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PROBLEM OF PROCESSING MATERIALS BY PRESSURE UNDER CREEPAGE CONDITIONS

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The pressure-processing of materials in the hot state is widely used in technology. The processing is usually not continuous, and deformation of the article is achieved due to "instantaneous" plastic deformation, while an increase in temperature, on the one hand, increases the plasticity of the material, and on the other reduces the force required for the deformation.

In recent years a considerable number of investigations have been made on the superplasticity of materials and the use of this phenomenon for the pressure-processing of materials. Superplastic behavior of a material is observed when it is in certain structural states, and in certain temperature ranges. But in all cases one of the decisive factors which facilitates superplastic deformation is slow loading. In such processes time plays an important part and deformation of creepage makes the main contribution to the total irreversible plastic deformations. Without dwelling on the physical reason and the similarities and differences in "instantaneous" plastic deformations and deformations of creepage, which develop with time, from the phenomenological point of view it can be stated that irreversible deformations determined by the laws of creepage are the initiating factors in superplasticity. In this sense, the hot processing of materials with slow loading should really be called "pressure-processing of materials under creepage conditions" [1]. Unlike the technological processes of processing materials in the superplastic state, processing under creepage conditions is less limited by technical difficulties and can be used in practice for all materials, including materials that are difficult to deform.

Publications on the use of creepage processes in the pressure-processing of materials have only appeared comparatively recently. In [2-4], neglecting the elastic–plastic components of the deformation and taking into account only deformation of creepage, solutions have been given of the problem of the sagging of a strip of a circular cylinder, longitudinal rolling, and a number of other problems encountered in technology. In [1, 5] some general considerations and experimental data on the possibility of using creepage in technological processes are presented, and the advantage of forming articles under slow rather than rapid loading conditions is pointed out. In [6] a description is given of a device which can be used in appropriate technological processes. But, on the whole, the number of papers on the experimental and theoretical principles of the use of creepage in the pressure-processing of materials is very small, which is undoubtedly the reason for the slow rate of development of this process.

Below we describe experiments which show the advantages of slow loading over fast loading. Using the generally accepted creep relations we give approximate methods of analyzing

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the bending of the elements of thin-walled constructions and we also compare the results with experiment. The applicability of the method is illustrated using the example of the formation of a ribbed panel.

In Fig. 1 we show $\sigma-\epsilon$ deformation diagrams of AK4-1 alloy at a temperature of 300°C with different loading rates $d\sigma/dt$ kg/mm^2•sec. It can be seen that when the loading rate is reduced, when the componentof the creep deformation to the total value of irreversible deformations is increased, the overall value of the deformations to the breaking moment ϵ_* increases monotonically. The area bounded by the abscissa axis and the deformation curve is the vlaue of the specific dissipated work of irreversible deformation $A_i = \int_0^\varepsilon \sigma d\varepsilon$. It is seen from Fig. 1 that its value remains practically constant and is independent of the rate of loading. Experimental investigations both in the area of solid-state mechanics and in metal physics show that the degree of damage of the material when it is deformed is fairly well correlated with the value of the work done, and, to a first approximation, it can be assumed that the damage is directly proportional to this quantity [7]. Hence, it follows that if during the pressure-processing of a material it is necessary to deform it to a certain value of the deformation ϵ_0 the degree of damage of the material on rapid loading is greater than on slow loading. This can be clearly seen from a comparison of the hatched areas under the curves in Fig. 1. As the temperature is increased this effect, as a rule, increases.

Similar results were obtained on the material AMG-6M at a temperature of 200°C [5], and on VT-5 titanium alloy at temperatures of 400-500°C, where deformation of creep is four times the value of the plastic deformation up to the instant of breakage, and also in a number of other materials.

The increase in the deformations ϵ_* when the rate of loading is reduced, observed experimentally, can be explained qualitatively as follows. When the material is loaded, inside it at the joints between the grains stresses arise whose value may differ considerably from the average macrostresses. At increased temperatures and for slow loading the stress "peaks" that arise can relax, and microcracks, nuclei for local breakage of the material, may occur at the joints of the grains for large rates of loading, which considerably reduce its overall reserves of strength.

