ESTIMATION OF ENERGY AND POWER PARAMETERS OF DEFORMATION OF THREE-LAYER SHEET CONSTRUCTIONS IN CONDITIONS OF Viscoplastic Flow OF THE MATERIAL

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ABSTRACT

Sheet structures consisting of several layers are used to produce power hull products of high specific strength. The technology of manufacturing of three-layer sheet structures is based on the processes of gas-forming of sheets in an inert gas environment or in vacuum. The molding process can be realized in the mode of viscoplastic flow, in which the material under deformation is both viscous and plastic. However, the theory of deformation of multi-layer panels in conditions of viscoplastic flow is not sufficiently developed. This paper presents an approach to the development of mathematical models of pneumatic forming in viscoplastic flow mode. Resulting equations can be used to establish the dependence of process stability and molding pressure on various process parameters.

Keywords: pneumatic forming, pressure, three-layer constructions, viscoplastic flow mode.

INTRODUCTION

In comparison with brazed or riveted sheet structures [1 - 4], the multi-layer ones made of titanium and aluminum alloys or steel provide a sharp reduction in weight, less labor input, and increased reliability. The technology of manufacturing of three-layer sheet structures is based on gas-forming of sheets in an inert gas environment or in vacuum, previously connected by fusion welding or by diffusion pressure welding.

Depending on the geometric dimensions, there are several methods of stamping of three-layer sheet structures. One of them provides trapezoidal corrugation of a sheet by the press, diffusion pressure welding with subsequent calibration of the package with gas. Other three-layered sheet structures are formed by the movement (expansion) of one of the sheets (coatings) on which the inner sheet (filler) is fixed in certain places. The filler is stretched when one of the coatings is moved and cavities are formed, the shape of which is close to trapezoidal one. The process is realized by creating gas pressure supplied between the coatings [5 - 8].

CALCULATIONS

Let us consider the deformation of anisotropic material under short-term creep conditions. By short-term creep we mean slow deformation under conditions of viscous or viscoplastic flow, neglecting the elastic components of deformation [9 - 12].

In conditions of viscoplastic flow of material ( \( \sigma_e > \sigma_{e0} \) ) the equations of state are [9, 10, 12]:

\[
\sigma_e = \sigma_{e0} \left( \frac{\varepsilon_{ep}}{\varepsilon_{e0}} \right)^d \left( \frac{\varepsilon_{ep}}{\varepsilon_{e0}} \right)^k \left( 1 - \omega_A^{cp} \right)^r
\]

\[
\dot{\omega}_A^{cp} = \frac{\sigma_e}{A_{ep}} \frac{\varepsilon_{ep}}{\sigma_{e0}},
\]

if the behavior of the material is described by the energy theory of nonlinear viscoplastic flow and fracture, and

\[
\sigma_e = \sigma_{e0} \left( \frac{\varepsilon_{ep}}{\varepsilon_{e0}} \right)^d \left( \frac{\varepsilon_{ep}}{\varepsilon_{e0}} \right)^k \left( 1 - \Omega^{cp} \right)^r.
\]
if the behavior of the material is described by the kinetic theory of nonlinear creeping plastic flow and fracture. Here $B$, $n$, $m$, $k$, $d$, $r$ are material’s constants, depending on the temperature of the tests; $A_{cp}$, $A_{np}$, $A_{enp}$, and $A_{cpnp}$ - specific fracture energy and maximum equivalent deformation for viscous and viscoplastic flows of material; $E_{e np}$ and $E_{e np}$ are the values of the equivalent deformation for viscoplastic and viscous flow of the material; $\omega_e$, $\omega_e$, and $\omega_A$ - damageability of the material for viscoplastic and viscous deformation according to deformation and energy fracture models, respectively.

The value of $\sigma_{e0}$, separating the viscous and viscoplastic flow is assigned, depending on the mechanical properties of the material at the given deformation temperature, sensitivity of the material to deformation hardening at a certain deformation rate $\xi_{e0}$.

Let us consider isothermal pneumatic forming of a structural element in the form of a trapezium being exposed to uniform gas pressure, varying during the deformation process according to the law $p = p_0 + a_p t^\beta p$, where $p_0$, $a_p$, and $t$ are the loading constants, at high temperature under slow deformation conditions (Fig. 1) [11, 14, 15].

We assume that the deformation is carried out under conditions of short-term creep; elastic deformations are neglected. The validity of the associated flow law in short-term creep mode is assumed. The workpiece material is assumed to be orthotropic with the main axes of anisotropy $x, y, z$.

The anisotropy of the mechanical properties of the workpiece is characterized by the anisotropy coefficients for the viscous flow $\{R_x, R_y\}$ and viscoplastic flow $\{R_x^{cp}, R_y^{cp}\}$ of the material.

The material is isotropically strengthened in the case of viscous deformation, due to the rate of deformation, and in the case of viscoplastic flow of material - due to the degree of deformation and the rate of deformation. Since the length of the trapezoidal structural element greatly exceeds its geometric dimensions in the plane of drawing, we assume that the case of plane deformation is realized, and consequently the rate of axial deformation in the direction of the main axis $X$ of anisotropy is zero $\xi_X = 0$.

