UDC 621.77.01
DOI: 10.37128/2520-6168-2024-2-8

IMPROVEMENT OF THE METHOD OF CONSTRUCTING LIMIT DEFORMATION CURVES FOR ROLL STAMPING PROCESSES

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The analysis of the construction of the curves of limit deformations of metals is carried out in the work. It was established that traditional methods of testing, such as deposition and stretching of cylindrical samples, do not ensure constancy of the stress state indicator, and therefore introduce the history of deformation into the construction of curves.

During deposition, there is an increase in the stress state indicator due to the curvature of the side surface of the sample (the formation of a barrel), which is caused by friction on the ends. And during stretching, the stress state indicator also increases, as a result of the formation of a neck due to the loss of deformation resistance. Therefore, measures were considered that would ensure obtaining reliable results when constructing the curves of limit deformations excluding the influence of deformation history. During deposition, such measures include the use of a plastic foil, softer than the sample material, on the ends of the samples and stepwise removal of the edges of the hole on their ends by grinding or deposition without foil. In addition, an experimental and computational method was considered, which involves the construction of deformation paths and correction of the limit deformation using the deformability criterion. During stretching, in the case of neck formation, the increase in deformation depends linearly on the ratio of the radius of curvature of the neck to its diameter.

An equation is presented, which can be used to take into account the influence of the neck parameters on the increase in limit deformations using the experimental and computational method. For the experimental determination of the ultimate deformation during stretching, a method of rolling cylindrical samples into a wedge with rolls, the radii of which increase during the rolling process, which allows to eliminate the appearance of a neck, is proposed. With sufficient accuracy for practice, the curves of limit deformations can be constructed based on the results of testing samples for torsion and sedimentation, and the values of limit deformations during stretching can be obtained using approximating dependencies tested for various metals. According to the above method, including the determination of plasticity by rolling, the curves of limit deformations of a number of steels were constructed.

Key words: *curves of limit deformations, rolling stamping, deposition, stretching, parameters, necks, plasticity, torsion, metals.*

Eq. 9. Fig. 5. Ref. 19.

1. Problem formulation

Production efficiency is a pressing need in contemporary mechanical engineering, where enhancing workpiece manufacturing processes is crucial during the primary molding stage. Optimal savings in material, labor, and financial resources are achieved by minimizing discrepancies between the geometric parameters of workpieces and the dimensions of finished parts, while ensuring the required physical and mechanical properties.

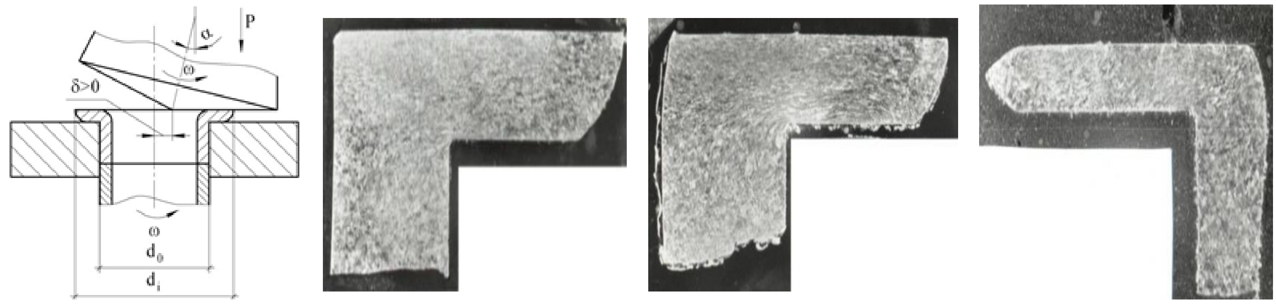
Modern metalworking demands high production efficiency, resulting in the widespread use of pressure metal processing (PMT) techniques for procurement operations. Cold deformation processes are particularly significant within this field, though their application is often constrained by the risk of metal failure.