To verify this we carried out the following experiments. Specimens of AK4-1 alloy at a temperature of 195°C, 1201 alloy at a temperature of 180°C, and V95 alloy at a temperature of 150°C were deformed to a certain fixed value of the deformation ϵ_0 under rapid loading conditions (the deformation process was continued for not more than 10 sec), and under slow loading conditions for a time of the order of two hours. After deformation of the specimens thin sections were made along the working length of the specimens and their microstructure was subjected to a metallographic analysis. The investigations showed that in specimens subjected to rapid loading, pores could be clearly seen along the grain boundaries, the structure was less uniform, and the orientation was not very pronounced. For slow deformation the structure was more uniform, the grains are stretched, and are oriented in the direction of deformation, and practically no pores are observed on the grain boundaries. For large values of the deformations ϵ_0 the difference between the specimens subjected to rapid and slow loading can also be detected by an external examination: the surface of the first specimens had a matte shade and a pronounced porosity, while the surface of the second remained quite smooth.

The following data also favor slow loading. Two batches of specimens, cut from monolithic panels of AK4-1 alloy after deformation at a temperature of 195°C under rapid and slow loading conditions, were subjected to standard tests with respect to such parameters as the shock viscosity, fatigue, long-term strength, creep, etc. For all the parameters, the batches cut from panels formed under slow loading had better characteristics than the batches cut from panels formed under rapid loading conditions. For example, the creep limit increased by 15-20%, and the time to breakage in the tests on long-term strength increased by an order of magnitude.

The above data clearly illustrate the advantages of processing materials by slow loading under creepage conditions both from the point of view of increasing the reserves of strength in manufactured articles compared with rapid processing, and from the point of view of reducing the power of the equipment required for processing the material. It is obvious that the

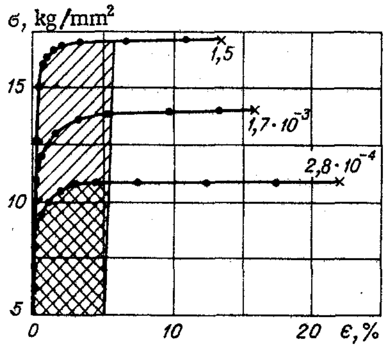

Fig. 1

higher the temperature at which the materials are processed by pressure, the more intensely does the stress relaxation process occur in elements of the formed article, and the less will be its elastic recovery. At sufficiently high temperatures we would expect practically complete absence of elastic springiness of the article after it has been processed. However, at high temperatures thermal softening of the material occurs which results in a loss of a number of important tensile properties. Their recovery by subsequent thermal processing is often inadmissible for articles made with high accuracy. In this sense pressure processing at medium temperatures has certain advantages due to deformation of creep. However, the problem of estimating the elastic recovery of articles is then important.

The geometry of the forming matrix, taking into account the advance on the value of the elastic recovery, should be determined by calculations of the elastic–plastic deformation of the article and the relaxation of the stresses in it as a result of the creep of the material. The time the article is kept at the temperature under load in the compressed state is important for the calculations, since the springiness is determined by the level of the nonrelaxed stresses at the instant when the load is removed.

We will illustrate the procedure for calculating the elastic springiness using examples of the calculation of beams for the case when a compression is applied to a matrix of radius R_N instantaneously with the temperature and the article is maintained in the compressed state for a time t_{co}. After the load is removed, the beam will have a residual radius of curvature R_{cu}, which is determined by the residual moment acting over the cross section of the beam at the instant the load is removed. Calculations of the relaxation of the moment were carried out using the generally accepted assumptions for pure bending of the beams. From the hypothesis of plane cross sections

$$\sigma/E + \varepsilon_p + \varepsilon_c = \varkappa_N(z + \delta), \ \varkappa_N = 1/R_N = \text{const} \tag{1}$$