We assume that the stressed and deformed states are uniform, and the stresses are evenly distributed along the thickness of the structural element. The stress $\sigma_z$, normal to the thickness of the workpiece, is assumed to be zero $\sigma_z = 0$ for a thin plate, i.e. it is assumed that the plane stress state is also realized.

In the case when $\sigma_0 > \sigma_{e0}$ the viscoplastic flow of a material occurs, the state equation of which according to the energy theory of short-term creeping and fracture, has the form (1), but according to the kinetic theory of short-term creep and fracture - the form (2) [10, 11, 16, 17].

Let us assume that deformation of the coating is determined by a pressure $p(t)$. Having put the input values $\sigma_0$, $\xi_{e0}$, and $E_{e0}$ into the first of the state equations of the material (1), we obtain

$$p^{\frac{1}{k}} dt = -\frac{1}{\sigma_0^{\frac{1}{k}}} \left[ -C_1 \ln \left( \sin \alpha \right) \right]^{\frac{1}{k}} C_1 \frac{\sin \alpha \cos \alpha}{(\sin^2 \alpha + \cos^2 \alpha)^{\frac{1}{k}}} \left( T_{\alpha 0} \sin \alpha \right)^{\frac{1}{k}}$$

for the case of stamping of a trapezoid element of a three-layered sheet structure and for the case of calibration we get
Basing on the equation (1) we can calculate the damageability for stamping process

\[
p = \sigma_{ct} \left[ -C_1 \ln \left( \frac{\sin \alpha}{\sin \alpha_0} \right) \right]^{\frac{1}{2k}} h_0 \sin \alpha \cos \alpha \left( 1 - \omega_i^{1/p} \right)^{\frac{1}{2k}} \frac{D_1 \left( r_1 + r_2 \right)}{\left( \xi_0 \right)^{\frac{1}{2k}}} \text{d} \alpha
\]

\[
\omega_i^p = - \frac{C_1 D_1 \left( r_1 + r_2 \right) p \ctg \alpha}{A_{cp} h_0 \sin^2 \alpha} \quad \text{d} \alpha
\]

and for calibration

\[
p = \sigma_{ct} \left[ -C_1 \ln \left( \frac{\sin \alpha}{\sin \alpha_0} \right) \right]^{\frac{1}{2k}} h_0 \sin \alpha \cos \alpha \left( 1 - \omega_i^{1/p} \right)^{\frac{1}{2k}} \frac{D_1 \left( r_1 + r_2 \right) \sin \alpha_0}{\left( \xi_0 \right)^{\frac{1}{2k}}} \text{d} \alpha
\]

\[
\omega_i^p = - \frac{C_1 D_1 \left( r_1 + r_2 \right) p \sin \alpha_0}{A_{cp} h_0 \sin^2 \alpha} \quad \text{d} \alpha
\]

The system of equations (7) and (9) or (8) and (10) is solved with the help of the iteration method and is determined by \( p = p(\alpha) \) and \( \omega_i^p = \omega_i^p(\alpha) \).

Dependence of \( \alpha \) on time is found according to the following conditions:
- for stamping process
  \[
  \alpha = \arcsin \left( \frac{-\xi_0 e^{Lt}}{C_1} \right)
  \]
- and for calibration
  \[
  \alpha = \arcsin \left( \frac{-\xi_0 e^{Lt}}{C_1} \right)
  \]

Let us consider the deformation of a trapezoidal element of a multilayer sheet structure with constant pressure \( p = \text{const} \).

Damageability in this case will be calculated according to the relation (1):
- for stamping process
  \[
  \omega_i^p = \frac{C_1 D_1 \left( r_1 + r_2 \right) p \ctg \alpha}{A_{cp} h_0}
  \]
- and for calibration
  \[
  \omega_i^p = - \frac{C_1 D_1 \left( r_1 + r_2 \right) \sin \alpha_0 p}{A_{cp} h_0 \sin \alpha_0 - \ctg \alpha}
  \]

In equations (13) and (14) it is assumed that
\[
\frac{\sigma^{cp}}{\sigma} = \frac{\xi^{cp}}{\xi} = \text{const,} \quad \frac{\sigma^{cp}}{\sigma} = \text{const,}
\]

\[
\xi^{cp} = \xi_{e_{\text{min}}}^{cp} = \xi^{cp}
\]