In the range of stamped blanks, a considerable portion consists of complex profile components. Recently, the rolling stamping method has become widely adopted for producing parts from ring blanks [1, 2, 3, 4]. This method is distinguished by its localized deformation zone, where the workpiece is formed through repeated rolling with cylindrical or conical rolls. This approach enhances the flow conditions of the workpiece material in contact with the tool, enabling the production of well-developed thin-walled elements. The desired product profile can be achieved by applying well-considered technological schemes and strategically positioning the deformable rolls relative to the workpiece [5, 6, 7, 8]. Rolling is also employed as a preparatory step before volumetric stamping of long parts to evenly redistribute the metal of the original workpiece, reduce excessive deformation unevenness, achieve high deformation degrees, and produce high-quality, defect-free products with optimal metal utilization. This process is characterized by local, non-stationary deformation, which facilitates the creation of complex profile blanks with significant deformation degrees. For certain ductile metals, performing this process under cold deformation conditions is advisable.

2. Analysis of recent research and publications

Understanding the stress-strain state (STS) of workpiece material and the impact of various technological parameters is crucial when developing rolling stamping processes. This information allows for the determination of process force parameters, evaluation of material deformability, assessment of tooling stability, targeted expansion of process capabilities, and prediction of product performance characteristics [10, 11]. One of the most common operations in pressure metal processing is planting, where only a portion of the workpiece is deposited. Planting enables the production of complex profiled products with well-developed thin-walled elements with high precision. However, achieving significant deformations also poses a risk of material failure due to inadequate deformability [12, 13, 14]. Various methods are employed to study the STS in pressure metal processing operations, including experimental, analytical, and simulation modeling techniques. Combined experimental and computational methods have demonstrated the highest accuracy and efficiency. This underscores the importance of investigating the STS of workpiece materials in planting using pressure metal processing methods.

The technological scheme of planting outer flanges on pipe blanks with a conical roll is shown in (Fig. 1, *a*). The most dangerous, from the point of view of destruction, was the external free side surface of the flange. At the same time, the displacement of the top of the roll in the direction of the contact spot, as shown in (Fig. 1, *a*), contributes to the departure of the material of the peripheral part of the flange of the workpiece from contact with the roll, as shown in (Fig. 1, *c*) and fully realized in (Fig. 1, *d*).



a ***b*** ***c*** ***d***

Fig. 1. Scheme of planting the outer flange of the workpiece by the rolling stamping method a) and the cross-section of the formed flange b), c), d) depending on the position of the top of the roll

3. The purpose of the article

The work employs both theoretical and experimental research methods. The study of metal deformability relies on solid mechanics, mathematical and applied plasticity theory, and phenomenological deformability theory. Experimental research was conducted under laboratory conditions using natural samples and modern devices alongside standard equipment. The experimental data were processed using mathematical statistics methods.

4. Results of the researches

In cold deformation processes, while metal strengthening and the creation of a beneficial microstructure occur, damage also accumulates, leading to reduced material density and diminished residual plasticity. As a result, exceeding a certain deformation threshold can deteriorate the operational characteristics of products, potentially causing the failure of blanks during processing or products during use.

Thus, ensuring the required quality of products processed using pressure metal processing (PMP) methods is not feasible without evaluating the deformability of metals. This involves assessing their ability to deform without failure while minimizing the depletion of their plasticity resources.

Plasticity refers to the ability of metals to undergo irreversible shape changes without breaking. Typically, this ability is limited, as metal deformation is accompanied by an increase in the density of linear and point defects, as well as the formation and growth of micropores and microcracks. This results in the loosening of the metal, leading to the development of primary cracks and eventual destruction, as illustrated in Fig. 2.

The accumulation of damage in the metal leads to a reduction in its density and alters various electrical characteristics [16]. Figure 3 illustrates how the density of alloys we studied changes as they exhaust their plasticity resource during cold deformation processes.