and the equation of equilibrium

$$\int_F \sigma dF = 0; \tag{2}$$

using well-known methods and taking the geometry of the beam cross section into account, we will determine the stressed state at the initial instant of time (the instant when compression is applied to the matrix). Here δ is the displacement of the neutral plane, the origin of coordinates is at the center of gravity of the cross section, ε_p is the instantaneous plastic deformation given by the equation

$$\varepsilon_p = K|\sigma|^{m-1} \ \sigma, \tag{3}$$

and ε_c is the deformation of creep, described by the creep equation

$$\frac{d\varepsilon_c}{dt} = f(\sigma, A), \quad A = \int_0^{\varepsilon_c} \sigma d\varepsilon_c. \tag{4}$$

From the stress state obtained, using the analytical approximation of the curve of instantaneous deformation and Eq. (3), we will determine the distribution of the plastic deformations over the height of the beam, which will henceforth be assumed to be "frozen" since reduction in the stresses continues to occur.

Substituting the stresses obtained from (1), taking into account the known instantaneous deformations of plasticity $\varepsilon_p^o(z)$, into the expression for the rates of deformation of creepage (4), we obtain an integrodifferential equation for determining the deformations of creep over the height of the beam with time,

$$\frac{d\varepsilon_c}{dt} = \varphi\left(\varepsilon_c, \varepsilon_p^0, \varkappa_N, \delta, A\right), \tag{5}$$

where $\delta = \int\limits_F \left(\varepsilon_p^0 + \varepsilon_c\right) dF/(\varkappa_N F)$ is found from the equilibrium equation (2) taking into account the hypothesis of plane cross sections (1). By dividing the cross section of the beam into intervals over the height and replacing the integrals in (5) by finite sums, we obtain a system of differential equations in ε_c^k. These can be solved by the Runge–Kutta method, as for pure bending of a beam with constant moment [8]. From the deformations of the creep obtained and the previously obtained plastic deformations, we determined the stresses over the height of the beam at any instant of time. The residual moment and the residual curvature of the beam can be calculated from the equations

$$M(t_{co}) = \int\limits_F \sigma z dF; \tag{6}$$

$$\varkappa_{cu} = \varkappa_N - M(t_{co})/EI, \tag{7}$$

where $I = \int\limits_F z^2 dF$.

In Fig. 2a the marks show the results of three experiments on the relaxation of the bending moment on beams of rectangular cross section (width 10 mm and height 20 mm) made of AK4-1T at a temperature of 200°C. The specimens were first aged for 15 h.

The results of tests of the short-term creep for a constant stress showed that the material possesses different properties of stretching and compression and has a pronounced strengthened creep section. The creep curves can be approximated by the relation

$$\frac{d\varepsilon_c}{dt} = \frac{B|\sigma|^{n-1}\sigma}{A^\alpha}, \text{ where } A = \int\limits_0^{\varepsilon_c} \sigma d\varepsilon_c,$$

with the following characteristics:

$$B_1 = 0.3\cdot10^{-54}(\text{mm}^2/\text{kg})^{n_1-\alpha_1}\ \text{h}^{-1},\ n_1 = 38,\ \alpha_1 = 0.54 \text{ for stretching,}$$

$$B_2 = 0.36\cdot10^{-23}(\text{mm}^2/\text{kg})^{n_2-\alpha_2}\ \text{h}^{-1},\ n_2 = 15,\ \alpha_2 = 0.90 \text{ for compression.}$$

The diagrams of instantaneous plastic deformation were approximated by relation (3) with the corresponding constants:

$$K_1 = 2.5\cdot10^{-45}(\text{mm}^2/\text{kg})^{m_1},\quad m_1 = 28 \text{ for stretching,}$$

$$K_2 = 6\cdot10^{-22}(\text{mm}^2/\text{kg})^{m_2},\quad m_2 = 12 \text{ for compression.}$$

The modulus of elasticity $E = 6\cdot10^3$ kg/mm². The results of the calculation with the above characteristics are shown in Fig. 2a by lines, where the initial bending moments corresponding to the three different curvatures $\varkappa_n$ mm^{-1} are shown by the arrows.

