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METHODS OF THEORETICAL ANALYSIS OF METAL FORMING PROCESSES

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Abstract: This article examines methods for the theoretical analysis of metal forming processes. The physical and mechanical foundations and deformation patterns are analyzed. A comparative study of modern analytical methods is presented. Factors improving processing efficiency are identified. The scientific novelty lies in the development of theoretical approaches. The results have practical significance for industrial applications. Conclusions indicate the potential for implementation in practice.

Keywords: metal forming, deformation, theoretical analysis, mechanical properties, process efficiency.

Annotatsiya: Ushbu maqolada metallarga bosim bilan ishlov berish jarayonlarini nazariy tahlil qilish usullari o‘rganiladi. Jarayonlarning fizik-mexanik asoslari va deformatsiya qonuniyatlari tahlil etilgan. Muallif tomonidan zamonaviy tahlil usullari qiyosiy ravishda ko‘rib chiqilgan. Ishlov berish samaradorligini oshirish omillari aniqlangan. Ilmiy yangilik sifatida nazariy yondashuvlar takomillashtirilgan. Olingan natijalar ishlab chiqarishda qo‘llash uchun muhim ahamiyatga ega. Tadqiqot xulosalari amaliyotga tatbiq etish imkoniyatini ko‘rsatadi.

Kalit so‘zlar: metallarga bosim bilan ishlov berish, deformatsiya, nazariy tahlil, mexanik xossalar, texnologiya samaradorligi.

Аннотация: В статье рассматриваются методы теоретического анализа процессов обработки металлов давлением. Проанализированы физико-механические основы и закономерности деформации. Автором проведено сравнительное исследование современных методов анализа. Выявлены факторы повышения эффективности обработки. Научная новизна заключается в совершенствовании теоретических подходов. Полученные результаты имеют практическое значение для производства. Сделаны выводы о возможности внедрения в промышленность.

Ключевые слова: обработка металлов давлением, деформация, теоретический анализ, механические свойства, эффективность технологии.

INTRODUCTION

The rapid development of metal forming technologies has led to the emergence of complex engineering problems in modern industry. In particular, determining the forces occurring during deformation processes, evaluating energy consumption, and selecting optimal technological parameters are of significant scientific and practical importance. The effective solution of these problems can only be achieved through scientifically based approaches, namely by conducting in-depth research on metal forming processes. Therefore, the integrated use of analytical, experimental, and experimental-analytical methods is considered essential in this field.

The object of the study is metal forming processes, while the subject of the study is the methods of their theoretical analysis. The aim of the work is to study the existing methods for investigating metal forming processes and to evaluate their effectiveness. To achieve this aim, the following tasks were set: to reveal the essence of analytical, experimental, and experimental-analytical methods, to analyze their advantages and disadvantages, and to determine their practical application possibilities.

Analytical methods are based on mathematical modeling and allow processes to be represented in a simplified form. However, the accuracy of initial data and the assumptions made significantly affect the reliability of the results. Experimental methods provide high accuracy through results obtained under real conditions, but they require considerable costs. Therefore, modern research increasingly applies experimental-analytical methods that combine both approaches.

REVIEW OF LITERATURE ON THE SUBJECT

A large number of scientific studies have been conducted by foreign and local researchers on the theoretical analysis of metal forming processes. In foreign literature, particular attention has been paid to the development of plastic deformation theory, where the works of G. Genki, I. Prandtl, R. Hill, and V. Prager occupy an important place. These researchers developed the theoretical foundations of stress state analysis, plasticity conditions, and the slip-line method. In addition, the scientific works of E. Zibel [1], G. Zaks [2], S. I. Gubkin [3], and I. M. Pavlov [4] served as the basis for the formation of engineering methods. Later, E. P. Cheksov [5] improved this approach and adapted it for practical engineering calculations.

