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## DETERMINATION OF PLASTICITY FOR PRE-DEFORMED BILLET

**Introduction.** Development and industrial introduction of effective metal forming technologies, which ensure a high level of operational properties and reliability of products is one of the most important tasks of engineering.

After various operations of metal forming, a technological heritage is formed. These are residual stresses, hardening, deformations gradient, residual plasticity, and other factors. These factors influence in the future the performance of products, which predetermines the task of creating methods for their evaluation. Most of these factors have been sufficiently investigated [1], but some of them, for example, evaluation of the plasticity of a pre-deformed billet, is a difficult and insufficiently investigated problem.

**Formulation of the task.** The purpose of this research is to develop a methodology for evaluating the plasticity of a pre-deformed metal.

**Research results.** Accumulated at all stages of deformation, the strain intensity (parameter Udquist), which is called the ultimate deformation ($e_p$), is taken as a measure of plasticity at the moment of destruction of the workpiece material at the place of final deformations:

$$e_p = \int\limits_0^{\tau_p} \dot{\varepsilon}_u d\tau, \qquad (1)$$

where $\dot{\varepsilon}_u$ – strain rates intensity.

Processes of metal forming are based on the ability of metals under the action of the applied load to pass into the plastic state.

Plasticity of metals depends on many factors, among which, in addition to the type of material, the main thermomechanical parameters of the process are: temperature, strain rate, strain state, deformation story, strain gradient and other.

The dependence of plasticity on the type of stress state with simple deformation and fixed temperature and rate process parameters is its mechanical characteristic. To determine the mechanical characteristic diagram, a material test is performed at various stress states under simple loading conditions, when the components of the stress tensor vary in proportion to one parameter.

The stress state will be characterized by the indices of the stressed state. The stress state index according to G. A. Smirnov-Alyaev [2]:

$$\eta = \frac{I_1(T_\sigma)}{\sqrt{3I_2(D_\sigma)}} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_1}, \tag{2}$$

where $I_1(T_\sigma)$ – the first invariant of the stress tensor, $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses, $I_2(D_\sigma)$ is the second invariant of the stress deviator or stress intensity:

$$\sigma_u = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}. \tag{3}$$

The parameter $\eta$ is useful when using the plasticity diagrams in the coordinates $e_p = f(\eta)$, and is equal to: $\eta = 1$ – uniaxial tension, $\eta = -1$ – uniaxial compression, $\eta = 0$ – shift (Fig. 1).
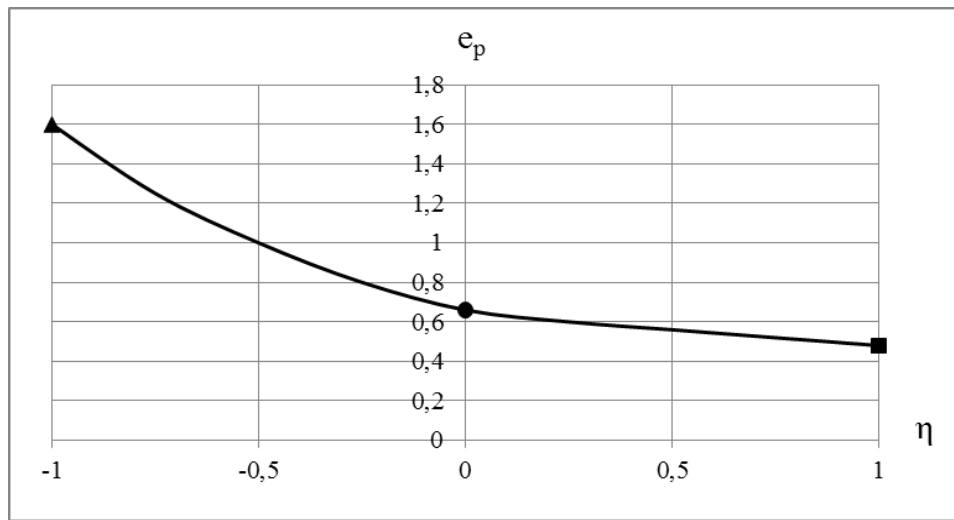


▲ – compression, ● – torsion, ■ – stretching.