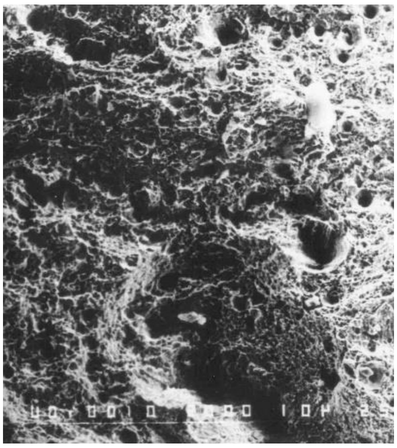


Fig. 2. Appearance of damage on the surface of the plastic failure zone:
1 – EI961 alloy; 2 – VT9 alloy; 3 – EP718 alloy

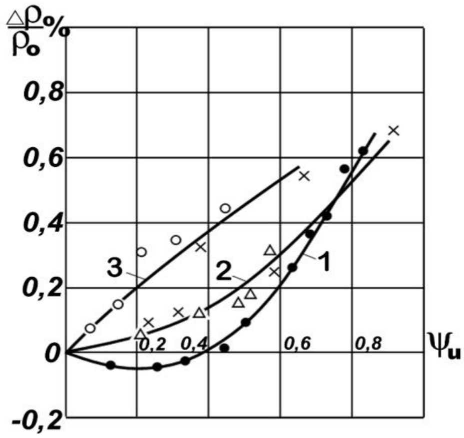


Fig. 3. Dependence of plastic loosening of metals $\Delta\rho/\rho_0$ on the value of the plasticity resource used: ψ_u :●, o – compression; △ – torsion; x – stretch
1 – EI961 alloy; 2 – VT9 alloy; 3 – EP718 alloy

As can be seen from fig. 2, at the initial stages of deformation of most metals, a slight intensity of density reduction is observed. EI961 alloy during deposition to values $\psi_u \le 0,4$ it even becomes somewhat denser, and only later does the density decrease. Titanium alloys VT8 and VT9 are deformed at a relatively small intensity of density reduction in the initial stages. In the EP718 alloy, the dependence of the decrease in density on the value of the used plasticity resource turned out to be close to linear. The amount of plastic loosening at 50% use of the plasticity resource for different materials and types of tests is within $\Delta p / p = 0,1 - 0,4$ %.

With the increase in the damageability of metals, the relative value of their loosening is leveled off, so that at the values of the $\psi_u = 0,8$ decrease in density for the studied alloys was $\Delta p / p \approx 0,6$ %. The conducted experiments showed that the subsequent heat treatment completely restores the initial density and plasticity of the material only to the values of the used ductile resource $\psi_u \le 0,4$

A main crack, which signifies the exhaustion of the metal's plasticity, is defined as a defect that results in an irreparable flaw in products. The size of the main crack can vary depending on the technological process. In cold deformation processes, detecting main cracks is facilitated by the fact that, in the absence of a pronounced gradient of metal damage, the catastrophic growth of a main crack occurs without a significant increase in the degree of plasticity.

Ductile deformation is accompanied by an increase in residual deformations. The deformed state at a point can be described by a symmetric tensor of the second rank $\dot{\varepsilon}_{ij} (i, j = 1,2,3)$ – the strain-rate tensor. The components of the strain rate tensor are related to the velocity field $U_i (i = 1,2,3)$ by the Cauchy relation:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \tag{1}$$

where $x_i (i = 1,2,3)$ – are the Euler coordinates.

As a measure of the deformation rates at a point, one of the variants of the strain rate tensor is accepted - the intensity of the deformation rates, which is a scalar positive value.

The measure of deformation at a material point is the accumulated deformation or degree of deformation:

$$\varepsilon_u = \int_0^{t_K} \dot{\varepsilon}_u dt, \tag{2}$$

where t_k – is the end time of the deformation process.

