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PREDICTION OF THE KINETICS OF TEMPERATURE FIELDS AND STRESS-STRAIN STATE OF DISSIMILAR PRODUCTS, MANUFACTURED BY LAYER-BY-LAYER FORMING

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Layer-by-layer forming of metal structures and elements of various-purpose mechanisms is a promising venue of high technology advance. Broad possibilities for optimization of technology parameters and accuracy of positioning the forming layers allow manufacturing thin-wall products of different geometry. Moreover, dissimilar structures can be produced by changing the filler material. Such a technological process requires thorough optimization of the respective technology cycle to guarantee the required quality of the dissimilar structure, depending on product shape, materials and features of a specific technology. This work is a study of the features of the kinetics of temperature field and stress-strain state of dissimilar structures during multilayer surfacing in the case of T-beam structures, made by xBeam 3D Metal Printer technology. 12 Ref., 6 Figures.

Keywords: *layer-by-layer forming, dissimilar structure, temperature field, stress-strain state, mathematical modeling*

One of the venues for application of modern technologies of layer-by-layer forming is realization of industrial systems of manufacturing dissimilar structural elements and parts of mechanisms. This allows producing complex-shaped structural elements with minimum metal consumption, compared to classical approaches of milling or welding, that causes interest in such technologies in aerospace and power sectors, instrument making, medicine, etc. [1–3]. As regards critical structures from light metals and alloys, for which the key design aspect is minimizing the weight at preservation of the required service properties (strength, corrosion resistance, rigidity, etc.), a rational method is combining different materials by permanent joining of dissimilar parts. It is known that producing dissimilar joints by fusion welding is limited for a large number of metal pairs for the reason of their low mutual solubility and proneness to formation of intermetallic inclusions and respective lowering of structure performance [4, 5]. Therefore, the methods of solid-phase welding, braze-welding, welding through interlayers, etc. are used for dissimilar material joining. One of the required measures at implementation of the respective technology is optimization of technology parameters, in particular based on the results of mathematical and computer modeling of physico-mechanical processes that determine the final product quality.

Manufacturing dissimilar metal structures by the methods of layer-by-layer forming is associated with the same basic technology problems, as fusion welding. However, slight overheating of metal at surfacing, and possibility of technology parameters optimization, allow implementation of the technological schematics of manufacturing sound dissimilar products. For this purpose, it is necessary to take into account the features of temperature field kinetics at layer deposition, as well as the residual stress-strain state (SSS) of the structure.

The objective of this study is numerical analysis of the characteristic features of the kinetics of the fields of temperatures, stresses and strains in dissimilar structures at their layer-by-layer forming for the case of a typical beam-shaped structural element.

Typical problems of technology parameters optimization at layer-by-layer forming of dissimilar structural elements. Depending on specific types of metals, fundamentally different approaches can be realized in the structural element, as regards achieving sound fusion of the layers in the area of dissimilar contact. In the case of continuous mutual solubility of metals, optimization of heat input parameters at forming layer deposition is determined by the same requirements for similar and dissimilar parts of the structures, namely the need for activation of the solid surface of the previous layer at simultaneous prevention of liquid metal overheating. In the previous studies, the authors showed that a rational method for temperature field optimization in such a case is appropriate selection of the delay time between deposition of the forming layers that allows removing excess heat into the substrate or the environment [6, 7].

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If a metal pair is characterized by limited mutual solubility, and their melting temperatures differ significantly, fusion of the dissimilar layers can be realized by braze-welding scheme [8]. The essence of this method consists in that under the impact of the heat source the metal with a higher melting temperature remains solid, while the metal with a lower melting temperature stays in the liquid state for some time, forming braze-welding contact. It allows lowering the maximum temperatures of heating of the contact surface of liquid and solid metals, thus reducing the risk of formation of intermetallic inclusions. Formally, the requirements to temperature field optimization in the dissimilar material contact are described by temperature-time dependencies of the latent period of intermetallic formation.