Fig. 1 – The plasticity diagram of steel 20 $\left( e_p = f(\eta) \right)$

In pressure processing of sheet materials, destruction can be accompanied by break or shear cut, sometimes mixed types of destruction are observed. When material destroyed by shear, it is proposed in [3] to present the plasticity diagram (fig. 2) as a function $e_p = f(\theta)$, in which the stress state index is defined as:

$$\theta = \frac{1 - k\eta}{\omega} \quad \theta = \frac{1 - k\eta}{\omega}, \tag{4}$$

where $k$ – the material parameter which is determined experimentally.

For steels of different grades, it can be taken as $k = 0,05$; for aluminum alloys, $k = 0,1$ [3]. In case of stretching – $\theta = 1,8$; shift – $\theta = \sqrt{3}$; uniaxial compression – $\theta = 2,1$; biaxial stretching – $\theta = 1,6$; biaxial compression – $\theta = 2,4$.

$$\omega = \frac{\tau_{\max}}{\sigma_u}, \tag{5}$$
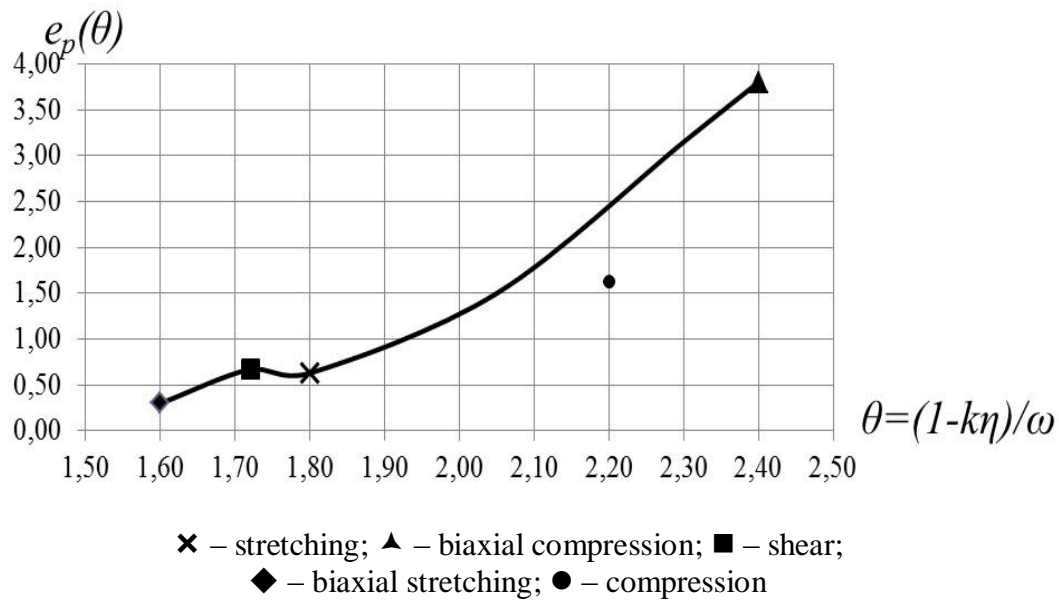
where – $\tau_{\max}$ the maximum tangential tension.



✖ – stretching; ▲ – biaxial compression; ■ – shear;
◆ – biaxial stretching; ● – compression

Fig. 2 – The plasticity diagram of steel 20 $\left(e_p = f\left(\theta\right)\right)$

In modeling if material destroyed by break, when the plane of failure is close to the plane on which the maximum normal stresses act in [3], plasticity diagrams are proposed to be represented in the case of a function (fig. 3) unified for different stressed states $\varepsilon_p = f\left(\beta\right)$ in which:

$$\beta = \frac{1 - s\eta}{\nu}, \tag{6}$$

where $\eta$ is determined by the equation (2),

$$\nu = \frac{\sigma_1}{\sigma_2}. \tag{7}$$

Here $\sigma_1$ – maximum of principal stresses $\sigma_1 \geq \sigma_2 \geq \sigma_3$; $s$ – the material parameter, which is usually taken equal to $k$.

In case of stretching: $\sigma_u = \sigma_1$, $\sigma_2 = \sigma_3 = 0$, $\beta = \dfrac{\left[1 - s(1)\right]\sigma_u}{\sigma_u} = 1 - s = 0,95$.