As a measure of plasticity, the plastic deformation accumulated until the moment of failure is taken [5]:

$$\varepsilon_* = \int_0^{t_p} \dot{\varepsilon}_u d\tau, \tag{3}$$

where t_p – is the time of deformation to failure.

In simple deformation, where the direction of principal deformations and the relative positions of principal axes with respect to the material fibers remain constant, the accumulated deformation (or degree of deformation) is equal to the magnitude of the logarithmic strains [3].

$$\varepsilon_u = \frac{\sqrt{3}}{2}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}, \tag{4}$$

where $\varepsilon_1 \varepsilon_2 \varepsilon_3$ – are the main logarithmic deformations.

The plasticity of the metal depends: on the brand and condition; the type of load, which determines the sign of the main deformations and the constancy of the position of the main axes relative to the fibers of the material; stress indicator; state of the surface of the deformed sample and scale factor; gradients of the deformed state and plastic loosening of the metal; the intensity of the change in the directions of the sliding planes, etc.

The primary factor affecting the plasticity of metals during cold deformation is the stress state scheme. The relationship between plasticity and the parameters defining this stress state scheme is known as the limit curve of deformation.

The concept of the dependence of plasticity on the stress state indicator has become the most widespread:

$$\eta = \frac{I_1(T_\sigma)}{3\sqrt{I_2(D_\sigma)}} = \frac{3\sigma}{\sqrt{3}\sigma_u}. \tag{5}$$

The indicator does η not take into account the influence of the third invariant of the stress tensor, therefore, the boundary stress curve in «$\varepsilon_u - \eta$» coordinates is not considered to be the only one for all possible types of stress state.

For an accurate assessment of metal deformability across various technological processes, it is essential to have a unified curve of boundary deformations that characterizes plasticity under different stress state schemes. Testing metals for plasticity in a high-pressure chamber using various methods has yielded different results for the same stress state indicator. Specifically, V.A. Matviychuk and I.S. Aliyev found that plasticity is greater during stretching compared to torsion. A.A. Bogatov demonstrated that test results vary, with the dominant characteristic depending on the metal grade. Additionally, Ogorodnikov V.A. established that, under equal stress state indicator values, plasticity during twisting in a high-pressure chamber is still lower compared to compression.

To avoid discrepancies in assessing metal deformability, it is essential to ensure that the conditions of identity for the Nadai-Lode parameter, which characterizes the type of stress deviator, are maintained in both the studied technological process and the experiments used to construct the limit deformation curv:

$$\mu_\sigma = 2\frac{\sigma_2 - \sigma_1}{\sigma_1 - \sigma_3} - 1 = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}. \tag{6}$$

The dependence of plasticity on the stress state scheme can be described by constructing the complete surface of plasticity in «$\varepsilon_u - \eta - \mu_\sigma$». coordinates. This dependence was proposed in the works of Gubkin S.I., but its construction is associated with difficulties of an experimental nature.

In the paper Ogorodnikov V.A. proposed to construct a plasticity surface in the coordinates «$\varepsilon_u - \eta - \chi$», where χ is an indicator that takes into account the third invariant of the stress tensor:

$$\chi = \frac{\sqrt[3]{I_3(T_\sigma)}}{\sqrt{3I_2(D_\sigma)}} = \frac{\sqrt[3]{\sigma_1\sigma_2\sigma_3}}{\sigma_u}. \tag{7}$$

The plasticity surface constructed in the " $\varepsilon_u - \eta - \chi$ " coordinates can be defined as the surface of boundaries deformations. The intersection of the surface with a plane perpendicular to the axis $\chi = 0$, leads to obtaining a curve of boundaries deformations in $\varepsilon_* = \varepsilon_*(\eta)$ coordinates . To construct the boundary deformation curves according to this technique, it is necessary to conduct time-consuming tests in a high-pressure chamber. This excludes the possibility of compressive testing of ductile materials, and tensile tests lead to distortion of results due to necking.