It is known that, in the case of a significant difference of the coefficients of linear thermal expansion, the residual SSS for dissimilar structures is characterized by stress concentration in the area of dissimilar material contact. Such a feature of the residual state should be expected for structural elements, manufactured by the methods of layer-by-layer forming. In view of the fact that higher stresses negatively affect the performance, the influence of manufacturing technology factor on residual SSS and methods for possible lowering of stress concentration in the area of the dissimilar joint should be determined.

Mathematical model of the kinetics of temperature field and stress-strain state at layer-by-layer forming of dissimilar beam structures. The first stage of investigation of the kinetics of the above-mentioned product state during layer-by-layer forming is prediction of temperature field development. The temperature field kinetics is determined by conductive propagation processes, for which the connection between moment of time t and temperature field $T = T(x, y, z)$ is described by 3D equation of heat conductivity:

$$\begin{gathered} c\rho(x,y,z,T)\frac{\partial T(x,y,z)}{\partial t} = \\ = \nabla\left[\lambda(x,y,z,T)\nabla T(x,y,z)\right], \end{gathered} \tag{1}$$

where λ, $c\rho$ are the heat conductivity and volume heat capacity of the structure material in the Cartesian system of coordinates (x, y, z), respectively.

Heat source in the considered case is the electron beam with thermal power q_I, and energy distribution in the heated spot can be described by a normal law. Heat sink from the considered structure surface occurs through radiant heat transfer and heat removal into the technological fixtures. Accordingly, the flow of radiant energy from item surface q_R depends on surface and ambient temperature, as well as reflective properties of the surface, and it can be quantitatively described by Stephan–Boltzmann law:

$$q_R = \varepsilon\sigma_{SB}\left(T^4 - T_C^4\right), \tag{2}$$

where ε is the degree of blackness of the radiating surface, $\sigma_{SB} = 5.67\cdot10^{-8}$ J·s^{-1}·m^{-2}·°C^{-4} is the Stephan-Boltzmann constant.

The thermal energy flow into the load-carrying fixture q_N is described by the Newton law in the following form:

$$q_N = \alpha_T\left(T - T_C\right), \tag{3}$$

α_T is the coefficient of surface heat removal.

Proceeding from the conditions of heat balance, the heat flow to the surface of nonuniformly heated body due to the processes of conductive heat conductivity, is equal to heat sink from the surface that allows formulating the boundary conditions for the problem (1):

$$\lambda(T)\frac{\partial T}{\partial \boldsymbol{n}} + q_I + q_R + q_N = 0, \tag{4}$$

where $\boldsymbol{n}$ is the normal to the surface of the considered area of the structure.

Considering (2)–(3), the boundary condition for equation (1) has the following form:

$$-\lambda(T)\frac{\partial T}{\partial \boldsymbol{n}} = -q_I + \alpha_T\left(T - T_C\right) + \varepsilon\sigma_{SB}\left(T^4 - T_C^4\right). \tag{5}$$

The process of melting and further solidification of metal in welding is accompanied by absorption and evolution of heat of phase transition of the first kind g_{ft}, respectively. This phenomenon occurs in a rather narrow range of metal temperatures, namely its solid-liquid state between the temperatures of liquidus T_L and solidus T_S that complicates mathematical description of the heat balance. In order to take into account the evolution/absorption of the latent heat of phase transition, the effective heat capacity of the material in $T_S - T_L$ temperature range was used in the following form:

$$c\rho(T) = \begin{cases} c\rho\left(T_S\right) + \dfrac{g_{ft}}{T_L - T_S}, T_S < T < T_L \\ c\rho\left(T_L\right), T \geq T_L \end{cases}. \tag{6}$$

In the liquid metal pool the features of heat transfer are due mainly to the processes of convective stirring, which are determined by hydrodynamics of the nonuniformly heated melt. In this work intensification of heat transfer in the liquid metal as a result of convective stirring was taken into account by increasing the coefficient of heat conductivity:

$$\lambda(T) = \begin{cases} \lambda(T), T_S < T < T_L; \\ \lambda\left(T_L\right)n_K, T \geq T_L, \end{cases} \tag{7}$$

where $n_K = 3–5$ is the coefficient that allows for the convective heat transfer in the weld pool liquid metal.