A significant contribution to the development of the energy method was made by N. S. Petrov, I. Ya. Tarasovkin, A. A. Pozdeev, Yu. I. Ovchinnikov, and other researchers, who proposed the analysis of deformation processes based on the energy balance principle. This approach is widely used in the calculation of complex technological processes and provides high efficiency in determining deformation forces and energy consumption.

The distinctive feature of the present study is that it considers the methods of theoretical analysis of metal forming processes within an integrated approach. In particular, the interrelation of analytical, experimental, and energy methods is analyzed, and their applicability limits and accuracy levels are evaluated. This, in contrast to existing studies, allows for more comprehensive and reliable results, thereby ensuring the scientific novelty of the research.

RESEARCH METHODOLOGY

In the preparation of this article, a comprehensive methodological approach aimed at the theoretical analysis of metal forming processes was applied. During the study, the theoretical analysis method was primarily used based on the review and systematization of existing scientific literature. Through this approach, the theoretical foundations of engineering, slip-line, and energy methods, as well as their application features, were clarified.

In addition, the comparative analysis method was widely employed. Using this method, the advantages and disadvantages of different theoretical approaches were compared, and their accuracy, applicability, and efficiency were evaluated. As a result of the comparative analysis, the conditions under which each method is most effective in practical applications were identified.

The analytical modeling method was also applied in the research process, where deformation processes were expressed through mathematical equations. This approach allowed for a theoretical description of the relationships between stress state, deformation parameters, and energy consumption. At the same time, the reliability of theoretical conclusions was assessed based on available experimental data.

Furthermore, a systems approach was used to consider metal forming processes as an integrated system. This approach made it possible to reveal the interconnections between different methods and to substantiate the feasibility of their combined application.

ANALYSIS AND RESULTS

In the theoretical analysis of metal forming processes, the results obtained from engineering, slip-line, and energy methods were studied on a comparative basis. During the research, stress state, deformation level, and energy consumption indicators were selected as the main evaluation criteria.

The conducted analysis shows that the engineering method provides quick results for simple geometrical parts; however, the error rate increases in complex deformation zones. The slip-line method describes the stress field more accurately, but it is characterized by a more complex and multi-stage computational process. The energy method, on the other hand, allows the deformation process to be evaluated based on an overall energy balance and provides the most stable results in practical calculations.

The analytical construction of slip-line fields is possible only for a small class of metal forming (MBBJ) problems.

For example, in the tensile deformation of a flanged component, the stress state is described by the following tensor:

$$T_\sigma = \begin{pmatrix} \sigma_\tau & 0 \\ 0 & \sigma_\theta \end{pmatrix}$$

In this case, $\tau_{\tau 0} = 0$, shear stress is absent, i.e., it is equal to zero. Therefore, $^{\pi}/_{4}$ the slip line at every point of the flange forms a constant angle with the radius.

$r = ae^{\varphi}$.

(5.15) based on this equation, a family of slip lines can be constructed.

On the outer surface of the flange, $\sigma_\tau = 0$.

C At the point $\sigma_\theta = \sigma_{cpA} = -k$. (5.3- as shown in the figure).

From the plasticity condition:

$$\sigma_\tau - \sigma_\theta = 2k.$$

From this, it follows that:

$\sigma_\tau = 0\ ,\ \sigma_\theta = -2k$.

At the inner radius, the following is obtained:

$\sigma_\tau = 0\ ,\ \sigma_\theta = 2k$.

Therefore, the average stress at point E is given by σ_{cpE} can be determined using the formula.

Example, $OA = R$ and $OB = R_b$. according to the formula, when moving from point A to point B, the slip line σ_{AB} is rotated by an angle:

$$\sigma_{AB} = ln\frac{R}{R_b}.$$

However, the pressure at point E is unknown. This value can be determined using the equilibrium equation of the body.