In work [6], a method of constructing surfaces $\varepsilon_* = \varepsilon_*(\eta, \mu_\sigma)$ by means of simple tests for tension, compression, pure shear and tests for the deposition of cylindrical samples in shells of different thicknesses was developed.

The lack of universality of the qualitative influence of the Nadaya-Lode index on plasticity in the conditions $\eta = const$ has led to the fact that many researchers explain the noted differences in plasticity with the imperfection of methods of testing samples for tension, torsion and compression. However, these explanations do not have well-founded confirmations.

In constructing boundary deformation curves, conventional testing methods for tension, torsion, and compression are employed. However, the imperfections inherent in these methods account for the variations observed in plasticity when using boundary deformation curves. In work [7] it was also confirmed that the plasticity of metals at constant values of the indicator η really depends significantly on the value μ_σ. However, the authors note that it is possible to assert the existence of a plasticity surface only if there are two different points on such a surface with the same value ε_*, but with different combinations of indicators η and μ_σ. However, this position has not been confirmed by experimental data.

Possible inaccuracies in describing the dependence of plasticity on the stress state scheme using boundary deformation curves are primarily observed in regions of comprehensive compression. In these areas, the risk of metal destruction during technological processes becomes less critical. In addition, in most deformability criteria, the integral function includes a model of the dependence of the boundary deformation ε_* from the indicator η. Therefore, when describing the dependence of plasticity on the scheme of the stress state, the curves of boundaries deformations in coordinates $\varepsilon_* = \varepsilon_*(\eta)$ were the most widespread. At the same time, contradictory values of plasticity obtained from different types of tests remain problematic. A major source of such contradictions is the "abnormal" increase in plasticity that occurs during neck formation in stretching tests. The analysis of the stress state of the materials of the workpieces during processing by SR methods showed that the indicator of the stress state η in the dangerous zone of the workpiece is within $-2 \le \eta \le 1$, and the Nadai-Lode parameter $0 \le \mu_\sigma \le 1$. The plasticity of materials can be determined by the results of testing cylindrical samples for deposition, torsion, and stretching, as well as by performing the specified types of tests in a high-pressure chamber. However, during such tests, problems often arise, which are related to the difficulty of maintaining a constant specified stress state scheme, uniform across the entire cross-section of the sample, as well as maintaining the conditions $\eta = const$ throughout the sample's test time.

Thus, in order to construct the curves of boundary deformations, need to know the nature of the "abnormal" increase in plasticity during the formation of the neck of the stretched sample, as well as ensure testing under the conditions $\eta = const$. The development of test methods for determining the plasticity of metals under complex deformation conditions is also of considerable interest.

Thus, determining the plasticity of metals during simple cold deformation is associated with a number of difficulties. By simple or stationary, we understand the deformation in which, $\beta_{ij}(\varepsilon_u) = const$, $\eta(\varepsilon_u) = const$, $\mu_\sigma = const$, where β_{ij} is the guiding tensor of the increase in deformations [4]. This type of deformation must, preferably, be ensured in the case of carrying out tests when constructing boundary deformation curves.
Matviychuk V.A., in work [2, 8], attributed the increased plasticity observed during stretching with neck formation, as shown in Fig. 4, to the phenomenon of complex deformation. In this context, complex deformation is understood as a situation where the direction tensor of the deformation rates. $\beta_{ij}(\varepsilon_u) \ne const$.

During stretching, the deformation process proceeds steadily, without the formation of a neck, if the deformation force P = $\sigma_u S$ (S is the cross-sectional area of the sample) increases with the increase in the intensity of the deformations:

$$\frac{dP}{d\varepsilon_u} = \frac{d(\sigma_u S)}{d\varepsilon_u} = S\frac{d\sigma_u}{d\varepsilon_u} + \sigma_u\frac{dS}{d\varepsilon_u} > 0, \quad (8)$$

where the terms $S\frac{d\sigma_u}{d\varepsilon_u}$ and $\sigma_u\frac{dS}{d\varepsilon_u}$ reflect, respectively, the deformation hardening of the material and the loss of strength of the sample, which is associated with a decrease in the area *S*.