The fairly good agreement between the experimental and theoretical data on the relaxation of the bending moments confirms the theoretical procedure.

It should be noted that calculations taking the first and second stages of creep into account involve a large amount of calculation. In practice when solving creep problems a simplification is used in view of the fact that the deformations of the first stage of creep are included in the instantaneous plastic deformation. This enables the defining creep equations to be simplified and reduces the amount of computer time required. Obviously, calculations using this approach differ from the true process during the initial period, but the theoretical values approach the experimental values with time.

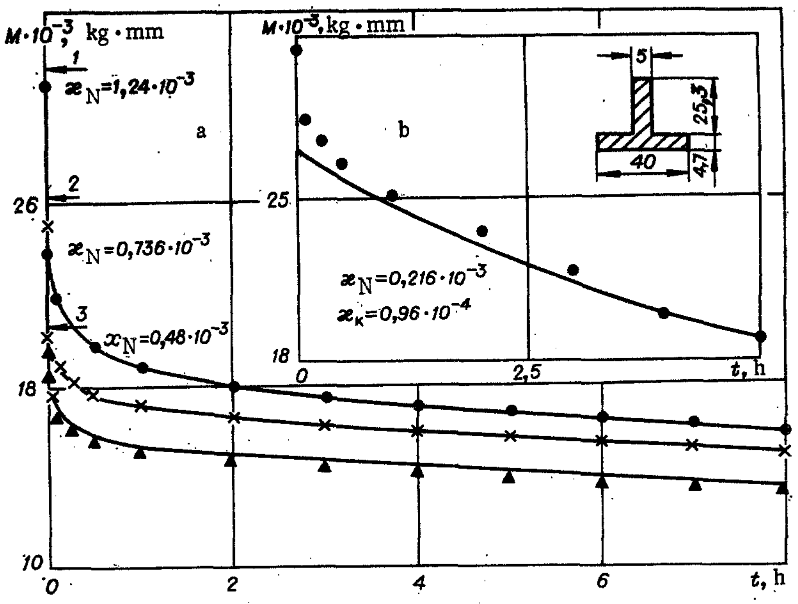

Fig. 2

The points in Fig. 2b show experimental data of the relaxation of the moment in a T-beam for $\varkappa_N = 0.216 \cdot 10^{-3}$ mm^{-1}, and the lines represent the results of calculations using the simplified equations. The material used was 1201-AT, and the temperature at which the tests were made was 180°C; the geometrical dimensions of the T-beam are shown in Fig. 2b, and the rib operates in compression. We used the following characteristics of the material in the calculation: $E = 5.7 \cdot 10^3$ kg/mm², in the region of stretching: $B_1 = 0.54 \cdot 10^{-38}$ $(\text{mm}^2/\text{kg})^{n_1}$ h^{-1}, $n_1 = 27$, $\alpha_1 = 0$, $K_1 = 0.74 \cdot 10^{-6}$ $(\text{mm}^2/\text{kg})^{m_1}$, $m_1 = 3$; in the compression region: $B_2 = 0.21 \cdot 10^{-49}$ $(\text{mm}^2/\text{kg})^{n_2}$ h^{-1}, $n_2 = 33$, $\alpha = 0$, $K_2 = 0.69 \cdot 10^{-18}$ $(\text{mm}^2/\text{kg})^{m_2}$, and $m_2 = 11$.

The value of the residual curvature of the T-beam $\varkappa_k$ was found from Eq. (7).

Figure 3 shows the distribution of the stresses over the height of a T-beam of AK4-1T material at different instants of time. We used the characteristics of the material in the delivered state in the calculations. The broken curve represents the residual stress curve after elastic recovery for a duration of the process $t_{co} = 5$ h.

