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THE PHENOMENON OF THERMODYNAMIC ACTION DURING PLASTIC DEFORMATION OF METALS AND THEIR ALLOYS

Abstract: *The most important problem of modern technology for mechanical processing of structural materials is to increase the efficiency of shaping operations. Its full value solution requires the establishment of a functional relationship between the parameters of the force influence on the workpiece and the characteristics of the natural adaptive behavior of the processed material. In this regard, using metals and their alloys as an example, the mechanism and general laws of thermodynamic excitation of solid crystalline bodies during plastic deformation are considered. The relationship between the change in the thermodynamic potentials of the substance of the deformed volume and its behavior during the process of shape forming, as well as in the postoperative period, is described. It is shown based on the synergetic method of analyzing highly nonequilibrium systems that from a technological point of view the most favorable adaptive functional response arises in the case when the deforming influence is exerted taking into account the natural ability of the workpiece substance to relaxation. The got results create the basis for improving the operations of mechanical processing of metals and their alloys by taking into consideration the properties and features of the natural deformation behavior of each concrete material under concrete conditions. They are applicable not only for metal forming operations, but also in cutting technology.*

Keywords: *metals and their alloys, pressure processing, mechanical action, thermodynamic excitation, thermodynamic potentials, thermodynamic action, deformation behavior.*

Problem Statement

The current level of development of production presupposes the use of flexible and cost-effective methods making it possible to produce from very different materials high-quality products that guaranteed have a given set of operating properties [1]. Their creation requires not only clear views about the behavior of each concrete material under specific conditions, but also ensuring the possibility of obtaining a quantitative estimation of the workpiece state parameters at each stage of its shape forming in order to make, if necessary, timely appropriate amendments in the course of the technological process. Such management corresponds to a qualitatively different, higher, technological level of production organization, based on the possibility of using with the greatest efficiency the natural properties of workpieces and the characteristics of their deformation behavior during the shaping process. An integrated approach, involving a synthesis of the results of both already became classical and the latest fundamental and applied research in the field of physics of deformable solids, metal forming technology, as well as in related fields of natural science is required to its implement.

Analysis of the latest research and publications

In 1973, British scientists M. F. Ashby and R. A. Verall, studying possible combinations of plastic deformation mechanisms, came to the conclusion that in fact metals and their alloys have an almost unlimited supply of plasticity [2]. It was shown subsequently that the possibility of its manifestation depends on the degree of development of adaptive processes of natural self-organization in the thermodynamic system of the deformed volume under the conditions of exerting a deforming influence on it. In other words, the deformation behavior of workpieces is determined by the conditions of their loading [3 – 6]. Meanwhile, in relation to the technology of pressure processing of metals and their alloys, methods for manufacturing products continue to be developed until now based on the concepts of the classical theory of plasticity, as well as the results of modeling and analysis of often very abstract general schemes of technological operations. In this case, the main attention is focused on determining the energy-power characteristics necessary to achieve the required degree of deformation of the workpiece. The reliability of the results obtained in this way is ensured by the use of empirical correction factors, which take into account the average statistical peculiarities of the dynamics of the deformation process, typical for processing of the selected range of materials on equipment of a concrete type in concrete production conditions [7 – 11]. At the same time, a number of more complex technological problems are not

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solved. Their list includes the calculation of the dynamic parameters of the workpiece heating and the associated structural changes during deformation, taking into account the anisotropy of the deformed material and the dynamics of its hardening, assessing the likely degree of post-operative warping of products in case if they are insufficiently rigid, and so on. Varied researches in the listed directions, of course, are being carried out [12 – 17], but their results are rather phenomenological in nature. Due to the lack of appropriate methodology, they are not used directly in the generally accepted practice of designing deformation operations. This significantly reduces the efficiency of technological processes for manufacturing articles.

The purpose of the research

The purpose of the research is to improve the method for designing technological operations for deforming metals and their alloys by establishing a functional relationship between the parameters of the force influence on the workpiece and the characteristics of the natural deformation behavior of its material during the shape forming process.

Main research material

Let a solid crystalline body, for example a metal or metal alloy, which is in a state of internal equilibrium, is subjecting to a deforming influence. During its course, over a time interval $\Delta t = t - t_0$, external forces perform work to change the linear dimensions and shape of the body

$$A_{ex} = \iint \vec{p}\, dS_c d\vec{l} = \iint \vec{p}\, dS_c \vec{v} dt, \qquad (1)$$

where l_0 and l respectively are the initial and final linear dimensions of the body in the direction of the external force action; $\vec{p}$ is the pressure exerted by such influence on its contact surface; S_c is the area of this surface; $\vec{v} = d\vec{l}/dt$ – the rate of changing of the linear dimension l during deformation.