Mathematical consideration of the joint problem of the temperature field kinetics and SSS development is based on finite-element description, using eight-node finite elements (FE). Increment of strain tensor was represented as follows [9]:

$$d\varepsilon_{ij} = d\varepsilon^e_{ij} + d\varepsilon^p_{ij} + \delta_{ij} d\varepsilon_T, \tag{8}$$

where $d\varepsilon^e_{ij}$, $d\varepsilon^p_{ij}$, $\delta_{ij} d\varepsilon_T$ are the components of tensor increment due to elastic deformation mechanism, instantaneous plasticity deformations, and kinetics of a nonuniform temperature field, respectively, $i, j = (x, y, z)$.

Tensors of mechanical stresses σ_{ij} and elastic strains $d\varepsilon^p_{ij}$ are interrelated by the generalized Hooke's law, i.e.

$$\varepsilon^e_{ij} = \frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}(K\sigma + \varphi), \tag{9}$$

where σ is the mean value of the normal components of stress tensor σ_{ij}, i.e. $\sigma = \sigma_{ii}/3$, $K = (1 - 2\nu)/E$ is the bulk modulus.

Increment of instantaneous plasticity deformations $d\varepsilon^p_{ij}$ from the stressed state in a certain FE can be calculated using linear dependence of scalar function Λ and deviator component of the stress tensor as follows:

$$d\varepsilon^p_{ij} = d\Lambda(\sigma_{ij} - \delta_{ij}\sigma). \tag{10}$$

The specific value of function Λ depends on the stressed state in the considered area of the structure, as well as on the shape of material yield surface. Proceeding from the above, the increments of the strain tensor can be represented in the form of superposition of the increment of the respective components [10]:

$$\begin{aligned} \Delta\varepsilon_{ij} &= \Psi\left(\sigma_{ij} - \delta_{ij}\sigma\right) + \delta_{ij}\left(K\sigma + \Delta\varepsilon_T\right) - \\ &- \frac{1}{2G}\left(\sigma_{ij} - \delta_{ij}\sigma\right)^* - \left(K\sigma\right)^*, \end{aligned} \tag{11}$$

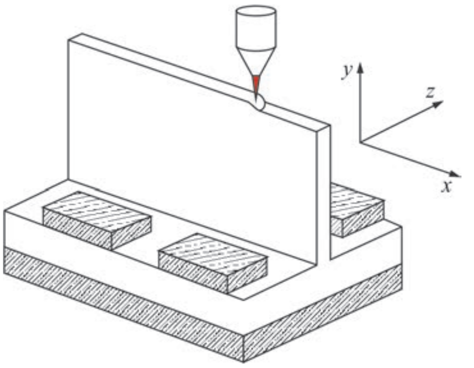

Figure 1. Scheme of layer-by layer forming of a T-beam structure using xBeam 3D metal printer technology

where symbol «*» refers the variable to the previous tracing step; Ψ is the function of material state that determines the condition of plastic flow, in keeping with Mises criterion:

$$\begin{aligned} &\Psi = \frac{1}{2G}, \text{ if } \sigma_i < \sigma_T, \\ &\Psi > \frac{1}{2G}, \text{ if } \sigma_i = \sigma_T, \\ &\text{state } \sigma_i > \sigma_T \text{ invalid.} \end{aligned} \tag{12}$$

Function Ψ is determined by iteration at each step of numerical tracing within the boundary problem of nonstationary thermoplasticity that allows solving the nonlinearity problem in plastic flow of the material.

