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Process modeling of elastic-plastic deformation of steel-aluminum compositions produced by impact bonding

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Abstract
The article analyzes features of the calculation methods of the process of forming the layered metal compositions. A mathematical model of elastic-plastic deformation is represented with taking into account the kinematic and mechanical hardening of composition materials and characteristics of the structure and properties of a joint zone. An example of calculation for the composition of “stainless steel - aluminum alloy” is given here.
Keywords: LAYERED METAL COMPOSITION, EXPLOSION WELDING, THE ELASTIC-PLASTIC DEFORMATION, TWO-LAYER SHELL, FINITE DIFFERENCE METHOD

Optimal operating properties of details, components and assemblies working in extreme conditions can be obtained only in the application of composite elements of construction made of dissimilar metals. The use of bimetal “stainless steel - aluminum alloy (AMg6)” allowed us to create lightweight design in chemical engineering and shipbuilding. By modeling the process of forming the billets from layered metal workpieces can be adapted to most of the methods of calculation of the elastic-plastic deformation.

The dynamics of a multi-layer shell at its pulsed deformation is the most viable to describe the finite-difference parametric model, which generalizes the algorithm for solving the difference scheme used for the calculation of isotropic shells of final length [1]. Deformed condition heterogeneity of multilayer separate layers determines the constancy of the volume of the selected item [2]. Difference ratio is complemented by expressions for the grid functions on the surface of the contact layer. Using these relations displacements and stresses at all points and the deformable layer of the workpiece can be found.

It should be noted that sufficiently reliable methods for determining the power parameters of the processes and regularities of forming layered metal compositions are not currently developed.

Work objective

Adaptation of parametric mathematical model of the process of forming a layered metal shell under pulsed deformation is based on the finite difference method and the establishment and generalization of mechanical properties data and regularities of their distribution over the thickness of the layered workpiece.

Materials of research

Let’s consider the case of a two-layer metal composition (hereinafter - bimetal) [3]. Bimetallic workpiece cover spatial Lagrangian grid X_1X_2 connected with the middle surface. We use the «circuit nodes.» The joint node of the computational grid (here an acceleration is determined) of each physical element is the datum of the appropriate weight, equal to the sum of the masses of the bimetal component and applied at the center of gravity of the element. All other quantities are defined in each component. Mass point components connected with weightless extensible direct joint.

From the equilibrium equations for every mn-th node of the workpiece we determine the acceleration, velocity and displacement of mesh nodes of the middle surface

$$\begin{cases} \nabla_\gamma M^{\beta\alpha}_{mn} - Q^{\beta}_{mn} R^{\beta}_{\gamma mn} + P^{\alpha}_{mn} + T^{\alpha}_{mn} + S^{\alpha}_{mn} = \bar{\rho} \ddot{X}^{\alpha}_{mn} - \rho \dot{X}^{\alpha}_{mn} c, \\ M^{\beta\alpha}_{mn} R^{\beta\alpha}_{mn} + \nabla_\beta Q^{\beta}_{mn} + P^{3}_{mn} + T^{3}_{mn} + S^{3}_{mn} = \rho \ddot{X}^{3}_{mn} - \rho \dot{X}^{3}_{mn} c, \\ \nabla_\beta L^{\alpha\beta} - Q^{\alpha}_{mn} = 0 \end{cases} \quad (1)$$

where ∇_β – covariant differentiation sign; M_{mn} – membrane forces; Q^{β}_{mn} – shear force; R_{mn} – curvature tensor; P^{j}_{mn} – an impact of impulse loading; T_{mn} – friction force in the peripheral zone of the workpiece; S_{mn} – force of braking elements of the matrix; $\bar{\rho}$ – reduced mass ; $\ddot{X}^{j}_{mn}$ – acceleration; c – the speed of sound in the workpiece; L – bending moments.

