

PLASTICITY AS A PHYSICAL-CHEMICAL PROCESS OF DEFORMATION OF CRYSTALLINE SOLIDS

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ABSTRACT

In the article were conducted a series of experiments of upsetting of steel samples. Deformation mechanism passes through the transition phase with the liquefied metal in the zone of plasticity and as a result we observe a structure obtained by recrystallization. The decrease in grain size during recrystallization and the presence of a certain amount of high-temperature phase in the material leads to the strengthening of this area, and in general to the work hardening. The mechanism of plastic deformation is topochemical and described by equation of I. I. Frenkel and Avrami-Erofeev-Kolmogorov. Based on the earlier proposed ideas about the mechanism of plastic deformation of metals, it is theoretically developed and experimentally verified a fundamentally new way to control the properties of the processed metal by changing the rigidity factor of the system processed material - deforming tool that allows to change the grain size of the processed metal in a wide range, and therefore its properties. The process can be easily implemented in any production, as it requires minimal changes in the existing production machines.

***Keywords:** plasticity, crystalline solids, plastic deformation, phase transformations.*

INTRODUCTION

The nature of plasticity and fracture of solid materials is studied in different branches of science, ranging from geomechanics and ending with nanotechnology. Geomechanics discusses the process of moving from geoplatform with their consequences in the form of mountain building, earthquakes, volcanic activity, to offset the mountain layers with the problems of securing mining. The scale of manifestations of plasticity range from 10^7 m to 1 m, and naturally recognizes the physical and chemical processes that lead to changes in the composition and structure of the interacting masses.

In solid mechanics the scale of deformable objects varies from 10^{-1} m to 10^{-10} m. This dimension overlaps the currently fashionable trend - nanostructured corresponding to 10^{-9} m. To the middle of the last century, the majority of authors examined the plasticity of crystalline materials, which include metals and alloys, from the

point of shear sliding mechanism of one of the planar surfaces relative to the others. Developed in the half of the last century, the theory of dislocations, as moving linear defects in the crystal structures and advanced on this basis, the hypothesis of disclinations as well as the previous hypothesis, has not made a significant refinement in the knowledge about the nature of plasticity.

One of the most representative areas of the theory of plasticity - formal physics and mathematics, in which the solution of applied problems of processing materials by pressure is given by the approximation of the laws of elastic deformation in the area of elastic-plastic and large plastic deformations. This approach, in most cases, proved to be quite effective, as allowed, by introducing into the resulting equations of empirical coefficients, solve with the necessary for processing of metals by pressure accuracy for many practical tasks.

In the works of scientific schools of V.A. Likhachev, V.E. Panin, E.E. Zasimchuk, A.A. Presnyakov was

clearly shown that the process of plastic deformation is autowave character, is a generator of dynamic forces and moments in the processing of metals by pressure. Despite considerable research of this schools, listed above in relation to real technological processes, there were no findings and no recommendations.

The formal understanding of the mechanism of plastic deformation at the same time did not denied its connection with the change of structure of metals and alloys, one manifestation of which is a texture formed by cold deformation. However, purposefully these issues were examined not as intensive, since it has long been considered that the dominant role in the deformation process play the above mentioned mechanisms, and the changes in the structure or appearance of new phases are associated in nature.

Many authors pointed out that the study of the microstructure of deformed materials allows to study only the result and not the process of structure formation. One of the first to the idea that the process of plastic deformation of metals has physical-chemical nature and occurs as a phase transformation was expressed by A.A. Bochvarov and Z.A. Swiderskaya [1] during describing the phenomenon of superplasticity discovered by them, and then supported by A. A. Presnyakov, and G.V. Starikova [2]. Visible results were obtained by Kravz-Tarnavsky [3], first gained during dynamic deformation of martensitic steel „strip“. The most complete analysis of experimental data on structural transformations during the deformation of metals with physical-chemical positions was done in [4 - 6].

Some researchers have concluded that the phase transition is the main mechanism of plastic deformation, ensuring the possibility of forming a solid body without destruction. Ya.I. Frenkel [7], and then B.N. Malyshev [8] suggested that the partial presence of metal in the solid body in a state of „fusion“. A.A. Presnyakov even further went and formed a view on the implementation of plastic deformation through the localization by the mean of mechanism „running neck“ [6]. Later in conjunction with the U.K. Duysemaliev [9] they explained the concept of „atomic gas“ responsible, in their opinion, for the manifestation of superplasticity of metals. And finally, academician V.E. Panin, which is one of the founders of the mesomechanical theory, also came to the conclusion that the plastic deformation of solids can develop only localized, as local structural transformation in the areas

of stress concentrators of different scales [10, 11].

