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DUCTILITY OF METALS AT NON-MONOTOUS LOADING

The paper considers the method of metals ductility evaluation at non-monotonous loading the, the given method applies the guiding tensor of deformations increment, its main components values are defined by Nadai-Lode parameter, the method is used for evaluation of non-monotonicity influence on the value of ductility resource used. The study of the process of transversal extrusion with further upsetting is performed.

Key words: *ductility, stress, deformation,non-monotonicity,deformability, damage tensor, destruction condition.*

In the majority of cases, plastic metal working is accompanied by non-monotonous plastic deformation of metals. Deformability criteria, based on scalar model of damages accumulation [1, 2, 3], do not allow to obtain real evaluation of plasticity in such processes. In the given paper boundary deformation is taken as the reference of ductility while non-monotonous loading. Boundary deformation is defined by the formula

$$e_p = \int_0^{t_p} \dot{\varepsilon}_u d\tau \,, \tag{1}$$

where $\dot{\varepsilon}_u$ – is the intensity of deformation rates, t_d – is deformation time before the destruction.

In [3] the criterion for evaluation of metals ductility while non-monotonous loading is suggested. Condition of distribution is assumed to be

$$\sum_{i=1}^{n} \psi_i^{a_i} = 1 \,, \tag{2}$$

where n – is a number of deformation steps, within the limits of which the form of stressed state does not change, a_i – is the magnitude, the value of which depends on the form of stressed state, ψ_i – is the resource of ductility, used at the given stage.

Magnitude ψ_i is defined by the formula

$$\psi_i = \frac{\Delta e_u(\eta_i)}{e_p(\eta_i)} \,,$$

where $\Delta e_u(\eta_i)$ is the increment in deformation degree at i^{-th} step if η_i = const, $e_d(\eta_i)$ –is limiting deformation value while simple loading in conditions of stressed sate of i-th deformation step, i.e. , if η_i=const.

As it is shown in [4] for evaluation of metals ductility while non-monotonous loading it is suggested to apply tensor of damages, components of which are defined in the following manner.

$$\psi_{ij} = \int_0^{e_u} F\left(e_u^*, \eta, \mu_\sigma\right) \beta_{ij} de_u^* , \tag{3}$$

where $\eta = \dfrac{3\sigma}{\sigma_u}$ – is the index of stressed state rigidity, $\sigma = \dfrac{1}{3}\sigma_{ij}\delta_{ij}$ – is average stress, μ_σ – is Nadai-Lode parameter, $e_u = \int_0^t \dot{\varepsilon}_u d\tau$ – is deformation degree, t – is time of deformation from the moment of plastic deformation start to considered deformation state.

The components of guiding tensor of deformations increment β_{ij} equal

$$\beta_{ij} = \sqrt{\frac{2}{3}} \frac{d\varepsilon_{ij}}{de_u} \,. \tag{4}$$

Function $F(e_u, \eta, \mu_\sigma)$ is the characteristic of material. Condition of destruction, suggested in [4], has the form

$$\psi_{ij}\psi_{ij}=1. \tag{5}$$

Applying destruction condition (5) the solutions of problems of two-stage, cyclic and compound loading are obtained. This proves the validity of tensor model.

V. M. Mikhailevych [5] suggested tensor-nonlinear model, according to which the components of damages tensor are defined by the formula

$$\psi_{ij} = \int_0^{e_u} \left(\mathrm{A}\beta_{ij} + \mathrm{B}\left(\beta_{ik}\beta_{kj} - \frac{1}{3}\delta_{ij} \right) \right) de_u, \tag{6}$$

where A and B – functions, which depend on loading conditions and mechanical properties of the material.

Calculations of the value of ductility resource used, applying the above-mentioned criteria are rather labour-consuming, as they require determination of $F(e_i, \eta, \mu_\sigma)$, A, B, functions as well as $\beta_{ij}(e_u)$ dependences.

The given research suggests the following model for the description of damages accumulation process at non-monotonous plastic deformation. Since the components of guiding tensor are defined by the formula (4), then applying physical equations of plastic flow theory

$$d\varepsilon_{ij} = \frac{3}{2}\frac{de_u}{\sigma_u}S_{ij} \tag{7}$$

we find. that

$$\frac{d\varepsilon_{ij}}{de_u} = \sqrt{\frac{3}{2}}\beta_{ij} = \frac{3}{2}\frac{S_{ij}}{\sigma_u} \tag{8}$$

or

$$\beta_{ij} = \sqrt{\frac{3}{2}}\frac{S_{ij}}{\sigma_u}, \tag{9}$$

where S_{ij} – are components of stresses deviator, σ_u – is the intensity of stress.