The system (1) of differential equations is replaced by finite-difference analogue. Sublayer constituting each layer is separated by material with shear modulus G^i and plastic shear resistance t_s^i. All bend concentrates at the location points of the masses.

In the first stage of calculation of multilayered shell it is split into elements and sub-layers and the initial and boundary conditions are determined. Rheological material model is selected in view of its physical properties. The components of acceleration $\ddot{x}_1$ and $\ddot{x}_2$ are identified in all nodes and nodes position at the initial time τ→1 from the formula that define the acceleration:

$$x^{i}_{1,\tau+1} = \ddot{x}^{i}_{1,\tau+1} \cdot \Delta t^2 + 2x^{i}_{1,\tau} - x^{i}_{1,\tau-1}, \quad (2)$$

$$x^{i}_{2,\tau+1} = \ddot{x}^{i}_{2,\tau+1} \cdot \Delta t^2 + 2x^{i}_{2,\tau} - x^{i}_{2,\tau-1}, \quad (3)$$

where Δt – the value of the integration step, τ – the number of the time step.

To determine the plastic strain increment we use a refined incremental theory of plastic flow for each sublayer. The corresponding stresses in the layers and sublayers are received from the approximate (finite-difference) equations for stresses and deformations. On stresses we define membrane (axial) forces and moments at the location points of mass [4]. Equation points (1) allow you to determine shear forces. Knowing the coordinates of points and considering bringing the condition of constancy of the volume the relative deformations of sublayers of each layer are counted. After this we find the increment of deformations $\Delta\varepsilon^{i}_{43,\tau+1}$, $\Delta\varepsilon^{i}_{4,\tau+1}$ and $\Delta\varepsilon^{i}_{3,\tau+1}$.

Assuming that the change in stress is in accordance with the generalized Hooke law we define the increment of stress. Thus each layer has a modulus of elasticity E^i, shear modulus G^i and Poisson's ratio n^i, where i is a number of layer:

$$\Delta\sigma_{3,\tau+1} = \frac{E^i}{1-\nu_i^2}(\Delta\varepsilon^i_3 + \nu^i \Delta\varepsilon^i_4)_{\tau+1}, \quad (4)$$

$$\Delta\sigma_{4,\tau+1} = \frac{E^i}{1-\nu_i^2}(\Delta\varepsilon^i_4 + \nu^i \Delta\varepsilon^i_3)_{\tau+1} \quad (5)$$

$$\Delta\sigma_{34,\tau+1} = G^i \Delta\varepsilon_{34}, \quad (6)$$

where ν^i is Poisson's ratio of i-layer, G^i is shear modulus of i-layer.

Next the check is carried out whether the resolved stress is within the area bounded by the yield curve. That means the generalized Huber-Mises yield criterion is calculated F_{t+1}.

At the layers boundary the conditions of continuity of the strain and stress is satisfied. When determining the accelerations we give raise the workpiece to the monolayer and the other parameters are determined for each component (Fig. 1).

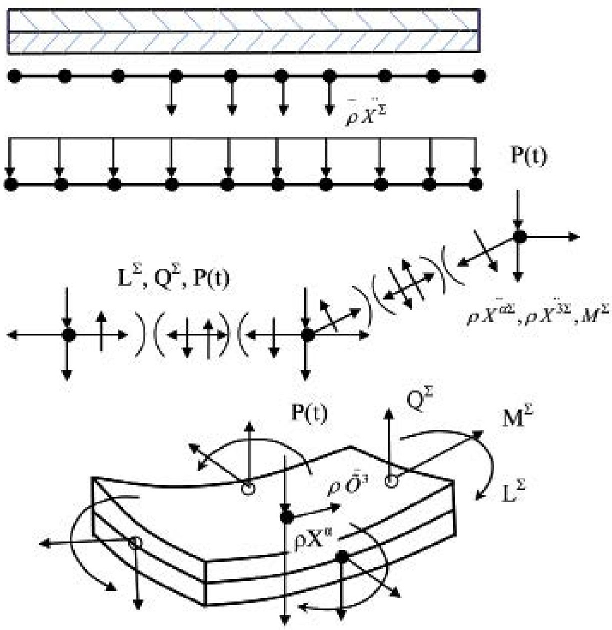


Figure 1. Design scheme of elastic-plastic deformation model of the two-layer shell