It is seen from the results shown in Fig. 3 that the base of the T-beam with part of the rib up to the central axis operates in the elastic region, and the stresses relax only in the shelf. Hence, for calculations of T-beam elements of profiles, including stepped T-beams, in which the center of gravity of the cross section is close to the base of the shelf, it is sufficient to use the plasticity and creep characteristics of the material only in compression, if the shelf is subjected to compression, or only in extension, if the shelf is stretched. This is confirmed by direct calculations. For profiles in which the neutral plane is the plane of symmetry, for an accurate calculation of the elastic recovery it is necessary to use the characteristics of the material in extension and compression.

By changing the initial curvature $\varkappa_N$, as a result of calculation we will have a set of residual curvatures of the beam $\varkappa_{cu}$ for the same duration of the process t_{co}. By constructing a $\varkappa_N = \varkappa_N(\varkappa_{cu})$, and specifying the required curvature of the article $\varkappa_a$, we can find from the nomogram the required curvature of the fittings $\varkappa_0 = \varkappa_N(\varkappa_a)$. By using the nomogram we can calculate the geometry of the fittings taking into account the advance on the value of the elastic springiness for articles of constant cross section with variable radius of curvature. For articles with variable rigidity it is necessary to have a number of nomograms for rigid basis elements.

It was noted above that the slow forming mode is preferable to rapid forming due to creep of the material, since a stable process occurs with minimum accumulation of damage in the material, which leads to an increase in the reserves of the article. The results shown in Figs. 2 and 3 relate to instantaneous elastic—plastic loading and subsequent stress relaxation. There are no basic difficulties in calculating the relaxation of the internal stresses for

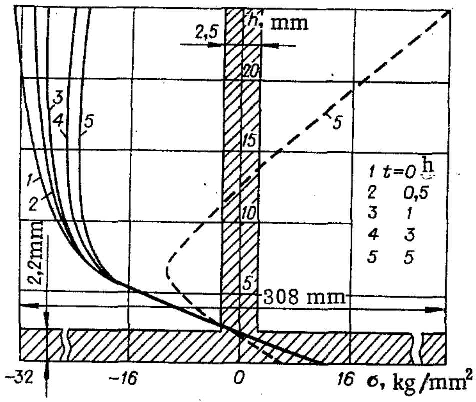

Fig. 3

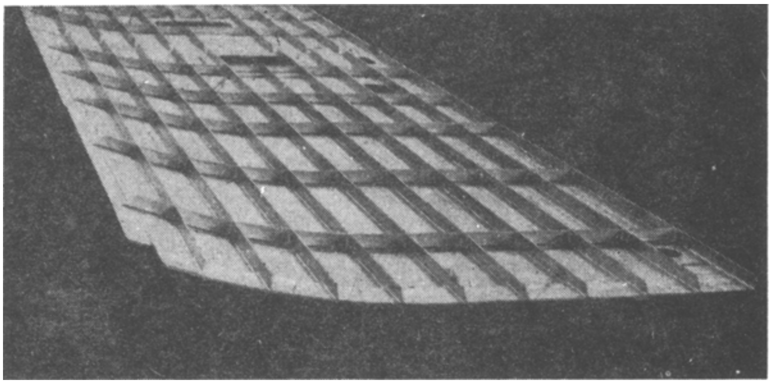

Fig. 4

slow loading of a beam. Direct calculations show that for certain rates of loading it is possible for forming to occur due solely to creep deformations, which provides the possibility of a considerable increase in the resource of the article.

The results obtained on T-beams form the basis of a calculation of the geometry of fittings for forming ribbed panels, taking their elastic recovery into account. The panel was divided into parts with T-shaped elements of different cross section. Since the base of the panel operates in the elastic region without stress relaxation, it was assumed that the relaxation processes in the neighboring and crossing ribs occur independently. This enabled us, using the nomograms of the basis elements of the panels, to calculate the geometry of the fitting as a whole for the whole panel.

Figure 4 shows the formed panel. The technological fitting carried out using the above theoretical procedure ensured the required forming accuracy. The technology for forming ribbed panels under creep conditions developed above has been introduced in one of the industries.

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