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ON THE INFLUENCE OF CURVATURE OF THE TRAJECTORIES OF DEFORMATION OF A VOLUME OF THE MATERIAL BY PRESSING ON ITS PLASTICITY UNDER THE CONDITIONS OF COMPLEX LOADING

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In the experimental investigations of the plasticity of cylindrical specimens of R9, R12, and R18 steels, subjected to simultaneous torsion with tension, it is discovered that, under the conditions of complex loading, the rate of accumulation of defects and their healing in the form of derivatives of the parameters of stressed state exerts a significant influence on the characteristics of plasticity. It is shown that, under these conditions, when the first and second derivatives of the dimensionless parameter of stressed state grow, the influence of curvature of the deformation paths of particles in the material on plasticity becomes more pronounced. The accumulated results enable us to select the phenomenological criteria of fracture, which give more reliable results of estimation of the applied plasticity resource in the technological processes of pressure treatment.

Keywords: deformability of metals, complex loading, deformation path, loading trajectory, deformation trajectory, deformation history, accumulation of defects.

The evaluation of the deformability of metals and alloys without their fracture represents a complex problem whose solution is based on the phenomenological theory of continuum mechanics. With the help of contemporary ideas concerning the mechanism of fracture, it is impossible to determine the level of strains in the case where metals are destroyed under the conditions of complex loading.

Hence, following the well-known terminology [1], as one of the main characteristics of the trajectory of loading of this kind we can mention its curvature. For the proposed description of the loading history, it is necessary to realize infinitely many trajectories and, hence, it becomes impossible to apply this approach in the phenomenological fracture criteria. Moreover, for the same conditions of forming, the loading trajectories are different [2]. Thus, it becomes necessary to study the process of loading of particles of the material in a six-dimensional space, which is quite difficult from the methodical point of view. Hence, we introduce a new space, namely, the space of accumulated strain intensity and dimensionless parameters of the stressed state [2–4], which enables us to model the processes of pressure treatment [5].

The aim of the present paper is to choose phenomenological fracture criteria and estimate the ultimate form changes with regard for the influence of curvature of the deformation trajectories of particles of the material on its plasticity under the conditions of complex loading in the course of pressure treatment.

Methods of Investigations

Consider the process of loading in the space of dimensionless parameters of the stressed state. We represent the stress tensor in the form [6]

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$$\sigma_{ij} = \tau S_{ij}^0 + \sigma\delta_{ij}, \tag{1}$$

where σ is hydrostatic pressure, S_{ij}^0 are the components of the directing tensor, S_{ij} are the components of the stress deviator, τ is its intensity, and $\tau^2 = S_1^2 + S_2^2 + S_3^2$, and S_1, S_2, S_3 are the principal components of stress deviator.

Dividing the left- and right-hand sides of expression (1) by the stress intensity σ_u, we obtain

$$\frac{\sigma_{ij}}{\sigma_u} = \sqrt{\frac{2}{3}} S_{ij}^0 + \frac{\eta}{3}\delta_{ij}, \tag{2}$$

where η is the parameter of stressed state that describes the influence of relative hydrostatic pressure (the first invariant of the stress tensor) on plasticity [7].

In the space of principal stresses, expression (2) takes the form

$$\frac{\sigma_1}{\sigma_u} = \frac{1}{3}\left(\eta - \frac{\mu_\sigma - 3}{\sqrt{\mu_\sigma^2 + 3}}\right); \quad \frac{\sigma_2}{\sigma_u} = \frac{1}{3}\left(\eta + \frac{2\mu_\sigma}{\sqrt{\mu_\sigma^2 + 3}}\right); \quad \frac{\sigma_3}{\sigma_u} = \frac{1}{3}\left(\eta - \frac{3 + \mu_\sigma}{\sqrt{\mu_\sigma^2 + 3}}\right). \tag{3}$$