Then the cycle is repeated with determination of acceleration grid nodes of the middle surface at the next stage of integration depending on (1)

$$\ddot{x}^{j}_{mn} = \frac{A^{0,5}_{mn}}{\bar{\rho}_o} \cdot \left(\begin{array}{l} \ddot{P}^{j}_{mn} + T^{j}_{mn} + S^{j}_{mn} + \quad {}^{j}_{mn} + \\ + \left(\dfrac{\partial V^{\beta j}_{mn}}{\partial x^\beta} + \bar{A}^{\beta}_{mn} \cdot \dfrac{\partial \bar{A}^{\gamma}_{mn}}{\partial x^\beta} \cdot V^{\gamma j} \right) \end{array} \right), \quad (7)$$

where A_{mn} – metric tensor determinant, $V^{\beta j}_{mn}$ – space-surface tensor.

The time interval Dt is selected from the stability condition of computation process [5]

$$\Delta t \le \Delta X_{5,j,0} \left[\rho^k_3 (1-\nu^k)^2 (E^k)^{-1} \right]^{0,5}, \quad (8)$$

where ρ^k_3 is the density of the k workpiece material; ν^k и E^k are Poisson's ratio and Young's modulus of the k workpiece material, respectively.

In the proposed algorithm the program «MALL» was developed allowing us to carry out the calculation of the stress-strain state in the process of forming a layered shell and define the final round deflections of the layered workpiece which is subjected to explosive loading.

At modeling process of pulsed deformation of layered workpiece «12H18N10T steel - aluminum alloy AMg2M» is adopted: diameter of the workpiece $D_3 = 0.2$ m, width of the flange portion of the workpiece 20 mm, thickness of aluminum alloy $d_1 = 1.5$ mm, the thickness of the steel layer $d_2 = 3$ mm. Depth of the layers part subjected to hardening is shown in Fig. 2.

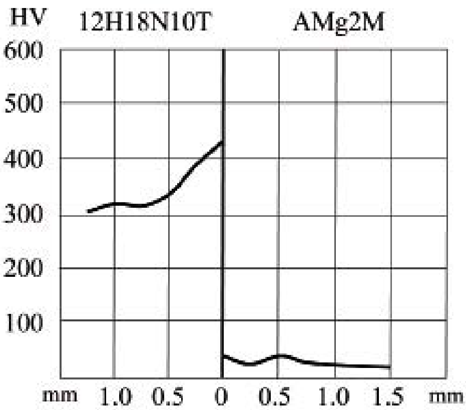


Figure 2. Hardness in the joint zone of bimetal 12H18N10T + AMg2M

The depth of the hardened layer reaches 0.4-0.6 mm, so the mechanical characteristics of the contact layers, the latter for the cladding and the first for the cladded we accept as increased.

The values of the center point moving of bimetallic workpieces obtained by explosion welding are shown in (Fig. 3a) and the combined operations of welding and explosive forming are shown in (Fig. 3b).

The efficiency of processes was assessed by two criteria:

1) relative deviation in wall thickness of the drop-stamped workpiece in diametrical (cross) section

$$\Delta\bar{\delta} = \frac{\delta_{k\,max} - \delta_{k\,min}}{\delta_0}, \qquad (9)$$

where d_{kmax}, d_{kmin} – the maximum and minimum wall thickness of the drop-stamped workpiece in the k-th point reduction; d_0 – the initial wall thickness of the stamped workpiece

