DETERMINATION OF THE RESERVE OF PLASTICITY UNDER THE ACTION OF A CURRENT

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A model of exhaustion of the reserve of plasticity of a material under the pulsed action of a current based on the hypothesis of damage of material in plastic deformation related to formation of crack-type defects is proposed. As the result of mosaic thermal action of the current melting-shut of the defects occurs and also formation of zones of local recrystallization and compressive residual stresses, which increases the reserve of plasticity (limiting plastic deformation). The question of the optimum selection of the current parameters during plastic deformation is studied on the basis of the proposed model.

In solution of production problems of working of metals by pressure it is necessary to have available information on the reserve of plasticity of the material (or the limiting plastic deformation). Here there is proposed a model of exhaustion of the reserve of plasticity under conditions of the electroplasticity effect. As is known, the electroplasticity effect [1-7] involves a significant improvement in plasticity (increase in limiting plastic deformation) of a previously deformed material under the pulsed action of an electric current of a certain specific energy \( q \approx 10^9 J/m^3 \) and time of this action \( \tau < 0.1 \text{ sec} \).

It has been experimentally established [1-7] that the electroplasticity effect has a maximum for the specific energy \( q \) but in this range depends weakly upon the time of action \( \tau \). This effect has a residual character and is observed both in separate and in the combined action of current and load. There is also a relationship of it to the form of preliminary plastic deformation and direction of action of the current. The qualitative basis of the effect is given in [1-4, 8-11], in which a version of the mosaic temperature field, which is caused by localization of the current energy at crack-type defects of the material activated in preliminary plastic deformation, is advanced and mathematically confirmed. Earlier [5-7] determining relationships of electroplasticity both under combined and separate action of current and deformation were proposed.

One of the possible approaches to construction of the model of exhaustion of the reserve of plasticity is construction of a model not dependent upon selection of the determining relationships since the effect of an increase in limiting plastic deformation is the determining one in electroplasticity. Such an approach may be used, for example, using the idea of damage of a material in plastic deformation [12, 13] and also a version explaining the electroplasticity effect by the thermal action of the current in crack-type defects of the material.

In plastic deformation of a material damage of it (formation of cracks) occurs, which leads to exhaustion of the reserve of plasticity. With damage there is a decrease in the effective (true) section in any section in a small element of the material. It may be assumed that the relative change (decrease) in the useful section with a normal of \( \Delta S_n/S_n^0 \) depends upon the plastic deformation normal to this cross section \( p_n = p_{ij} n_i n_j \). Failure starts if in one of the cross sections \( \Delta S_n = S_n^0(\Delta S_n/S_n^0 = 1) \). Let us assume that

\[
\frac{\Delta S_n}{S_n^0} = \begin{cases} 
\alpha(p_n/p_c), & f(1) = 1 \quad \text{with} \quad p_n \geq 0; \\
0, & \text{with} \quad p_n < 0
\end{cases}
\]

(1)

where \( p_c \) is the limiting plastic deformation at which failure starts for uniform tension. With \( p_n < 0 \) the cross section with the normal \( n \) is not damaged since cracks do not open up from compressive plastic deformations.
Under the action of the current together with formation of zones of local contraction "healing" of the formed cracks occurs, which leads to an increase in the reserve of plasticity (limiting plastic deformation) and therefore determines the electroplasticity effect. As the result of experiments [1-4] it has been established that the effect depends not only upon the tensor of preliminary plastic deformation \( \mathbf{p}_0 \) and the specific energy of the current \( q \) but also upon the direction of action of the current \( \bar{q}/q \) (the vector \( \bar{q} \) is directed parallel to the vector of current density and has the value \( q \)). The decrease in the relative effective section \( \Delta S_n/S_n^0 \) under the action of a current will depend upon the normal preliminary plastic deformation in the cross section \( \mathbf{n} \mathbf{p}_n \) and upon the specific energy of the current and its direction relative to the section. This relationship, continuing the ideas of [5-7], is represented in the form

\[
\frac{\Delta S_n}{S_n^0} = f \left( \frac{p_n}{p_c} \right) - \psi \left( \frac{p_n}{p_c} \right) \chi(q) g(\bar{q}/q, \mathbf{n}) \, ,
\]

and with \( p_n < 0 \) the second term in Eq. (2) must be assumed to be equal to zero.

We should note that under the action of a current on crack-type defects of a material in addition to melting-shut of them in the vicinity of the crack tip zones of local recrystallization and compressive residual stresses occur [8-11], which hinders crack propagation in further plastic deformation and consequently influences the effective section of the elementary section, causing an increase in it. Since the intensity of the compressive residual stresses and local recrystallization and therefore of the change in effective section related to them depends almost linearly upon the preliminary plastic deformation, the relationship of the compressive residual stresses and recrystallization to specific energy is described by the capshaped function \( \chi(q) \) and to the direction of action of the current in relation to the section considered by the function \( g(q, q, \mathbf{n}) \) and then the addition to the change \( \Delta S_n/S_n^0 \) from the action of residual stresses and recrystallization has the same form as the second term in Eq. (2).

The functions (2) determined in a macroexperiment reflect the influence of the whole combination of factors (melting-shut, recrystallization, and compressive stresses) on the change in effective section of the section. This makes it possible to assume that Eq. (2) takes into consideration in the second term the influence of compressive residual stresses and local recrystallization and then this influence will take into consideration the model constructed below. The influence of local recrystallization and local residual stresses may be so significant that after substitution in Eq. (2) of the experimentally determined functions with certain \( p_n \), \( p_n^0 \), and \( \bar{q} \) the value of \( \Delta S_n/S_n^0 \) will be negative. This leads to a stronger electroplasticity effect than is possible in principle taking into consideration only melting shut of the microcracks.

Since the current acts on a crack [8] proportionally to the square of the cosine of the angle between the normal to the cracks and the vector of current

\[
g(\bar{q}/q, \mathbf{n}) = q n_1 n_2 n_3 / q^2 \, ,
\]

must be assumed.

As a first approximation for a qualitative analysis let us assume that the relationship of \( \Delta S_n/S_n^0 \) to \( p_n \) and \( p_n^0 \) is linear and then on the basis of Eqs. (1)-(3) there may be introduced the tensor which we will call the tensor of damage:

\[
\omega_{ijkl} = \frac{1}{p_c} (p_{ij} \delta_{kl} - \chi(q) \, p_{ij} q_{kl}/q^2) \, .
\]

With use of this tensor Eq. (2) may be rewritten in the form

\[
\Delta S_n/S_n^0 = \omega_{ijkl} n_1 n_2 n_3 \, .
\]

To determine the limiting condition when the reserve of plasticity is exhausted let us introduce the integral characteristic of damage at the point \( \varnothing \), which is the average relative decrease in the effective area for all sections:

\[
\Omega = \frac{1}{2\pi} \int \int_{a\beta} \frac{\Delta S_n}{S_n^0} \cos \beta d\alpha d\beta \, ,
\]

which with use of Eq. (5) may be represented in the following manner:

\[
\Omega = \frac{1}{2\pi} \int \int_{a\beta} \omega_{ijkl} n_1 n_2 n_3 \cos \beta d\alpha d\beta \, ,
\]

438