Hence, we can define loading trajectories in the three-dimensional space with coordinates e_u, η, μ_σ or e_u, η, χ. The dependences $\eta(e_u)$, $\mu_\sigma(e_u)$, and $\chi(e_u)$ are called "deformation paths" [2]. The (Nadai–Lode) parameter

$$\mu_\sigma = 2\frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1$$

characterizes the type of stressed state. This parameter does not change in the case of superposition of the equiaxial tension or compression over the stressed state. The parameter

$$\chi = \frac{\sqrt[3]{I_3(T_\sigma)}}{\sqrt{3I_2(D_\sigma)}}$$

describes the influence of the third invariant of the stress tensor on plasticity under conditions of triaxial stresses. The accumulated strain

$$e_u = \int_0^t \dot{\varepsilon}_u \, d\tau$$

is a measure of plasticity (Odqvist parameter). Relation (3) also implies that if $\eta = \text{const}$ and $\mu_\sigma = \text{const}$, then the loading is simple and, for $\eta = \eta(e_u)$ and $\mu_\sigma = \mu_\sigma(e_u)$, the loading is complex [8].

The main advantage of specifying the loading trajectories in the space of dimensionless parameters of the stressed state η, μ_σ, and χ is connected with the fact that the type of deformation path is, in this case, unambiguously determined by the conditions of form changes typical of the analyzed process, i.e., it is practically independent of the mechanical properties of the material [5, 9]. Hence, one can reproduce the procedure of

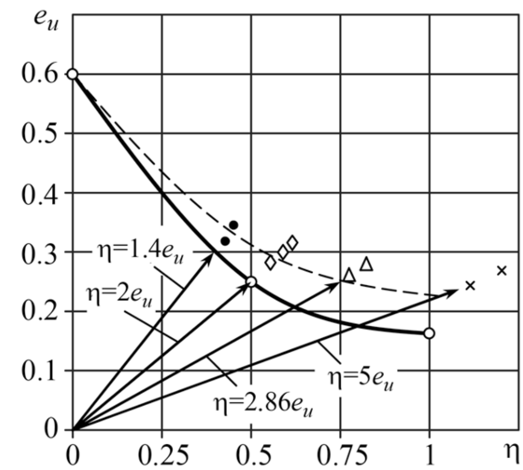

Fig. 1. Influence of the shape of deformation paths on the rate of damage accumulation and the plasticity of R12 steel [2]: numerical analysis according to criterion (4) (dashed line), plasticity diagram (η = const) (—o—); fracture under the conditions of complex deformation (●, ◇, ×, △).

pressure treatment on model materials. However, in this case, it is necessary to have the hardening curves $\sigma_u = f(\varepsilon_u)$ and the plasticity diagrams $\varepsilon_p = f(\eta)$, $\varepsilon_p = f(\mu_\sigma)$, and $\varepsilon_p = f(\chi)$.

The first derivative of the parameters of the stressed state $\left(\frac{d\eta}{de_u}, \frac{d\chi}{de_u}, \frac{d\mu_\sigma}{de_u}\right)$ characterizes the rate of accumulation of defects (or their healing depending on the sign of the derivative), whereas the second derivative $\left(\frac{d^2\eta}{de_u^2}, \frac{d^2\chi}{de_u^2}, \frac{d^2\mu_\sigma}{de_u^2}\right)$ describes the curvature of deformation paths. The rate of accumulation (or healing) of defects appears in the form of functions in the following criterion [2]:

$$\psi = \int_0^{e_u^*} \left(1 + 0.2\arctan\left(\frac{d\eta}{de_u} + \frac{d\chi}{de_u}\right)\right) \frac{[e_u(\eta,\chi)]^{0.2\arctan\left(\frac{d\eta}{de_u}+\frac{d\chi}{de_u}\right)}}{[e_p(\eta,\chi)]^{1+0.2\arctan\left(\frac{d\eta}{de_u}+\frac{d\chi}{de_u}\right)}} de_u \le 1, \tag{4}$$

with the help of which we can estimate the used plasticity resource or the limiting level of strains in the course of pressure treatment under the conditions of three-dimensional stressed state in the case of complex loading. This criterion contains the first derivatives of the parameters of stressed state characterizing the rate of accumulation of defects. We now consider their influence on the accumulation and healing of defects.

