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# Analysis of the SPF of a titanium alloy at lower temperatures

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**Abstract**

This paper analyses a possibility to decrease the temperature of the industrial forming of the VT6 alloy. Experimental laboratory studies of the mechanical properties of the material show that one can lower the temperature of industrial superplastic forming. A developed mathematical model is proposed and enables to calculate an optimum pressurization taking into account the structural state of the shell material and principles of the shell friction on the die surface.

The calculated pressurization enables to obtain the optimum superplastic properties of the material in the maximum area of the deformed shell.

The proposed model has been checked up experimentally. In laboratory conditions, the forming of special workpieces with calculated pressurization has been conducted. The experimental researches confirm the made theoretical forecasts about a capability of decreasing the forming temperature of SPF VT6 alloy components.

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*Keywords:* Titanium alloy; Mechanical properties; Superplastic forming; Friction; Mathematical simulation; Experimental check

## 1. The purposes and research problems

Titanium alloys are used in the aerospace industry thanks to their high specific strength (i.e. the ratio between ultimate strength to density). Unfortunately, the cold-pressing of the titanium sheets is impossible. Consequently, semi-finished materials of titanium alloys are rather expensive, in particular because of the large number of technological process stages (numerous vacuum remelt, labor-consuming heat treatment, and so on). The superplastic state is an effective way to manufacture complex parts at once and consequently enables to lower the cost of their manufacturing.

Diphasic titanium alloys enable serial superplastic forming from industrial sheets without any special preparation of the structure. Therefore, they are named “naturally” superplastic.

Optimum temperature of the SPF for the widespread titanium alloy VT6 (Ti–6% Al–4% V) corresponds to 900–925 °C [1,2]. It is then desirable to lower the SPF temperature in order to reduce the oxidizing and erosion of matrices, and in order to lower the cost of the forming equipment and to increase its service life.

The present researches have been carried out with the purpose of defining the temperature dependence of mechanical properties of titanium alloys and their ability to superplastic deformation. The first experimental stage is the origin of a developed fundamental theory of optimization of the SPF at lower temperatures. A great amount of attention is given to numerical construction of the forecasts forming and its experimental check.

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## 2. Statement of the problem on slow drift of physically non-linear mediums with due regard for contact friction

The numerical model will consider the contact between the die and the sheet. This section aims to present the way the friction is calculated.

The statement of a boundary problem form changing of a material in conditions close to supeplasticity will be surveyed. The system of differential equations describing process form change at a forming also will be obtained. The large attention will be given to a way of the definition of boundary conditions on a contact surface of a title block and shell. The constructed mathematical model will be used at a numerical simulation of technological processes.

Let the body under consideration be located within an area with the boundary $S$ in the Cartesian system of coordinates $X_m$ at a given time $t$. Let us designate the vector of superficial forces acting on the part of the boundary surface $S_\sigma$, as $\overline{P}_n = P_{n_i} \cdot \overline{k}_i$, the vector of displacement speeds, preset on the other part of the boundary surface $S_u$, as $\overline{\varphi} = \varphi_i \cdot \overline{k}_i$. Mixed boundary conditions of contact type are preset on the boundary section $S_{\sigma u}$. It is naturally supposed that $S_\sigma + S_u + S_{\sigma u} = S$. Then, boundary conditions on the contour of a body being deformed can be written down as follows:

$$\begin{aligned}
&\overline{S}_n = \overline{P}_n, \overline{S}_n = \overline{S}_i \cdot L_{n_i} = \sigma_{ij} \cdot L_{n_i} \cdot \overline{k}_j && \text{on the } S_\sigma;\\
&\overline{U} = \overline{\varphi}, \overline{U} = u_i \cdot \overline{k} && \text{on the } S_u;\\
&\overline{P}_n = \overline{S}_\alpha \cdot L_{n_\alpha} = \sigma_{\alpha_j} \cdot L_{n_\alpha} \cdot \overline{k}_j, \overline{U} = u_\beta \cdot \overline{k}_\beta && \text{on the } S_{\sigma u};
\end{aligned} \quad (1)$$

$\alpha, \beta = 1, 2$; $\alpha + \beta = 3$ (there is no summation by the indexes $\alpha$ and $\beta$).

Let us introduce designations:

$\sigma_{ij}$ are components of the stress tensor;
$\dot{\varepsilon}_{ij}$ are components of the strain rate tensor;
$u_i$ is the displacement speed of particles of the medium.