As a result:

$$\sigma_\tau + \sigma_\theta = -2k + 4k\ ln\frac{R}{R_b}.$$

From this, it follows that:

$$\sigma_\tau - \sigma_\theta = 2k.$$

By combining these two equations, we obtain:

$$\sigma_\theta = 2k\ ln\frac{R}{R_b},$$

$$\sigma_\tau = -2\mathrm{k}(1 - \ln\frac{R}{R_b}).$$

Table 1. Nodal coordinates of the slip-line field (x–z values)

Index	x	z
1,1	0,428	0
1,2	0,647	0,286
1,3	0,792	0,636
1,4	0,845	1,04
1,5	0,789	1,464
1,6	0,617	1,88
2,2	1,018	0
2,3	1,333	0,413
2,4	1,552	0,944

2,5	1,634	1,571
2,6	1,545	2,256
3,3	1,867	0
3,4	2,338	0,615
3,5	2,673	1,429
3,6	2,804	2,414
4,4	3,134	0
4,5	3,83	0,937
4,6	4,37	2,205
5,5	5,06	0
5,6	6,17	1,453
6,6	8,04	0

The contour of the die used for pressing is transferred onto the constructed diagram according to scale. As a result, the slip-line field matches the beginning of the calibrating belt.

Let us assume that the walls KC and LD are tangent to the slip line AMQ, while BN forms the boundary of the deformation zone ABNRMA. The contours AKM and BLN represent the boundaries of the rigid zones.

If the slip-line field is known, it becomes possible to carry out a detailed analysis of the stress state. Unfortunately, the standard method described above is applicable only to a limited class of problems (for example, punch indentation into a plate, sheet drawing, die pressing, and wedge-shaped cavity compression, etc.).

Most bulk forming problems cannot be solved using this method. In such cases, alternative graphical methods for constructing slip-line fields must be used.

If the KC and LD lines do not pass through the nodal points M and N, it is necessary to use points from another slip-line family (for example, point P). In some cases, several of these approaches are considered. However, before that, it is necessary to review the properties that facilitate the construction of slip lines.

A slip line is a trajectory of maximum shear stress. From this, the following four simple properties of slip lines are derived (Figure 1):