Using equations (13) and (14) at \( \omega_i^p = 1 \) we get the angle of midline arc opening at the moment of fracture \( \alpha^* \) for stamping and calibration respectively

\[
\alpha^* = \arctg \left( \frac{A_{cp} h_0}{C_1 D_1 \left( r_1 + r_2 \right) p} \right)
\]

and

\[
\alpha^* = \arctg \left( \frac{A_{cp} h_0}{C_1 D_1 \left( r_1 + r_2 \right) \sin \alpha_0 p + \ctg \alpha_0} \right)
\]
When stamping the trapezoidal elements, the dimensionless value of fracture time can be determined by formula

$$
\bar{t}_{o_{1}} = -\int_{\alpha_{o}}^{\alpha} \left(1 - \omega_{o}^{p}\right) \left(\sin \alpha\right)^{d/k} \left(\cos \alpha\right)^{d/k} \frac{d\alpha}{\alpha \tan \alpha} \left[-\ln \left(\sin \alpha\right)\right]
$$

where

$$
\bar{t}_{o_{1}} = \frac{p^{1/k} c_{e_{0}} ^{d/k} \xi e_{0} D_{e_{0}}^{d/k} \left(r_{1} + r_{2}\right)^{1/k}}{\sigma_{e_{0}} c_{1} C_{1} h_{1}^{d/k} \left(\sigma_{e_{0}}\right)^{d/k} C_{1} C_{1} h_{0}^{d/k}}
$$

in the case of calibration

$$
\bar{t}_{c_{o}} = -\int_{\alpha_{o}}^{\alpha} \left(1 - \omega_{o}^{p}\right) \left(\sin \alpha\right)^{d/k} \left(\cos \alpha\right)^{d/k} \frac{d\alpha}{\alpha \tan \alpha} \left[-\ln \left(\sin \alpha\right)\right]
$$

where

$$
\bar{t}_{c_{o}} = \frac{p^{1/k} c_{e_{0}} ^{d/k} \xi e_{0} D_{e_{0}}^{d/k} \left(\alpha_{o} + r_{2}\right)^{1/k}}{\sigma_{e_{0}} c_{1} C_{1} h_{1}^{d/k} \left(\sigma_{e_{0}}\right)^{d/k} C_{1} C_{1} h_{0}^{d/k}}
$$

If the material is subject to the kinetic theory of viscoplastic flow and fracture, then the damageability is calculated according to the equation (2): for stamping process

$$
\omega_{e}^{p} = \frac{C_{1}}{\key c_{e_{0}}^{p} \xi e_{0}} \int_{\alpha_{o}}^{\alpha} \alpha \frac{d\alpha}{\alpha \tan \alpha} = \frac{C_{1}}{\key c_{e_{0}}^{p} \xi e_{0}} \ln \left(\frac{\sin \alpha}{\sin \alpha_{o}}\right)
$$

and for calibration

$$
\omega_{e}^{p} = -\frac{C_{1}}{\key c_{e_{0}}^{p} \xi e_{0}} \int_{\alpha_{o}}^{\alpha} \alpha \frac{d\alpha}{\alpha \tan \alpha} = -\frac{C_{1}}{\key c_{e_{0}}^{p} \xi e_{0}} \ln \left(\frac{\sin \alpha}{\sin \alpha_{o}}\right)
$$

It is assumed that \( e_{e_{0}}^{p} = \text{const} \), since

$$
\frac{\sigma^{p}}{\sigma_{e}} = \text{const} \quad \text{and} \quad \frac{\xi^{e_{0}}}{\xi_{e_{0}}} = \frac{\xi^{p}}{\xi_{e_{0}}} = 1.
$$

The maximum angle \( \alpha^{*} \) is calculated under the condition that \( \omega^{p}_{o} = 1 \), as follows:

$$
\alpha^{*} = \arcsin \frac{\xi^{p}}{c_{1}}
$$

and

$$
\alpha^{*} = \arcsin \left[ \frac{\sin \alpha_{o} e_{c_{1}}^{p}}{c_{1}} \right]
$$

in the cases of stamping and calibration of trapezoidal elements of multi-layer sheet structures.

The analysis of relations (21) and (22) shows that the limits of pneumatic forming do not depend on the deformation time.

Basing on equations (3) or (4), it is possible to establish the law of pressure \( P(t) \) change, if we substitute the values \( \omega^{p}_{o} \), that are calculated according to formulas (19) or (20) in cases of stamping or calibration of trapezoidal elements.

Let us consider the solution, when \( \xi^{p}_{e} = \xi_{e_{0}}^{p} \). In this case, when stamping or calibrating, the pressure \( p(\alpha) \) is determined by equations (7) or (8), taking into account the relations (19) or (20).

Expressions characterizing the change in the angle \( \alpha \) with time of deformation, are written as follows: for stamping process

$$
\alpha = \arcsin \left[ \frac{\xi^{p}_{e_{0}}}{c_{1}} \right]
$$

and for calibration

$$
\alpha = \arcsin \left[ \frac{\sin \alpha_{o} e_{c_{1}}^{p}}{c_{1}} \right]
$$

Let us assume that \( \rho = \text{const} \). According to formulas (19) or (20), it is possible to estimate the damageability, and the dimensionless time of coating fracture \( \bar{t}_{s_{o}} \) is found by formulas (17) or (18) with \( \omega^{p}_{o} \) being substituted by \( \omega^{p}_{o} \).

**CONCLUSIONS**

The obtained equations can be used to establish the dependencies of process stability and molding pressure on various process parameters, which in turn will make it possible to develop recommendations for designing the technological processes of pneumatic forming.

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REFERENCES