According to the laws of dynamics [18] mechanical action of these forces

$$A_{ex}\,\Delta t = \iiint \vec{p}\, dS_c\, d\vec{l}\, dt = \iint d\left(m_d \vec{v}\right) d\vec{l} = \int \left(m_d \int d\vec{v} + v \int dm_d\right) d\vec{l} =$$

$$=\rho \int\left(V_d \int d\vec{v}+\vec{v} \int d V_d\right) d\vec{l}=\rho V \int\left(e \int d\vec{v}+\vec{v} \int d e\right) d\vec{l}\ , \tag{2}$$

where $m_d = \rho V_d$ is the mass of the displaced volume of the deformable substance; ρ – its density; $V_d = Ve$ – the displaced volume of substance; V – the volume of body; $e = \ln(l/l_0)$ – the true degree of relative deformation when its linear dimension changes in the range from l_0 to l.

This action upsets the internal balance in the deformed volume of the substance, as a result of which a field of additional internal reactive forces appears in it. According to the Le Chatelier – Brown principle [19], they will aspire to compensate for external influences, thereby preventing body deformation.

The volumetric distribution of additional internal forces $\vec{f}_V$ may be represented as the integral sum of their distributions $\vec{f}_S$ over the area S of all surfaces identified in the space of the deformable volume V. In practice, it is most convenient to consider in this capacity various families of plane sections of the body. In the general case of a section oriented at an angle $0 < \alpha < 90^\circ$ to the direction of external influence, the forces acting in its plane will be decomposed into components normal $\vec{f}_S^{\,n}$ and tangential $\vec{f}_S^{\,\tau}$ with respect to this section. Their specific values will determine the magnitude, respectively, of the normal $\vec{\sigma}$ and tangential $\vec{\tau}$ components of the mechanical stress in the considered section. Taking this into account, the resultant of the spatial system of additional internal forces arising in the volume of the solid crystalline body at its deformation,

$$\int_V \vec{f}_V\, dV=\int_V \frac{\partial \vec{f}_S}{\partial l} dV=\int_V \frac{\partial \vec{f}_S^{\,n}}{\partial l} dV+\int_V \frac{\partial \vec{f}_S^{\,\tau}}{\partial l} dV=\int_V \frac{\partial \vec{\sigma}}{\partial l} dV+\int_V \frac{\partial \vec{\tau}}{\partial l} dV\ , \tag{3}$$

Then, in absolute value, the work that these forces will do in a unit of volume of the body, hindering its deformation,

$$A_{in}=\int_{l_0}^{l} f_V\, dl=\int_{l_0}^{l} f_S \frac{dl}{l}=\int_0^{\varepsilon} f_S\, d\varepsilon=\int_0^{\varepsilon} f_S^n d\varepsilon+\int_0^{\varepsilon} f_S^\tau d\varepsilon=\int_0^{\varepsilon} \sigma\, d\varepsilon+\int_0^{\varepsilon} \tau\, d\varepsilon=\int_0^{\varepsilon} f_{ij}\, d\varepsilon\ , \tag{4}$$

where $\varepsilon = (l - l_0)/l = \Delta l/l$ is the conditional degree of relative deformation of the body in the external force direction; f_{ij} and ε_{ij} are the operators of the stress and the strain tensors respectively.

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Equalities (3) and (4) show that the creation of the field of additional internal forces and, consequently, their ability to make a work are associated with the creation of a stress-strain state in the volume of the solid crystalline body. According to the energy conservation law the entrance of energy necessary for this occurs due to the work (1) done by the external forces during loading. The amount of energy ΔE_{ab} that the substance of a body absorbs during its course is determined by the value of uncompensated energy flow passing through the contact surface area of the body over the time interval Δt :

$$\Phi_{ab} = \frac{\Delta E_{ab}}{\Delta t}, \tag{5}$$

It follows from the expression (2) that the creation of this flow is a component of the action of external forces on the body. According to the first law of thermodynamics [20], the energy transported by it will be partially expended on increasing the internal energy U of the body and, ultimately, will be dissipated into the environment in the form of heat, and partially will be spent to a work (4) of additional internal forces f_{ij}. Thus, taking into account equalities (1) and (5), we obtain that the amount of energy absorbed by a body, when a deforming influence is exerted on it, is

$$\Delta E_{ab} = \int_{t_0}^{t} \Phi_{ab}\, dt = \int_{l_0}^{l} \int_{S_c} p\, dS_c dl = \int_V dU + \int_V dA_{in} = \int_V dU + \int_V \int_0^{\varepsilon} f_{ij} d\varepsilon_{ij} dV, \tag{6}$$

Equality (6) shows that plastic deformation is based on the mechanism of thermal excitation of substance of a solid crystalline body. It consists in interrelated changes in the thermodynamic potentials of the deformable volume. Other consequences of the action of this mechanism are the heating of the body and the creation of a stress-strain state in its volume.