Let us present tensor σ_{ij} in the form

$$\sigma_{ij}=S_{ij}+\sigma\delta_{ij}, \tag{10}$$

where $\sigma = \frac{1}{3}\sigma_{ij}\delta_{ij}$ – is average stress.

Besides, we will apply the already known relations

$$\mu_\sigma = \frac{2S_2 - S_1 - S_3}{S_1 - S_3}, \tag{11}$$

$$S_1+S_2+S_3=0, \quad 2\sigma_u^2 = (S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2. \tag{12}$$

After the solution of the system (11), (12) we find

$$\frac{S_1}{\sigma_u} = \mp\frac{1}{3}\frac{\mu_\sigma - 3}{\sqrt{\mu_\sigma^2 + 3}}, \quad \frac{S_2}{\sigma_u} = \pm\frac{1}{3}\frac{2\mu_\sigma}{\sqrt{\mu_\sigma^2 + 3}}, \quad \frac{S_3}{\sigma_u} = \mp\frac{1}{3}\frac{\mu_\sigma + 3}{\sqrt{\mu_\sigma^2 + 3}}. \tag{13}$$

It follows from (4) and (13) that the main components of tensor β_{ij} equal

$$\beta_1 = \mp\frac{1}{\sqrt{6}}\frac{\mu_\sigma - 3}{\sqrt{\mu_\sigma^2 + 3}}, \quad \beta_2 = \pm\frac{1}{\sqrt{6}}\frac{2\mu_\sigma}{\sqrt{\mu_\sigma^2 + 3}}, \quad \beta_3 = \mp\frac{1}{\sqrt{6}}\frac{\mu_\sigma + 3}{\sqrt{\mu_\sigma^2 + 3}}. \tag{14}$$

It is assumed that in case of non-monotonous loading the destruction occurs if certain function of tensor ψ_{ij} invariants reaches certain value. The first invariant of this tensor equals zero due to incompressibility of the material $\beta_1+\beta_2+\beta_3=0$. Without taking into consideration the third invariant destruction condition may be written as

$$\psi_1^2+\psi_2^2+\psi_3^2=1. \tag{15}$$

To define the type of function $F(e_i,\eta,\mu_\sigma)$, that is the part of (3), let us consider simple loading, at which β_{ij}, η, μ_σ remain constant, then [4]

$$\psi_{ij}=\beta_{ij}\int_0^{e_u^*}F(e_i,\eta,\mu_\sigma)de_i=\beta_{ij}\varphi(e_i,\eta,\mu_\sigma), \tag{16}$$

where $\varphi(e_i,\eta,\mu_\sigma)=\int_0^{e_u^*}F(e_i,\eta,\mu_\sigma)de_i$. (17)

As $\beta_1^2+\beta_2^2+\beta_3^2=1$ it follows from (15) that while destruction, if $e_i=e_d$, то $\varphi(e_d,\eta,\mu_\sigma)=1$. Besides

$$\varphi(0,\eta,\mu_\sigma)=0. \tag{18}$$

Complying these conditions, we assume, that [4]

$$\varphi=(1-a)\frac{e_u}{e_p(\eta,\mu_\sigma)}+a\frac{e_i^2}{e_p^2}, \tag{19}$$

Where $e_d(\eta,\mu_\sigma)$ – is the surface of boundary deformations, a – is the constant, the value of which depends on mechanical characteristics of the metal. In the given paper a is assumed to be equal a=0,48.

Complying with the relations (3), (17), (19) we assume that in general case

$$\psi_1=\int_0^{e_u}\left(1-a+2a\frac{e_i}{e_p(\eta,\mu_\sigma)}\right)\beta_1\frac{de_i}{e_p(\eta,\mu_\sigma)}. \tag{20}$$

Similar expressions can be obtained for ψ_2 and ψ_3, which compose the condition of destruction (15).

We use destruction criterion (15) for investigation of the process of lateral pressing out with further upsetting of cylinder blanks, made of steel 10. Flow diagram of the process is shown in Fig 1. At the first stage the process of lateral pressing out is performed, at the second stage-the upsetting of the obtained flange is realized (Fig 1). Calculation of the stressed-strained state was performed by means of coordinate grids method, in this case, the technique suggested in [6] was applied. The process of pressing out and the process of upsetting were performed in three stages. Ways of deformation $\eta(e_i)$, $\mu_\sigma(e_i)$ were constructed, taken into account the influence of main technological parameters: relative thickness of the flange h/d_0 and relative value of curving edge r/d_0. As the ways of deformation is coordinates e_i, η, μ_σ practically do not depend on the material, for investigation of the stressed- strained state the samples made of antimonid lead (d_0=20 mm, l_0=60 mm), cut into pieces were used. By means of sharpened cutting tool rectangular dividing grid, with 2 mm base is applied on polished surface of one of the halves of assembled piece. Then the pieces were soldered and pressing out of separate pieces to different degrees of deformation was performed in three stages. Three pieces, obtained at the end of each transition of lateral pressing out, were used for realization of three transitions of contour upsetting. Thus, each piece characterizes strained state at the end of each stage. At the end of state the pieces were disoldered and the coordinates of deformed grid nodes were measured.