In [2], one can find the data obtained in the course of testing of cylindrical specimens made of materials that do not form a "neck" under uniaxial tension. Among these materials, we can mention R6M5 and R12 quick-cutting steels and 40Kh and 45 steels that were subjected to joint torsion and tension under the conditions of variable hydrostatic pressure (up to 2000 MPa). In this case, we realized the programs of deformation guaranteeing either the constancy of parameters of the stressed state or their variations along different deformation paths. If η = const and χ = const at the time of fracture, then dependence $e_u = f(\eta)$ forms the diagram of plasticity. If we realize the deformation paths of the material in the form of straight lines inclined to the strain axis (Fig. 1), following the function

$$\eta = Be_u, \tag{5}$$

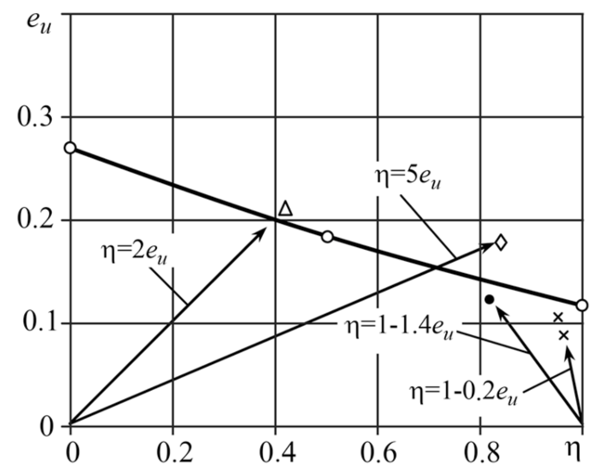

Fig. 2. Influence of the shape of deformation paths on the plasticity of R9 steel [2] (the same notation as in Fig. 1).

where $B = 1.4, 2, 2.86,$ and $5,$ then the fracture occurs not at the time of intersection with the plasticity diagram but somewhat later. In other words, if

$$\frac{d\eta}{de_u} > 0,$$

then we observe the effect of healing of defects. Furthermore, if

$$\frac{d\eta}{de_u} < 0$$

(Fig. 2), then fracture occurs prior to the intersection of rectilinear rays with the plasticity diagram, i.e., the formation of defects is mode intense.

In the book [2], we introduced the coefficient of influence of the history of deformation (the first and second derivatives of the parameters of stressed state with respect to the strain intensity) on the ultimate level of strains:

$$w = \frac{e_p(\eta)}{e_p(\eta = \text{const})}, \tag{6}$$

where $e_p(\eta)$ is the limiting level of strains with regard for the deformation history and e_p is the ultimate level of strains for $\eta = \text{const}$. As the first derivative of the parameter of stressed state increases, the influence of the coefficient w becomes stronger. If

$$\frac{d\eta}{de_u} > 5,$$

then it reaches 1.8 for R18 steel.

It is also established that the derivatives of deformation paths strongly affect the accumulation of defects, their healing, and hence, the degree of plasticity. For the deformation paths close to $\eta = \text{const}$ (trajectories of small curvature), it is possible to estimate the ultimate strains by using the Smirnov–Alyaev criterion [10]:

$$\psi = \frac{e_u}{e_p(\eta)} \le 1, \tag{7}$$

which does not take into account the influence of deformation history on plasticity.

If the first derivative varies within the range

$$0.5 \le \frac{d\eta}{de_u} \le 1.75$$

and the curvatures of deformation path take values

$$0.25 \le \frac{d^2\eta}{de_u} \le 2,$$

then we can get satisfactory accuracy by using the Kolmogorov criterion [11]:

$$\psi = \int_0^{e_p^*} \frac{d\bar{e}_u}{[e_p(\bar{e}_u)]} \le 1. \tag{8}$$

If

$$\frac{d\eta}{de_u} \ge 2$$

and the curvature of the deformation path

$$\frac{d^2\eta}{de_u^2} \ge 3,$$

then criterion (4) gives the highest possible accuracy.

Results and Discussion

We now present an example of the technological process in which metal particles form trajectories with mean curvature in the process of deformation and the deformation paths are described by the curves in the form of square parabolas.

In this case, the parameter of stressed state η varies from – 2 (biaxial compression) to – 5 (uniform compression). As an example of process of this kind, we can consider rotary swaging when the blanks are deformed by conic convergent dies guaranteeing the conditions of uniform pulsed pressure (Fig. 3).