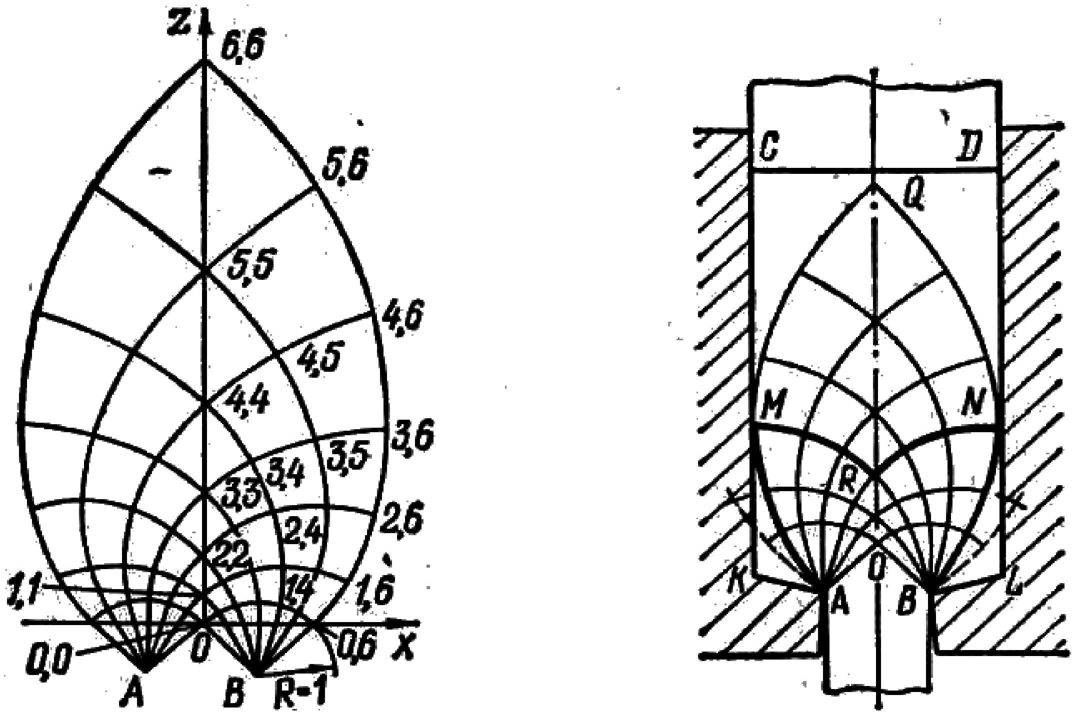

Figure 1. Slip-line field and deformation zone scheme

Two-parameter slip-line nodal network with a 15° increment.

Slip-line field formed during the pressing of a flat billet through a rough container.

slip lines are continuous;

they form two families, α and β, and resemble a dense network;

slip lines belonging to the α family are perpendicular to those belonging to the β family;

slip lines intersect at an angle of π/4;

Another property is proven using Hencky's theorem mentioned above. The angle between tangents drawn at the intersection points of two slip lines belonging to one family with lines of the other family remains constant.

To prove this, consider the curvilinear quadrilateral ABCD, formed by tangents drawn to the α and β slip lines (Figure 2)

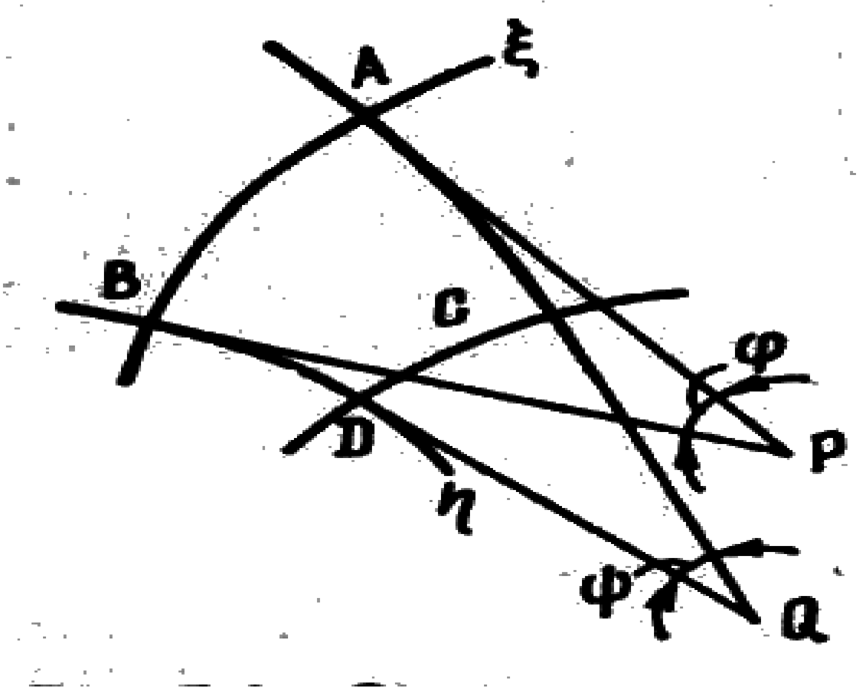

Figure 2. Slip-line scheme for proving Hencky's theorem

To prove this, consider the curvilinear quadrilateral ABCD, formed by tangents drawn to the α and β slip lines.

At points A, B, C, and D, tangents are drawn to the slip lines belonging to the η family, and their intersection points are denoted as P and Q.

Then the following is obtained:

$\angle APB = \varphi, \angle CQD = \varphi.$

As a result, a second-order differential equation is obtained:

$$\frac{d^2\omega}{d\theta^2} = 0.$$

By integrating it, we obtain:

$\omega = \phi(\eta) + F(\varepsilon).$

Here, $\phi(\eta)$ va $F(\varepsilon)$ —η and ε are arbitrary functions taken along the coordinate axes.