The ability of a substance to absorb energy and, due to this, move from one state to another is determined by the magnitude of possible changes in the system of its thermodynamic potentials: enthalpy (total heat), internal energy, Gibbs energy (Gibbs thermodynamic potential), free and bound energy. Internal energy U characterizes the energy of thermal chaotic motion and interaction of particles – atoms, ions or molecules – in the considered volume of substance. Enthalpy

$\mathrm{H} = U + f_{ij}V$ is a measure of the amount of energy that a substance, being in a state of equilibrium with the environment, is capable to convert into heat and work. Bound energy TS characterizes part of the internal energy that cannot be transferred to other bodies during the work performed by the substance, provided that its temperature T and entropy S are constant. Free energy $F = U - TS$ reflects that part of the internal energy, due to the change in which the thermodynamic system of the considered volume of substance is capable to make a work against external forces in a reversible isothermal process. Finally, the Gibbs energy $G = \mathrm{H} - TS$ characterizes the ability of the considered volume of matter to make a work due to its internal sources, that is, due to a change in enthalpy [20]. Taking into account these concepts, it follows from the first law of thermodynamics (6) that

$$\Delta E_{ab} = \int_{l_0}^{l}\int_{S_c} p\,dS_c\,dl = \int_V d\mathrm{H} = \int_V dF + \int_V d(TS) + \int_V\int_0^{\varepsilon} f_{ij}\,d\varepsilon_{ij}\,dV, \quad (7)$$

Equality (7) makes it possible to determine what part of the absorbed energy falls on the elastic component of deformation (the first item in its right-hand side), what part will be spent on structural changes in the plastic domain and heating of the body (the second item), and what part will be spent on counteracting to external forces (third item).

Change of enthalpy [5, p. 77]

$$d\mathrm{H} = dU + d(f_{ij}V) = dF + d(TS) + d(f_{ij}V) = dG + d(TS).$$

Expressing from here the value of the change in free energy and substituting the result into equality (7), we obtain a formula that allows estimating the natural deformability of a solid crystalline body in each concrete case of its loading:

$$\Delta E_{ab} = \int_{l_0}^{l}\int_{S_c} p\,dS_c\,dl = \int_V d(TS) + \int_V dG - \int_V\int_0^{\varepsilon} f_{ij}\,d\varepsilon_{ij}\,dV, \quad (8)$$

According to the equality (8), it is determined by the value of the Gibbs energy of the perturbed volume of substance. Knowledge of this quantity allows us to predict whether the body will behave as low-plastic, plastic or short with the chosen deformation method. The corresponding conclusion is easiest to do by analyzing the relationship between the change in the Gibbs energy dG of the substance

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deformable volume V and the work $f_{ij}d\varepsilon_{ij}dV$ that additional internal forces will do in it, hampering its deformation. If $dG > f_{ij}d\varepsilon_{ij}dV$, the body will behave like plastic, when $dG \approx f_{ij}d\varepsilon_{ij}dV$, its behavior will be low-plastic, and if $dG < f_{ij}d\varepsilon_{ij}dV$, the body turns out to be brittle.

Equalities (6), (7) and (8) are different ways to write the synergistic management function that, based on the thermodynamics laws, describes the process of forced adaptation of a solid crystalline body by exerting a deforming influence on it. Considering the loading conditions, they allow us to evaluate the real efficiency of the external action (2) performed on the body and, depending on the choice of integration limits, to explain the features of the deformation behavior of the processed material at its micro-, meso- or macroscopic structural levels.