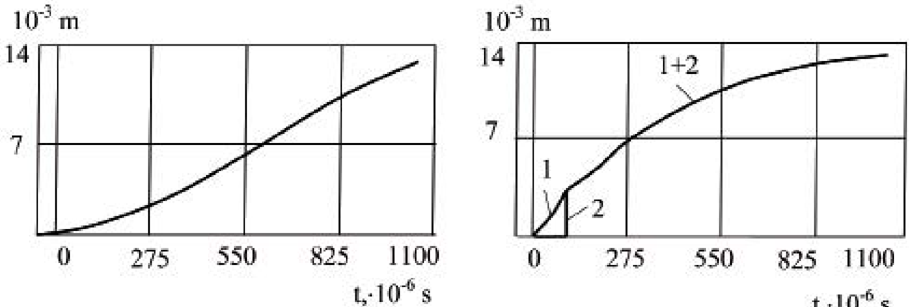
2) the relative intensity of the deformation over the cross section of drop-stamped workpiece

$$\Delta\bar{\varepsilon}_i = \frac{\varepsilon_{ik\,max} - \varepsilon_{ik\,min}}{\varepsilon_{is}}, \qquad (10)$$

where e_{ikmax}, e_{ikmin} – maximum and minimum deformations intensity value in the points of reduction (k); e_{is} – the intensity of the deformation corresponding to the transformation of metal workpiece into the plastic state.

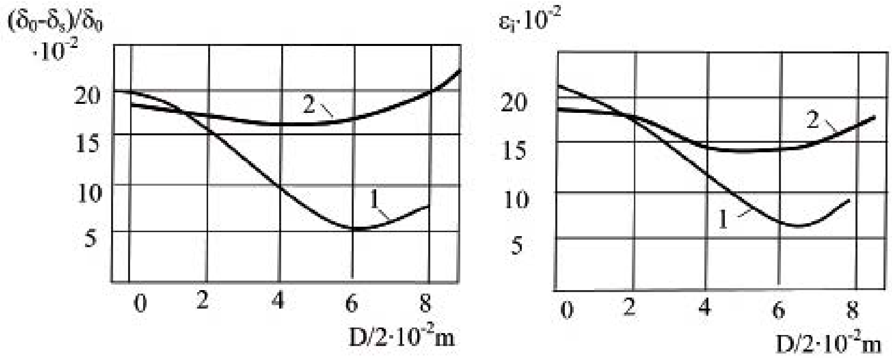
The results of calculations of deformation on radius (in the range 0-80 mm) of drop-stamped bimetallic workpiece obtained by explosion welding is shown in Fig. 4a, when combining the operations of explosion welding and explosion forming is shown in Fig. 4b. The process occurs when rigid clamping flange workpiece width of which is 20 mm.

Analysis of the results of numerical simulation showed that the quantitative characteristics (movement, velocity and acceleration) of the bimetallic workpiece during deformation and in its final state correspond to those given in [6], the experimental results obtained by high-speed photographic recording; the error of the characteristics lies within the confidence intervals.



a) b)

Figure 3. The moving center point of the bimetallic workpiece: a – when explosion welding; б – when combined operations of welding and explosive forming; 1 - AMg2M; 2 - 12X18H10T



a) b)

Figure 4. The deformation of the bimetallic workpiece in diametrical section:
a- changes in the relative deformations across the thickness (stretch pressing); b - distribution of intense deformations; d_0, d_s – initial and current thickness of the workpiece; 1 - explosion stamping; 2 - the combination of the operations of welding and explosive forming

Conclusion

1. The method of calculation of technological parameters under pulsed deformation of layered compositions that provide plastic deformation of the surface layers when contacting is developed.

2. On the basis of finite-difference approximation of the equations modeling the mechanics of the dynamic behavior of layered worpiece is proposed depending on calculation of its kinematics and stress-strain state.

3. Calculation results showed that the combination of operations of welding and forming explosion reduces non-uniform thickness of the workpiece in 3.2-3.45 times and almost even intensity deformation distribution along the diametrical section of the stamped workpiece.

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