Using equation (5.17), the angles formed by the tangents AP and BP can be determined (Figure 3):

$\omega_A = \phi(\eta_A) + F(\varepsilon_A), \omega_C = \phi(\eta_C) + F(\varepsilon_C),$

$\omega_B = \phi(\eta_B) + F(\varepsilon_B), \omega_D = \phi(\eta_D) + F(\varepsilon_D),$

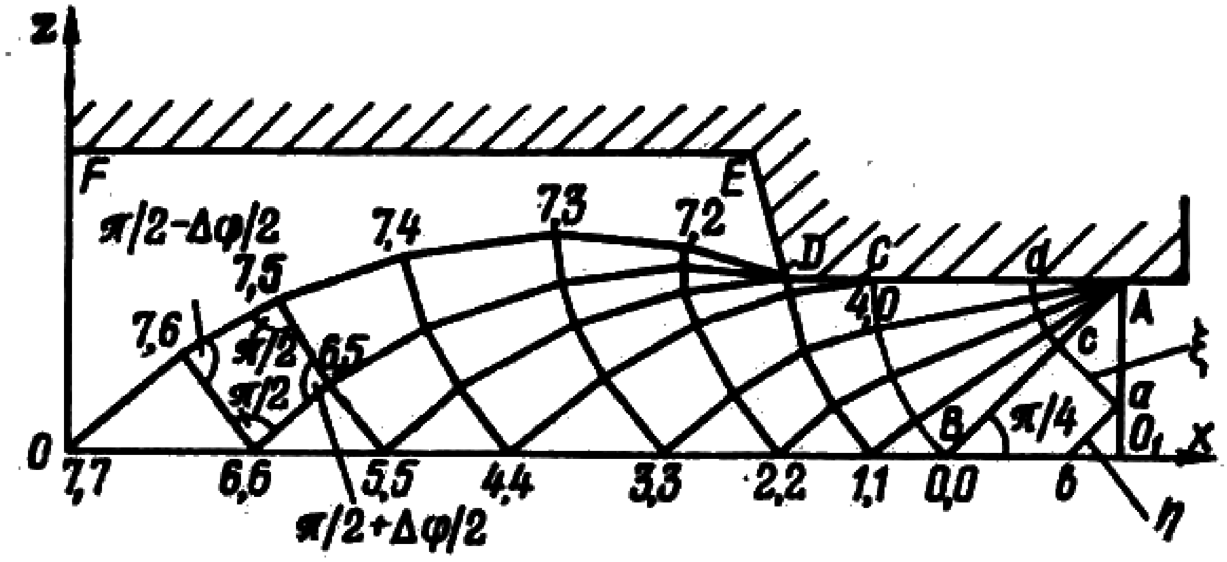

Figure 3. Slip-line field diagram in plane strain deformation

Slip-line field in the upsetting of an infinitely long stepped strip (for simplification, a large increment step is used in the figure). η- When moving along the η-line in a coordinate system, the quantity η remains constant. Therefore $\phi(\eta_A) = \phi(\eta_B)$, $\phi(\eta_C) = \phi(\eta_D)$.

Then,φ is obtained by pairwise subtraction of equations

$\varphi = F(\varepsilon_B) - F(\varepsilon_D)$.

η Along the line, the quantity ξ does not change. Therefore,

$F(\varepsilon_B) = F(\varepsilon_D)$, $F(\varepsilon_A) = F(\varepsilon_C)$.

From (5.19), an important practical conclusion follows:

$$\varphi = \omega.$$

This equation expresses a property inherent in Hencky's theorem.

Hencky's theorem makes it possible to construct slip-line fields using graphical methods. One of the most widely used approaches is the piecewise-linear slip-line network method

Let us consider the problem of upsetting a stepped strip. For this purpose, the billet is placed in the first quadrant

This equation expresses a property inherent in Hencky's theorem.

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Let us consider the problem of upsetting a stepped strip. For this purpose, the billet is placed in the first quadrant

$$2\Delta\varphi \approx 7{,}5^\circ$$

The next lines are drawn in the following order: Starting from point 1,2, the lines belonging to the ξ family are constructed. Then, lines belonging to the η family are drawn.