Traditionally, most of the existing machining methods suppose the rendering of a force influence, which, if we don't take into account the own dynamics of the technological system machine – device – tool – workpiece and the effects of dynamic instability arising from loading and unloading, is constant. Such influence breaks the natural course of the plastic flow of metals and their alloys. As a result, a vortex dissipative structure, which gives the plastic flow the character of an unstable or, more precisely, non-stationary process, appears in the deformed volume. Exactly it is responsible for the development of the parabolic stage of strain hardening [21 – 24]. Another consequence of such contravention is the energetic supersaturation of the deformed volume. It is reflecting in the intense heating of the workpiece and the appearance of big residual stresses in its volume. Their relaxation causes postoperative deformation of the product and, in the case of strong energy supersaturation, can lead to its fracture. The same phenomena are typical for plastic deformation by impact or explosion, when the workpiece is exposed to the influence of strong dynamic loads.

The regularity of intense heating and quick strain hardening of metals and their alloys under constant force influence or dynamic loading can be explained, if we consider the difference $dG - f_{ij}d\varepsilon_{ij}dV$ on the right-hand side of equality (8) as a quantity that determines the kinetic energy and, consequently, the intensity of plastic flow. Since the possibility of changing the value of the Gibbs energy, that characterizes the natural ability of a solid body to deform, is restricted to some limiting value, which depends on the physical nature and properties of the crystalline substance under the considering conditions, it follows from equality (8) that all excessive energy absorbed by the body under loading will be spent on changing the bound energy of the deformable volume and on execution of the work (4) against external forces. The bound energy TS is also finite and also depends on the physical nature and properties of the body. It can change both at the expense of a change in body temperature T and at the expense of a change in the degree of statistical disorder, that is entropy S of its crystalline structure. In accordance with the thermodynamics laws [20], provided constancy the aggregation state and preservation of the deformable volume integrity, the possibility of changing its entropy during heating or cooling are limited by the specific heat capacity of the substance:

$$c = \frac{T}{m}\frac{\partial S}{\partial T},$$

where m is the mass of the workpiece body.

According to the Dulong and Petit law the heat capacity of metals and their alloys remains practically constant at temperatures typical for most technological operations of the machining. It follows hence that the main part of the change in the bound energy of the deformed volume will occur due to the change of its entropy during the process of adaptive reorganization of the crystal structure [25]. This conclusion is true not only for the case of plastic deformation, but also for heat treatment. The structure change is accompanied by an increase in the potential energy of intracrystalline interaction [26]. Accordingly, the work (4), which additional internal forces make, counteracting deformation, also increases. As can be seen from equality (8), provided that the integrity of the deformable volume is preserved, its value $f_{ij} d\varepsilon_{ij} dV$ can increase only due to a decrease in the difference $dG - f_{ij} d\varepsilon_{ij} dV$, that is due to a decrease in the intensity of plastic flow. In combination with the conditions of deformation, the interrelation of these factors determines the appearance on the hardening curve of a section with a parabolic dependence of the deformation resistance (true stresses) on the degree of

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deformation. As the degree of energy supersaturation increases, the parabola coefficient is changed. In accordance with the J. F. Bell's theory on the quantization of the parabolic response function during finite plastic deformations [27], the rate of this process depends on the physical properties of the deformable solid body, the type and state of its crystalline structure, as well as on the amount of the energy flux (5) absorbed by the body per unit time, that is from the loading dynamics (2).

According to the energy conservation law the change in the difference $dG - f_{ij}d\varepsilon_{ij}dV$ determines the amount of the total, mechanical and thermodynamic, internal action that does in the volume of a deformable solid body during a time interval $\Delta t = t - t_0$:

$$A_{in}\Delta t = \int_{t_0}^{t}\int_{V} dGdt - \int_{t_0}^{t}\int_{V}\int_{0}^{\varepsilon} f_{ij}d\varepsilon_{ij}dVdt, \quad (9)$$

Taking this concept into account, it follows from equalities (2) and (8) that the mechanical action of external forces

$$A_{ex}\Delta t = \int_{t_0}^{t}\int_{l_0}^{l}\int_{S_c} p\,dS_c dl dt = S\int_{t_0}^{t}\int_{V} dTdt + T\int_{t_0}^{t}\int_{V} dSdt + \int_{t_0}^{t}\int_{V} dA_{in}dt, \quad (10)$$

Equality (10) is another form of writing the synergistic management function of the plastic deformation process. Using this equation, we can show that an internal residual action occurs in the volume of the workpiece after the cessation of loading. It occurs in the process of relaxation due to a decrease in the thermodynamic potentials of the disturbed substance:

$$A_{in}^{r}\Delta\tau = \int_{\Delta\tau}\int_{V} dA_{in}^{r}dt = \int_{\Delta\tau}\int_{V} dGdt - \int_{\Delta\tau}\int_{V}\int_{0}^{\varepsilon} f_{ij}d\varepsilon_{ij}dVdt = -S\int_{\Delta\tau}\int_{V} dTdt - T\int_{\Delta\tau}\int_{V} dSdt, \quad (11)$$

where $\Delta\tau$ is the time of disturbance relaxation.