To clarify the effect of inhibiting the development of cracks in the growth zone of the neck, experiments were conducted on the distribution of ring samples over a deformable cylindrical mandrel. This setup aimed to better understand how deformation in this specific arrangement affects crack development and plasticity. The use of rings with a two- or three-fold ratio of width to wall thickness made it possible to increase the degree of deformation ε_p, so that rings made of low-plastic alloys OT4, VT9, VT25 were destroyed without significant formation of a neck (Fig. 4). At the same time, the experimental values of the boundaries deformations corresponded to the calculated ones, without an "abnormal" increase in plasticity.

Fig. 4. Type of ring samples brought to destruction by distribution on deformable mandrels

The research findings indicate that the formation of a neck actually inhibits crack propagation and enhances the plasticity of metals. This increase in plasticity is likely due to changes in the nature of the deformation state. Specifically, the development of a "pore layer"- which contributes to crack propagation-occurs in a localized region along the slip bands. During deformation, the slip lines are oriented at an angle of π/4 relative to the free surface.

With the formation of the neck and the curvature of the lateral surface, the direction of the slip lines shifts, leading to the accumulation of plastic loosening in varying directions. Inside the neck, the sliding strip segments into shorter sections and follows a zigzag trajectory. This change in the movement of metal particles, which experience the highest levels of plastic loosening, results in an overall increase in plasticity. At the same time, the increase in deformation Δε_* established in [8] depends linearly on the ratio of the radius of curvature of the neck R to its diameter $d_ш$, and when $R/d_ш \geq 0{,}5$ can be described by the equation:

$$\Delta\varepsilon_* = 0{,}85 - 0{,}57\,R/d_ш\ . \qquad (9)$$

In fig. 5 shows a graphical view of the dependence (9) of the increase in the degree of plasticity Δε_* on the ratio of the radius of curvature of the neck R to its diameter d_h for different materials: O – VT9, △ – VT25, ×– OT4, □ – EP517, ▽– EI961, ⌓ – EP866, ◇ – EP718.

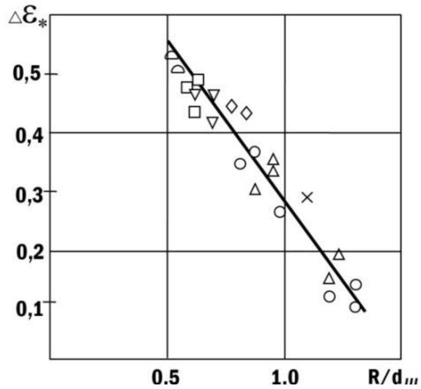


Fig. 5. The dependence of the increase in the degree of plasticity $\Delta\varepsilon_*$ on the ratio of the radius of curvature of the neck R to its diameter d_h for different materials.

It is important to recognize that the presence of local thinning on workpieces during pressure treatment processes indicates a defect. Therefore, it is reasonable to define the limit deformation as the critical value for assessing plasticity ε_p. If workpieces are destroyed in technological processes without the formation of a neck, the plasticity values obtained from stretching tests can be used for an objective assessment of deformability.

5. Conclusions

The analysis of existing methods for testing metals for plasticity and constructing limit deformation curves has revealed shortcomings due to the instability of the stress state indicator. Challenges in studying metal plasticity arise from the absence of methods to create a unified limit deformation curve. Issues such as neck formation during the stretching of cylindrical samples, barrel formation during deposition, and increased plasticity resulting from complex deformation further complicate the process.

Based on the research results, an equation was developed to determine the increase in plasticity based on the ratio of the radius of curvature of the neck to its diameter. This equation accounts for the "abnormal" increase in plasticity that occurs during neck formation in stretching. Additionally, an experimental-calculation method was proposed, which involves constructing deformation trajectories during the deposition of cylindrical samples and correcting the limit deformation according to the deformability criterion. A method for stamping by rolling cylindrical samples with rolls, whose radii increase during the rolling process, has also been developed.