The favorable scheme of the stressed state under loading of this kind enables one to treat blanks made of low-plastic difficultly deformed metals and alloys. Nevertheless, for certain conditions of deformation, cracks are often initiated in the central part of the blanks made of low-plastic materials. Therefore, it is necessary to prevent fracture of the products with the help of computational tools of the phenomenological theory of deformability based on the criteria of deformability.

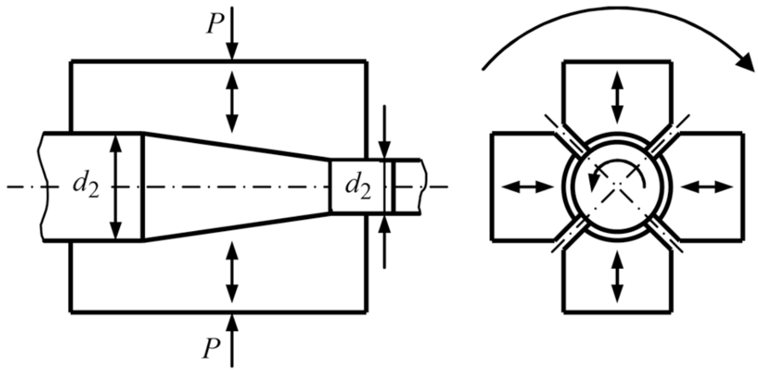

Fig. 3. Schematic diagram of deformation of the blank in the case of its rotary swaging.

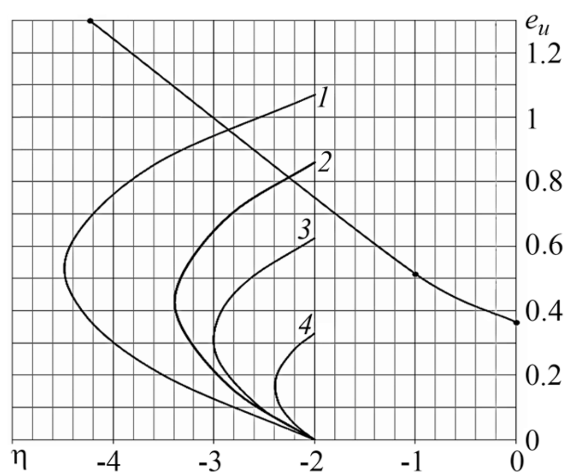

Fig. 4. Deformation paths of particles made of D1-T duralumin along the symmetry axis of blanks under the conditions of rotary swaging [2]: (1–4) deformation paths for different degrees of swaging $\delta = 0.37, 0.305, 0.240,$ and 0.135.

Criteria (4), (7), and (8) take into account the data on the deformation paths of particles of the material in the dangerous domain of the deformed blank and also the plasticity diagram $e_p = f(\eta)$. The deformation paths $\eta = f(e_u)$ of particles of the material of blanks in the dangerous domain were obtained in [12] for different degrees of swaging $\delta = 0.135, 0.24, 0.305,$ and 0.37.

In Fig. 4, the plasticity diagram of D1-T duralumin is compared with the deformation paths $\eta = f(e_u)$ of particles of the material of blanks subjected to different degrees of swaging (curves 1–4).

The used plasticity resource ψ was equal to 1.05 according to criterion (4), to 1.621 according to criterion (7), and to 0.981 according to criterion (8). In the case of maximal reduction ($\delta = 0.37$), we detected a crack in the central part of the blank, which confirms the results of calculations according to criterion (4).

Thus, for the processes accompanied by form changes, when the derivatives of deformation paths of particles of the material lie within the limits

$$-5 \le \frac{d\eta}{de_u} \le 5,$$

criterion (4) exhibits the best agreement with the experimental data.

CONCLUSIONS

We propose to consider the processes of plastic deformation in the space of accumulated strain intensity and the dimensionless parameters of the stressed state. In these coordinates, the processes of accumulation or healing of defects depend on the rate of damage accumulation. Under the conditions of complex loading, when the rate of damage accumulation in the form of the first derivative of the parameter of stressed state $\frac{d\eta}{de_u} \geq 5$ and the second derivative $\frac{d^2\eta}{de_u^2} > 1$, the results given by criterion (4), which takes into account the influence of deformation history on plasticity, prove to be most close to the experimental data.

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