For shear: $\sigma_1 = \tau$, $\sigma_2 = 0$, $\sigma_3 = -\tau$, $\sigma = \sqrt{3}\tau$, $\beta = \sqrt{3}$.

For compressing: $\sigma_1 = \sigma_2 = 0$, $\sigma_3 = -\sigma$, $\beta = \dfrac{\left[1 - s(-1)\right]\sigma}{0} = \infty$.

Thus, the functions ep ($\eta$, $\theta$, $\beta$) are the plasticity diagrams, which show how the limit deformation depends on the stress state indicators. The diagrams are based on experimental testing of materials under conditions of linear or plane stress states (stretching, compression, torsion (shear)) and other types of tests.

If an experimentally constructed plasticity diagram is known, can it be constructed after preliminary plastic deformation for any kind of stress state? This determines the solution of the above problem in the future. Its solution is based on the tensor description of damage accumulation [6].
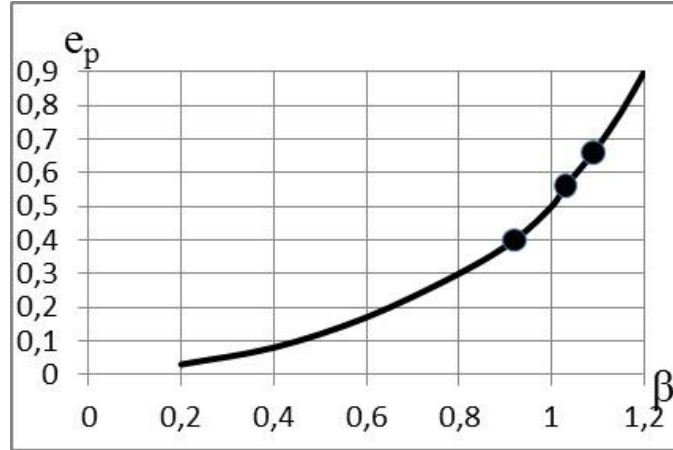
Fig. 3 – The plasticity diagram of steel 20 $\left(e_p = f(\beta)\right)$

If the plasticity diagram by component of the damage tensor $\psi x$, $\psi xy$, ... and the diagram of the accumulated deformation in the plastic deformation determined in the $X$, $Y$, $Z$ coordinate system are known, then a plasticity diagram of the deformed metal can be constructed. Let it be required to determine the plasticity of this material under a stressed state, to which the stress state indicators equivalent $\eta'_1, \eta'_2$, and the tensor $\beta'_x$, $\beta'_{xy}$, ... Then increments of the damage tensor components with additional deformation before destruction will be equal to:

$$\Delta\psi_{xy} = \beta'_{xy}\left[\varphi\left(\overline{e}_0 + e'_0, \eta'_1, \eta'_2\right) - \varphi\left(\overline{e}_0, \eta'_1, \eta'_2\right)\right] . \tag{8}$$

Destruction process can be represented as equation:

$$\left(\psi_x + \Delta\psi_x\right)^2 + \left(\psi_{xy} + \Delta\psi_{xy}\right)^2 + \left(\psi_{yx} + \Delta\psi_{yx}\right)^2 + ... = 1. \tag{9}$$

Or:

$$\Delta\psi_x^2 + \Delta\psi_{xy}^2 + \Delta\psi_{yx}^2 + ... + 2(\psi_x\Delta\psi_x + \psi_{xy}\Delta\psi_{xy} + \psi_{yx} + ...) + \psi_0^2 = 1, \tag{10}$$

In equation (10):

$$\psi_0^2 = \psi_x^2 + \psi_{xy}^2 + \psi_{yx}^2 + .... \tag{11}$$

From the equalities (8), (10) we obtain the quadratic equation, from which we find:

$$\varphi(\overline{e}_0 + e'_0, \eta'_1, \eta'_2) = \varphi(\overline{e}_0, \eta'_1, \eta'_2) - D + \sqrt{1 + D^2 - \psi_0^2} , \tag{12}$$

where

$$D = \beta'_x\psi_x + \beta'_{xy}\psi_{xy} + \beta'_{yx}\psi_{yx} + .... \tag{13}$$