The introduction of rolling stamping methods into production ensures an increase in the metal utilization ratio to 0.8 and a 30-35% reduction in processing time.

In rolling stamping, the accuracy of product dimensions relies on both the precision of the tool dimensions and the deformation scheme. Typically, rolling ensures a processing accuracy of quality levels 8-11. The surface roughness of the product is influenced by the roughness of the tool and the quality of the lubricant. When using tools with high-quality working surfaces, the surface roughness of the product can be maintained at a micron level. Additionally, the ability to utilize low-power equipment for producing large-sized products, particularly through rolling stamping, makes this method effective for small-scale production.

This method allows for testing cylindrical samples under constant loads, providing plasticity values under conditions of single axial compression. Limit deformation curves, with the required accuracy for practical applications, can be constructed based on test results for torsion and settling, using approximate dependencies. This technique has been used to construct the limit deformation curves for various steels.

The proposed test methods enable the determination of metal plasticity under various constant stress states, enhancing the reliability of assessing deformability in pressure metal processing (PMP) operations. This, in turn, facilitates the development of resource-efficient stamping and rolling processes by:

- Reducing the number of transitions and preventing defects due to material destruction.
- Improving product quality through the formation of a favorable microstructure and optimizing the use of the plasticity resource.

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ВДОСКОНАЛЕННЯ МЕТОДИКИ ПОБУДУВИ КРИВИХ ГРАНИЧНИХ ДЕФОРМАЦІЇ ДЛЯ ПРОЦЕСІВ ШТАМПУВАННЯ ОБКОЧУВАННЯМ

В роботі проведений аналіз побудови кривих граничних деформацій металів. Встановлено, що традиційні способи випробувань, такі як осадження і розтягування циліндричних зразків, не забезпечують сталості показника напруженого стану, а отже вносять історію деформування в побудову кривих.

При осаджуванні відбувається зростання показника напруженого стану внаслідок викривлення бокової поверхні зразка (утворення бочки), яке викликане тертям на торцях. А при розтягуванні показник напруженого стану також зростає, в результаті утворення шийки через втрату стійкості деформування. Тому були розглянуті заходи, які б забезпечили отримання достовірних результатів при побудові кривих граничних деформацій з виключенням впливу історії деформування. При осаджуванні до таких заходів відносяться використання пластичної, більш м'якої ніж матеріал зразка, фольги на торцях зразків та поетапне видалення крайок лунки на їх торцях шліфуванням або осаджуванням без фольги. Крім того, був розглянутий експериментально-розрахунковий метод, який передбачає побудову шляхів деформування та корегування граничної деформації за допомогою критерію деформовності. При розтягуванні, у випадку утворення шийки, приріст деформації лінійно залежить від відношення радіуса кривизни шийки до її діаметру.

Приведено рівняння, за допомогою якого експериментально-розрахунковим методом можна врахувати вплив параметрів шийки на підвищення граничних деформацій. Для експериментального визначення граничної деформації при розтягуванні запропоновано спосіб вальцювання циліндричних зразків на клин валками, радіуси яких зростають в процесі вальцювання, що дозволяє усунути появу шийки. З достатньою для практики точністю криві граничних деформацій можна будувати за результатами випробування зразків на кручення і осаджування, а значення граничних деформацій при розтягуванні отримувати з використанням апробованих для різних металів апроксимуючих залежностей За приведеною методикою, включаючи визначення пластичності вальцюванням, були побудовані криві граничних деформацій низки сталей.

Ключові слова: *криві граничних деформацій, штампування обкочуванням, осадження, розтягування, параметри, шийки, пластичність, кручення, метали.*

Ф. 9. Рис. 5. Літ. 19.

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