Deviators of stresses and of strain rates are designated with a wavy line atop:

$$\tilde{\sigma}_{ij} = \sigma_{ij} - \sigma \cdot \delta_{ij}, \qquad \sigma = \frac{1}{3}\sigma_{ij} \cdot \delta_{ij}, \qquad \tilde{\dot{\varepsilon}}_{ij} = \dot{\varepsilon}_{ij} - \dot{\varepsilon} \cdot \delta_{ij},$$

$$\dot{\varepsilon} = \frac{1}{3}\dot{\varepsilon}_{ij} \cdot \delta_{ij} = \frac{1}{3}\dot{\theta}. \quad (2)$$

The Cauchy ratios connecting components of the strain rate tensor and particles displacement speed look like:

$$\dot{\varepsilon}_{ij} = \frac{u_{i,j} + u_{j,i}}{2} \quad (3)$$

The second invariants of the deviators $\tilde{\sigma}_{ij}$ and $\tilde{\dot{\varepsilon}}_{ij}$ will also be of essential importance. The square roots of these invariants (modules of deviators) are designated as:

$$\tilde{\sigma} = \sqrt{\tilde{\sigma}_{ij} \cdot \tilde{\sigma}_{ij}} = \sqrt{\frac{2}{3}} \cdot \sigma_u; \qquad \tilde{\dot{\varepsilon}} = \sqrt{\tilde{\dot{\varepsilon}}_{ij} \cdot \tilde{\dot{\varepsilon}}_{ij}} = \sqrt{\frac{3}{2}} \cdot \dot{\varepsilon}_u \quad (4)$$

Deviators of stresses and strain rates are proportional, as well as for the non-linear isotropic viscous liquids case:

$$\tilde{\sigma}_{ij} = 2\mu \cdot \tilde{\dot{\varepsilon}}_{ij} \quad (5)$$

By squaring the left and right parts of this ratio, we shall receive:

$$2\mu = \frac{\tilde{\sigma}}{\tilde{\dot{\varepsilon}}} = \frac{2}{3}\frac{\sigma_u}{\dot{\varepsilon}_u} \quad \text{or} \quad \sigma_u = 3\mu \cdot \dot{\varepsilon}_u \quad (6)$$

Then:

$$\sigma_{ij} - \sigma \cdot \delta_{ij} = \frac{2}{3}\frac{\sigma_u}{\dot{\varepsilon}_u}(\dot{\varepsilon}_{ij} - \dot{\varepsilon} \cdot \delta_{ij}). \quad (7)$$

The hypothesis of medium incompressibility is accepted when solving problems of deformation of metals. However, doing so, number of equations (and accordingly number of values to be sought) increases. This frequently leads to essential increasing memory and operation time when calculating by means of computer. Besides, when using the finite elements method, the condition of incompressibility can lead to difficulties and even makes it impossible to use the simplest and convenient triangular elements [3].

One can avoid these difficulties considering the medium to be compressible [4,5]. Let us accept that spherical parts of the stress tensor and strain tensor are connected by means of Hooke's law:

$$\begin{aligned}
\sigma &= K \cdot \theta = K \int_0^t \dot{\theta}\, \mathrm{d}t \\
&= K \left[ \int_0^{t_1} \dot{\theta}\, \mathrm{d}t + \int_{t_1}^{t_2} \dot{\theta}\, \mathrm{d}t + \cdots + \int_{t_{n-1}}^{t} \dot{\theta}\, \mathrm{d}t \right] \\
&= K \sum_{i=0}^{n-1} \Delta t_i \cdot \dot{\theta}_i + K \cdot \Delta t_n \cdot \dot{\theta}_n = \sigma^* + K \cdot \Delta t \cdot \dot{\theta}.
\end{aligned} \quad (8)$$

Integral–differential equations of motion can be reduced to differential equations of the same order.

After accomplishing the correspondent substitutions in (7), ratios between stresses and speeds can be written as follows:

$$\sigma_{ij} = \mu(u_{i,j} + u_{j,i}) + \left[ \left( K \cdot \Delta t - \frac{2}{3}\mu \right) u_{p,p} + \sigma^* \right] \delta_{ij}. \quad (9)$$

The field of temperatures $T$, for the problems under consideration, is supposed to be known, and consequently the equations of mechanics of continua become closed to the only relationship $\sigma_{ij} \sim \dot{\varepsilon}_{ij}$.

Shape change of the material in the superplastic state takes place at a low strain rate. The deformation process is slow enough to be considered as quasistatic. Thus, the whole forming time is divided into subintervals $\Delta t$ within which displacement speed is considered to be changeless. It enables the equilibrium equation to be fulfilled at each step of the deformation:

$$\sigma_{ij,j} = 0. \quad (10)$$