begin{cases} T_{i-1}(x, y, i\Delta t), & y \leq (i-1)h \\ T_{i-1}(x, (i-1)h, i\Delta t), & (i-1)h \leq y \leq ih \end{cases} \quad (\text{Eq. 7})$$

$$x=0, x=L, y=-H: \mathbf{q} \cdot \mathbf{n} = \alpha(T_i - T_0) \quad (\text{Eq. 8})$$

$$y=ih: \mathbf{q} \cdot \mathbf{n} = \alpha(T_i - T_0) + \sigma \varepsilon (T_i^4 - T_0^4) + q(x, t) \quad (\text{Eq. 9})$$

$$q(x, t) = \begin{cases} q_0, & t \leq t_0 \cup |x| \leq d/2 \\ 0, & t > t_0 \end{cases} \quad (\text{Eq. 10})$$

a)

b)

Figure 1. The problem setting of layer-by-layer sintering of a thin vertical wall: a) a schematic demonstration of the nature of movement of the laser beam on the surface of the sintered product; b) a finite element model for solving a problem in a flat setting. The cross section of the sintered wall is shown

Figure 2. Change in the temperature profile $T(0, y)$ throughout the height of the growing wall and in the platform below it. Temperature profiles that occur every 10 calculation steps are shown. The profiles are constructed for time moments preceding the next laser exposure, that is, when the surface of the product manages to cool down after the action of the previous laser pulse. The dashed line shows the solution, without taking into account the growth of the product and without taking into account the pulsed action of the laser