The proposed approaches were implemented in software, using highly efficient algorithms for parallel solving of the boundary problem of nonstationary thermoplasticity [11]. It allowed conducting the respective studies of the influence of technology parameters of layer-by-layer forming on the current and residual states of various T-beam structures.

Results and their discussion. A complex of studies in the context of the above problems was conducted for the case of layer-by-layer forming of T-beam structure, using xBeam 3D Printer technology (Figure 1) from the following combinations of alloys: similar structure from titanium alloy VT6; dissimilar structure from titanium alloys VT6 and VT1; dissimilar structure from titanium alloy VT6 and commercially pure aluminium. It should be noted that both the similar structure (VT6), and dissimilar titanium structure (VT6–VT1) have no features of layer fusion caused by metallurgical incompatibility so that a common criterion can be used for temperature field optimization. Simultaneous fulfillment of the following conditions was selected as such a criterion [6]:

- absence of previous bead remelting;
- ensuring inter-bead fusion.

Thus, on the base of numerical study of the temperature field kinetics it is necessary to determine the optimum time intervals between deposition of dissimilar structure beads *dt* that allow satisfying the above conditions and producing sound fusion of the layers, depending on their ordinal number *N*.

For a dissimilar titanium-aluminium structure (VT6–Al), direct application of the above criterion will not guarantee producing a sound product that is related to limited solubility of aluminium in titanium. Therefore, at deposition of an aluminium bead on titanium it is necessary to prevent mixing of their liquid phases. It is known, however, that titanium alloy VT6 has a considerably higher melting temperature than aluminium (1640 °C, compared to 660 °C) that allows application of braze-welding principle for joining them. As was noted above, here a short time of contact with liquid al-

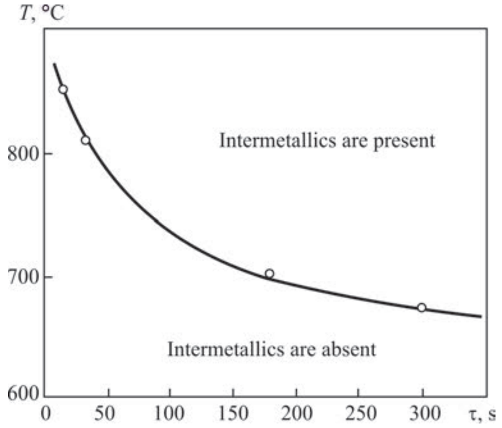

Figure 2. Temperature dependence of the duration of latent period of intermetallic formation at surface contact of titanium and aluminium [12]

uminium should be guaranteed, which depends on contact surface temperature that is related to the presence of the so-called latent period of intermetallic formation [12], the temperature dependence of which is given in Figure 2. Therefore, in addition to the conditions of optimization of the temperature field of the similar part of the structure at contact of dissimilar beads it is necessary to take into account the time of molten aluminium contact with solid titanium.

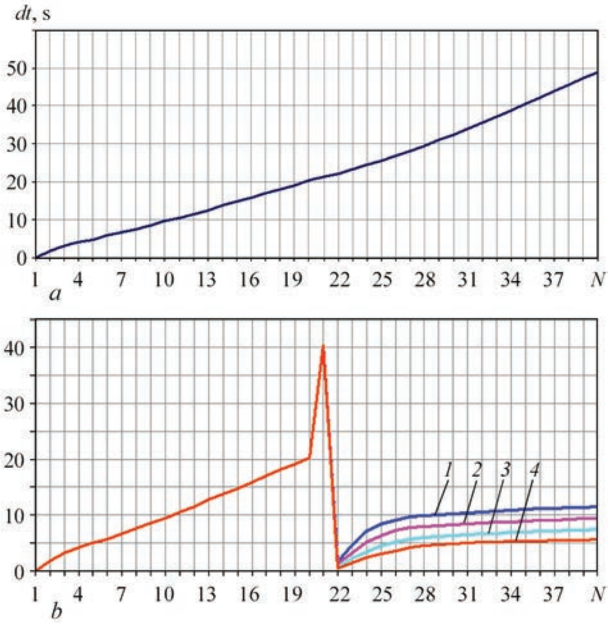

Figure 3. Dependence of time intervals between deposition of dissimilar structure beads *dt*, that allows obtaining sound fusion of the layers, from the bead ordinal number *N*: *a* — VT6 — VT1; *b* — VT6 — Al (*1* — *q*; *2* — 0,9 *q* ; *3* — 0,8 *q*; *4* — 0,7 *q*)