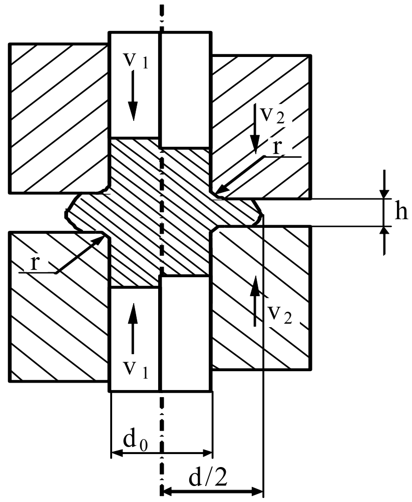

Fig. 1. Flow diagram of the process of lateral pressing out with further upsetting of the obtained flange

In addition, dividing grid was applied on lateral surface of pieces, made of steel 10, then lateral pressing out and contour upsetting was performed in the same manner as pieces, made of lead were deformed.

Accumulated deformation was determined by the formula

$$e_i = \int_0^t \dot{\varepsilon}_i d\tau ,$$

where $\dot{\varepsilon}_i$ is the intensity of deformation rate, t – is time of deformation.

Components of stresses deviator were calculated by the relations, allowing to take into account the influence of plastic deformation non monotonousness [7], that occurs in the considered process

$$S_{ij} = \frac{2}{3}\sigma_u(e_u)\frac{\dot{\varepsilon}_{ij}}{\dot{\varepsilon}_u} - \frac{1}{3}\int_0^{e_u}\left(1-\beta\left(e_u^*\right)\right)\sigma\left(e_u^*\right)\cdot\varphi\left(e_u^* - e_u^0\right)\frac{d^2\varepsilon_{ij}}{de_u^2}\left(e_u^*\right)de_u^*. \quad (21)$$

Dependences $\beta(e_i)$, $\varphi(e_i - e_i^0)$ for steel 10 were obtained experimentally, applying the technique [7]. Experimental results were approximated by the functions

$$\beta=0,34+0,66exp(-62e_i), \quad (22)$$

$$\varphi=0,19+0,81(-22,3(e_i - e_u^0)^{0,806}). \quad (23)$$

Constants of (22) and (23) were defined, applying the method of least squares.

Components of stress tensor were determined by integrating balance differential equations

$$\begin{aligned} &\frac{\partial\sigma_r}{\partial r} + \frac{\partial\tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\varphi}{r} = 0 \\ &\frac{\partial\tau_{rz}}{\partial r} + \frac{\partial\sigma_z}{\partial z} + \frac{\tau_{rz}}{r} = 0 \end{aligned}, \quad (24)$$

using integral equation

$$P = 2\pi\int_0^R \sigma_z r dr , \quad (25)$$

where r – is the radius of deformed piece, P – is the effort, measured in the process of deformation of investigated piece.

The obtained results of stresses and deformations calculations were used for construction of loading ways $\eta(e_i)$, $\mu_\sigma(e_i)$, as well as for calculation of βi values.

The surface of boundary deformations for steel 10was approximated by the dependence, obtained in [6]

$$e_p(\eta,\mu_\sigma)=0,68\ exp(0,43\mu_\sigma-0,91\eta). \qquad (26)$$

The value of the ductility resource used was calculated by the formula

$$\psi=\psi_1^2+\psi_2^2+\psi_3^2\,. \qquad (27)$$

For evaluation of geometric parameters of lateral pressing out process with further upsetting on the ductility we carried out calculations of the ductility resource used ψ by the formula (27) for three cases: 1 – relative value of curve radius of transition edge r/d_0=0 and relative thickness of the flange h/d_0=0,141; 2 – r/d_0=0,106 and h/d_0=0,236; 3 – r/d_0=0,213 and h/d_0=0,33. From the results of the calculation of ductility resource used value ψ, it follows that the third case is optimal. For instance, if the diameter of the flange d=36mm (d_0=20mm), then ψ in dangerous point equals for the first case ψ=0,620, for the second case - ψ=0,510, and for the third case - ψ=0,382, that is for investigated interval of h/d_0 and r/d_0 values the increase of these results in considerable reduction of ψ.

The difference between the values of ψ, obtained by the formula (27) and experimental data does not exceed 20 %. It should be noted that the usage of the peculiarities of non-monotones of plastic deformation allows to obtain flanges, the diameter of which exceeds the diameter of flange, obtained by means of conventional lateral pressing out by 60 – 80%.

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