After the approximation, the equation for the plasticity of the deformed metal is obtained:

$$e'_p = e_p\left[-\frac{\overline{e}_0}{e_p} - \frac{1-a}{2a} + \sqrt{\left(\frac{\overline{e}_0}{e_p} + \frac{1-a}{2a}\right)^2 - \frac{D}{a} + \frac{1}{a}\sqrt{1 + a^2 - \psi_0^2}}\right] \tag{14}$$

Here $e_p$ is the plasticity of the undeformed metal under a stressed state with $\eta_1 = \eta_1'$, $\eta_2 = \eta_2'$. Parameter $a$ is the approximation coefficient given in the criterion [6].

$$\psi_{ij} = \int_0^{e_u} (1 - a + 2ae_u^* / e_p)\beta_{ij} de_u^* / e_p . \tag{15}$$

According to the experimental data given in [6], a = 0,5.

Thus, using (16), it is possible to calculate the ultimate deformation of a deformed metal for any exponent of the stressed state.

Using phenomenological theories of deformability, in which the accumulation of damage is described by tensor models, it allows us to predict the technological heritage of the material in the form of residual plasticity for finished part.

If during the processing the components of the damage tensor at a given point of the workpiece are C, then during the subsequent stretching test in the direction of the x1 axis at a given point, the components of the tensor change by the amount $\Delta\psi_{ij}$.

If the destroy equation under such stretching is written as:

$$\left(\psi_{ij} + \Delta\psi_{ij}\right)\left(\psi_{ij} + \Delta\psi_{ij}\right) = 1, \tag{16}$$

then from it it is possible to obtain an equation for the limiting additional deformation of the stretching in the direction to the $x_1$ axis [5]:

$$\frac{e_{p11}}{e_p} = -\frac{1}{2} - \frac{e_i^*}{e_p} + \sqrt{\left(\frac{1}{2} + \frac{e_i^*}{e_p}\right)^2 - \sqrt{6}\psi_{11} + \sqrt{6\psi_{11}^2 + 4(1 - \psi_{ij}\psi_{ji})}}, \tag{17}$$

where $e_i^*$ is the accumulated deformation during the forming of the workpiece; $e_p = e_p(\eta = 1)$ is plasticity of the metal at $\eta = 1$; $e_{p11}$ is residual plasticity in stretching to the direction 11.

Since $\psi_{11}$ depends on the direction to $x_1$, the residual plasticity of $e_{p11}$ also turns out to depend according to direction. Thus, using eq. (19), one can estimate the plasticity anisotropy in any zone of branching on pipe, which is produced by the method of cold plastic deformation.

As an example, which illustrates the practical significance of this research, we can give to evaluate the plasticity for bends, which is produced by the cold plastic deformation method on combined scheme, which includes deforming stretching of the billet. In this case, the billet in the pipe form undergoes plastic bending followed by loss of plastic deformation stability.

In [7] the equation (18) obtained on the basis of the tensor representation about the accumulation of damages is presented, which makes it possible to estimate the residual ductility of the finished bend.

$$\frac{e_p}{\delta_p} = \frac{D_1 b}{200}\frac{e_i^*}{\delta_p} + \frac{D_1 b}{100}\sqrt{\left(\frac{1}{2} + \frac{100e_i^*}{D_1 b\delta_p}\right)^2 + \sqrt{2}\left[\psi_S - \psi_\theta + \sqrt{(\psi_S - \psi_\theta)^2 + (1 - \psi_{ij}\psi_{ji})}\right]}, \tag{18}$$

where $\delta_p$ – elongation at break, $b = \dfrac{C_1}{B_1}$ ($C_1$ = 1,03, $B_1$ =0,55 for steel 20; $C_1$ = 1,08, $B_1$ = 0,67 for steel X18H9T) $D_1$ = 0,66 for steel 20; $D_1$ = 0,73 for steel X18H9T.

$$\psi_\alpha = \psi_\theta = \frac{1}{4}\sqrt{\frac{2}{3}} \cdot \left[ \frac{e_i}{e_{p(\eta=2)}} + \left( \frac{e_i}{e_{p(\eta=2)}} \right)^2 \right];$$

$$\psi_S = -(\psi_\alpha - \psi_\theta) = -2\psi_\alpha; \qquad (19)$$

$$\psi_{ij}\psi_{ij} = \frac{1}{4}\left[ \frac{e_i}{e_{p(\eta=2)}} + \left( \frac{e_i}{e_{p(\eta=2)}} \right)^2 \right]^2.$$

In this research, an experimental verification to theoretical research of the residual plasticity for billets, previously deformed before obtain finished products, is carried out.