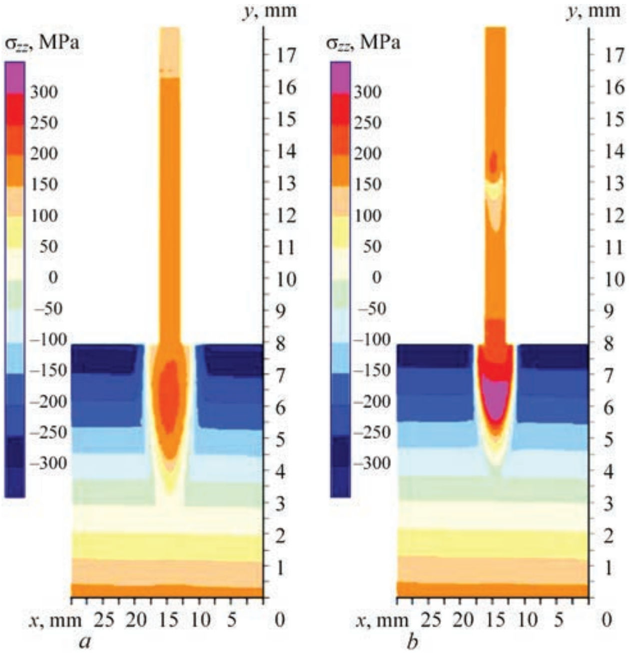

Figure 4. Field of residual stresses σ_{zz} in the cross-sections of a similar (VT6) (*a*) and dissimilar structures (VT6–Al) (*b*)

As shown by calculation results, at layer-by-layer forming of dissimilar beam structure from titanium alloys VT6 and VT1, the relatively small difference in physical properties of these materials and continuous solubility result in the presence of the dissimilar transition only slightly influencing the structure state. So, dependence of optimum time interval of delay between layer deposition *dt* that ensures sufficient dissipation of excess thermal energy in the item, practically does not change its nature after the 20th bead, when material change occurs (Figure 3, *a*)

In the case of a significant difference in physico-mechanical properties of the materials, as is the case in VT6–Al pair, transition to another material (in this case, from titanium alloy to aluminium) requires considerable changes of heat input parameters and delay interval *dt*. So, transition from titanium layer deposition to the aluminium part of the item should be accompanied by a certain cooling of the titanium part with the purpose of lowering the surface temperature

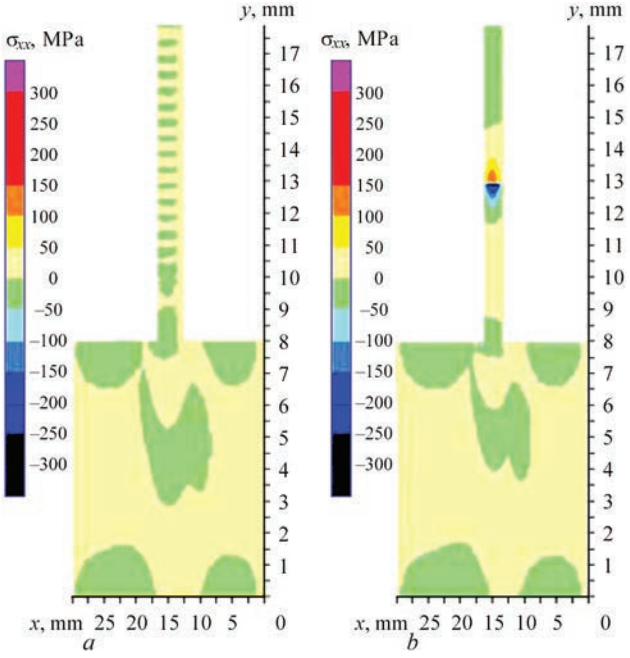

Figure 5. Field of residual stresses σ_{xx} in the cross-sections of a similar (VT6) (*a*) and dissimilar structures (VT6–Al) (*b*)