For example, the lines 0–0.1 and 1–1.1 are constructed first. Then the lines 2,0–2,1 and 1,1–1,2 are drawn.

As a result, a slip-line field is formed. This network consists of several triangular elements. For example, at point 1,0 the angle is

$$\frac{\pi}{2}+\frac{\Delta\varphi}{2}$$

is equal to

At point 2,1, the angle is

$$\frac{\pi}{2}-\frac{\Delta\varphi}{2}$$

These angles are characteristic for all elements of the slip-line field network.

The next construction starts from point A. Here, a slip line belonging to the α family extends in the direction AD.

The slip lines along the BC segment define the boundary of the deformation zone, where the stress state changes.

As a result, the following regions are formed:

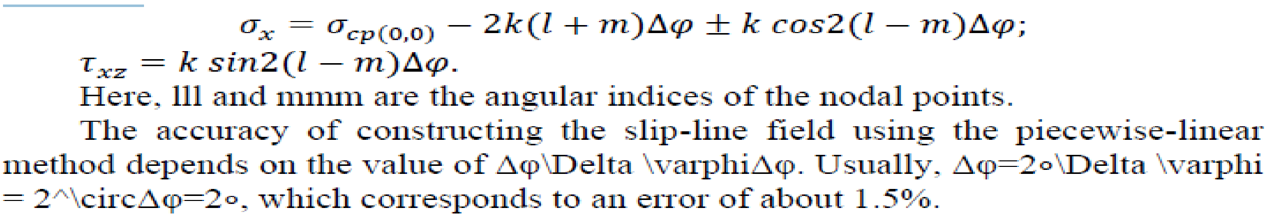
(AOB) — region of uniform stress

(ABC) — deformation zone

(BCDO) — region of a different stress state

Thus, using the slip-line field, it is possible to determine the stress state at any point of the body.

Using Hencky's integral and transformation formulas, the following is obtained:



$$\sigma_x = \sigma_{cp(0,0)} - 2k(l+m)\Delta\varphi \pm k\,cos2(l-m)\Delta\varphi;$$

$$\tau_{xz} = k\,sin2(l-m)\Delta\varphi.$$

Here, lll and mmm are the angular indices of the nodal points.

The accuracy of constructing the slip-line field using the piecewise-linear method depends on the value of Δφ\Delta \varphiΔφ. Usually, Δφ=2∘\Delta \varphi = 2^\circΔφ=2∘, which corresponds to an error of about 1.5%.

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Because of this, piecewise-linear networks can be effectively used in solving many metals forming (OMD) problems.

However, the slip-line field is not the only method for solving such problems. For example, if slip-line fields differ at various points of the workpiece, averaged values are taken.

CONCLUSIONS AND SUGGESTIONS

that the engineering, slip-line, and energy methods used in the evaluation of metal forming processes have their own advantages and limitations. The engineering method provides fast and simple calculations; however, its accuracy decreases in complex deformation states. The slip-line method enables a highly accurate representation of the stress field, but its practical application requires complex computations. The energy method, on the other hand, evaluates the deformation process based on an energy balance and stands out as the most stable and universal approach in practical applications.

The analysis identified several key issues, including uncertainty in initial parameters, simplification of mathematical models, and high computational complexity in some methods. These factors directly affect the accuracy of results and the efficiency of practical applications.

To address these issues, the following recommendations are proposed:

-integrated use of analytical and experimental methods in modeling deformation processes;

-application of modern experimental techniques and numerical simulations for determining initial parameters;

-development of computer-based models to automate slip-line field construction;

-creation of optimization algorithms for deformation zones based on the energy method;

-combined application of multiple methods in complex technological processes to improve accuracy.

In conclusion, for effective analysis of metal forming processes, it is advisable not to use the existing methods separately, but as an interconnected system. This approach improves accuracy, efficiency, and economic feasibility in production processes.

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