From the outer zone of the bends 90° – 57 × 4; 90° – 89 × 4,5, made of steel 20 ($\delta_P = 30$ %), flat samples were cut out. For the tensile test to longitudinal and circumferential directions of the steeply bend these samples were used. The stretching of these samples showed that their residual elongations to longitudinal and circumferential directions are approximately the same. The table 1 shows the theoretical and experimental results of residual plasticity.

Table 1 – Comparison by residual plasticity (theoretical and experimental results)

| Size of bend | Theoretical results | | | | experimental results | | Divergence |
|---|---|---|---|---|---|---|---|
| | $\psi$ | $e_{PS}$ | $e_{Ppas}$ | $e_{P\alpha}= e_{P\theta}$ | $e_{P\alpha}$ | $e_{P\theta}$ | % |
| 90° 57×4 | 0,35 | 0,58 | 0,27 | 0,43 | 0,41 | 0,37 | 9,3 |
| 90° 89×4,5 | 0,4 | 0,59 | 0,25 | 0,41 | 0,38 | 0,35 | 14,6 |

One of the most important characteristics bends which made by the cold plastic deformation method is their residual plasticity under working loads (especially under cyclic pressure loads at elevated temperatures). This plasticity is estimated approximately by the stretching test results of samples cut from the bends to different directions.

**Conclusions.**

1. The calculation method for determining the plasticity of pre-deformed metals during their processing by pressure has been developed. This method is based on a fracture model, which in turn is based on the tensor description of damage accumulation. With known mechanical characteristics, as well as with known plasticity diagrams, the fracture model makes it possible to evaluate the plasticity of pre-deformed bend for any kind of stress state.

2. When manufacturing steeply curved branches using the pipe extrusion method, the procedure was tested. Verification of the mathematical model has shown a high level of its adequacy, and it can be used in assessing the plasticity of pre-deformed billet.

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## РОЗРОБКА ЕКСПЕРИМЕНТАЛЬНОЇ МЕТОДИКИ ТА ОЦІНКА ГРАНИЦІ ПЛАСТИЧНОЇ ДЕФОРМАЦІЇ ТИТАНОВОГО СПЛАВУ ОТ4-0 В УМОВАХ НАДПЛАСТИЧНОСТІ

**Вступ.** В технологіях обробки матеріалів тиском ефективно використання явища надпластичності, яке надає можливість обробляти важкодеформовані та малопластичні матеріали. Висока пластичність для цих матеріалів проявляється при наявності ультрадрібнозернистої структури та деформаціях в відповідних температурно-швидкісних умовах [1, 2, 3, 4].

**Постановка задачі.** В роботі виконана оцінка граничних деформацій листового титанового сплаву ОТ4-0 при формоутворенні мембрани з відносною товщиною стінки 0,005.

При формоутворенні мембрани газовим середовищем реалізується двовісний розтяг. Даний вид випробувань використовується для оцінки пластичних властивостей металів. Внаслідок великих пластичних деформацій при випробуваннях на двовісний розтяг отримуємо більш повну оцінку механічних властивостей листового металу [5].

Оцінка пластичних властивостей проведена для деформування мембрани в умовах надпластичності. Важливо встановити при процесі надпластичної деформації зв'язок між зовнішніми параметрами деформування (зусиллям, температурою) з глибиною формоутворення мембрани в часі та розподілом деформації по її твірній.

Метою роботи є оцінка границі пластичної деформації на основі процесу формоутворення мембрани з тонколистового сплаву ОТ4-0 в умовах надпластичності. Отриманні результати передбачено використовувати для розрахунків технологічного процесу формоутворення складних деталей з титанових сплавів газовим середовищем.

**Результати роботи.** На величину пластичної деформації впливає схема напруженого стану. При формоутворенні мембран вид напружено-деформованого стану на випуклій поверхні характеризується постійністю. На випуклій поверхні нормальне напруження дорівнює нулю $\sigma_3 = 0$. З цього випливає, що $\sigma_1 = \sigma_2$, $\sigma_i = \sigma_1$. Реалізується