By analogy with external mechanical action (2), its synergistic development causes the occurrence of postoperative deformation, the magnitude of which depends on the degree of thermodynamic excitation of the workpiece's substance, that is, on the amount of energy (5) absorbed by the workpiece during the disturbance process:

$$A_{in}^{r}\Delta\tau = \rho V\int\left(e_r\int dv + v\int de_r\right)dl_r = -S\int\limits_{\Delta\tau}\int\limits_{V} dTdt - T\int\limits_{\Delta\tau}\int\limits_{V} dSdt, \qquad (12)$$

Equalities (11) and (12) describe a particular case of a spontaneous adaptive response that arises in the disturbed volume of a solid crystalline body. A similar response arises in the process of external influence too. Analysis of the relationship between equalities (10) – (12) shows that its natural development takes place if this influence is carried out taking into account the ability of the workpiece’s substance to relaxation.

The stated analysis is applicable not only to the case of mechanical processing of structural materials, primarily metals and their alloys, by pressure, but also to cutting operations. It is also true for other types of technological influence. Various cases of combined influence carried out with the aim of additional activation of the workpiece material have the special interest among them. These include heating, ultrasonic influence, electrical impulse stimulation, etc. In accordance with the Boltzmann’s time-temperature superposition principle [28], their usage makes it possible to reduce the value of the applied load or, if its value is unaltered, to achieve a greater degree of one-time deformation. However, at the same time, the problem of internal action remains. In the case of strong energetic supersaturation, it can lead to destruction of the workpiece during its machining or in the postoperative period.

Conclusions

1. The process of plastic deformation of solid crystalline bodies is based on the mechanism of thermodynamic excitation of the substance. It consists in interrelated changes in the thermodynamic potentials of the deformed volume.

2. The magnitude of such changes determines the behavior of a solid crystalline body, for example metal or metallic alloy, during its machining, as well as in the postoperative period.

3. For the technological point of view, the most favorable behavior of machining material arises when the external influence on the workpiece is taking into account its natural ability to relaxation.

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ЯВИЩЕ ТЕРМОДИНАМІЧНОЇ ДІЇ ПРИ ПЛАСТИЧНОМУ ДЕФОРМУВАННІ МЕТАЛІВ ТА ЇХ СПЛАВІВ

Аналіз останніх досліджень та публікацій показує, що при проектуванні технологічних операцій обробки металів тиском основна увага досі традиційно зосереджується на визначенні енергосилових характеристик, необхідних для досягнення необхідного ступеня деформації заготівлі. При цьому через відсутність відповідної методики зовсім не враховується динаміка розвитку природних процесів адаптації термодинамічно збудженого обсягу речовини, яка визначає характер деформаційної поведінки заготівлі. Це суттєво знижує ефективність технологічних процесів виробництва виробів.

Метою дослідження є вдосконалення методу проектування технологічних операцій деформування металів та їх сплавів шляхом встановлення функціонального зв'язку між параметрами силового впливу на заготівлю та характеристиками природної деформаційної поведінки її матеріалу в процесі формоутворення.

Основний матеріал дослідження. На прикладі металів та їх сплавів розглянуто механізм і загальні закономірності термодинамічного збудження твердих кристалічних тіл при пластичному деформуванні. Описано зв’язок між зміною термодинамічних потенціалів речовини об’єму, що деформується, та його поведінкою в процесі формоутворення, а також у післяопераційний період. На основі синергетичного методу аналізу сильно нерівноважних систем показано, що найбільш сприятливий з технологічної точки зору адаптивний функціональний відгук виникає у разі, коли деформуючий вплив виявляється з урахуванням природної здатності речовини заготівлі до релаксації. Отримані результати створюють основу для вдосконалення операцій механічної обробки металів та сплавів шляхом урахування властивостей та особливостей природної деформаційної поведінки кожного конкретного матеріалу у конкретних умовах. Вони застосовні не тільки для операцій обробки металів тиском, але і технології різання.

Ключові слова. Метали та їх сплави, обробка тиском, механічна дія, термодинамічна збудження, термодинамічні потенціали, термодинамічна дія, деформаційна поведінка.

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