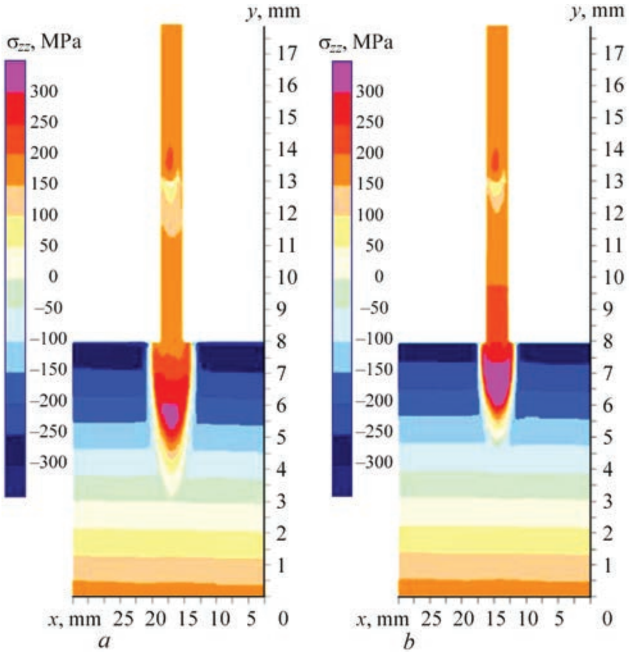

Figure 6. Impact of heat input q_1 on the field of residual longitudinal stresses σ_{zz} in the cross-section of a dissimilar (VT6–Al) structure: *a* — 5; *b* — 4 kW

before deposition of a lower melting metal (Figure 3, *b*). Further deposition occurs by the modes characteristic for aluminium structure fabrication.

The difference between mechanical properties of titanium and aluminium results in formation of local stress concentrations. As shown by numerical modeling results, the most marked stress increase in the area of the dissimilar joint occurs in the longitudinal direction (σ_{zz} stresses, Figure 4), as well as in the transverse direction (σ_{xx}, Figure 5). Moreover, the nonuniformity of cooling by the surfaced structure height, caused by the need to stop the process at transition from the titanium to the aluminium part, leads to σ_{zz} increase in the substrate area, compared to the similar structure. Here, the change of heat input power only slightly affects the stress raiser in the dissimilar transition area, but it allows redistributing the residual stresses to certain extent in the area of tee flange transition to the web (Figure 6).

Conclusions

1. A package of mathematical models and computer programs was developed for numerical prediction of the temperature field kinetics and stress-strain state of typical structural elements during layer-by-layer forming by xBeam 3D Printer technology.

2. Criteria of selection of the optimum time between deposition of the forming beads are proposed. For dissimilar contact of metals with an essential difference in the melting temperatures, the temperature mode should ensure the condition of non-melting of the refractory part of the structure by braze-welding principle.

3. The features of residual fields of stresses and strains in the cross-section of a dissimilar structure (VT6-Al), compared to similar structure (VT6), were studied in the case of layer-by-layer forming of T-beam structures by xBeam 3D Printer technology. It is shown that presence of a dissimilar transition and the need for a significant cooling of the last titanium bead before aluminium bead deposition determines formation of a local stress raiser (of longitudinal and transverse stresses). Here, the change of the heat source power has an only slight impact on maximum stresses in the area of the dissimilar transition, largely determining the local stress-strain state in the area of tee flange transition to the web.

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