Research on plastic flow of metals, carried out by the Kazakhstan school of researchers under the guidance of A.A. Presnyakov [6] with photographing of specimens during tension and simultaneous continuous registration of the efforts, gave a presentation of the development of plastic flow in metals and alloys, different from the conventional. It was experimentally shown that the initial stage of plastic flow of samples during tension, which had previously considered as stage of uniform flow, flows very unequal. Deformation periodically localized in narrow zones, which can reach enormous values (up to 30 000 %) with the formation of “micro neck” or “mini neck”.

Research methodology

The experiments on creep during tensile loading of cylindrical samples, performed by a number of authors on a variety of titanium alloys, aluminium and high-alloy steels showed [12] that for most metallic materials the dependence of yield strength on the degree of deformation, built in a semi-logarithmic or logarithmic coordinates, have a linear character.

The mathematical description of the strain rate for such experimental data was proposed by Y. I. Frenkel [7], considering the plastic deformation as the “liquefaction” of the metal with the formation of centers or nuclei of the new phase:

$$\dot{\epsilon} = B \exp(-Q/RT) \quad (1)$$

where B is coefficient, Q - activation energy, R - Boltzmann constant, T- test temperature.

Conducted in the present work, the experimental studies of the deformation of the cylindrical samples at upsetting confirmed the results obtained by A. A. Presnyakov [7] during tensile loading. Because plastically deformable body is an open thermodynamic system, the deforming tool is both a source of mechanical energy and heat removal surface from a deformable metal.

If consider the idea that the metal becomes “quasi-fluid”, even without explaining the mechanism of the transition in such state border slip cones arising, in the opinion of the Gubkin, during upsetting that must be considered as isotherms, separating areas of high (light - side surface) and hindered (ends) plasticity (Fig. 1). The fact that during dynamic loading of steel samples the structure of this boundary is converted to martensite [3] shows the physical-chemical nature of the mechanism

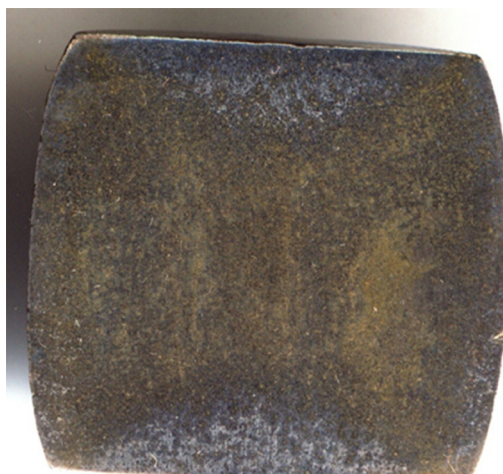


Fig. 1. Closeup of a longitudinal section of upsetted steel sample.

of plasticity of metals. Its implementation is provided by the structural-phase transformations, which develop on diffusion-less mechanism due to the high speed of loading, when the diffusion process is difficult.

RESULTS AND DISCUSSION

Below are the results of experiments on upsetting of steel cylindrical samples with a record of external parameters on the camera (Fig. 2). Sample upsetting with the ratio of height to diameter 1:1; 2:1 and 3:1 were carried out on a hydraulic press through polished plates. The rate of deformation is about 1 mm/min. The registration of the loads is conducted using tensorresistive load cells.

As for tension, the process of upsetting of metal samples in the first stage is the period of “quasiuniform” deformation with forming of “mini neck” and only if the total upset about 30 % begins to develop a common barrel. In addition, in logarithmic coordinates $\lg \varepsilon - \lg \sigma$, where ε is the deformation rate, and σ is the resistance to deformation, dependence of the resistance to deformation from the deformation degenerates into a series of intersecting lines.

This behavior depends on the presence of straight line kinks with the accumulating degree of deformation, on the one hand, reflects the special role of certain degrees of deformation in the change of the stress-strain state of the material, and, on the other hand, is a confir-

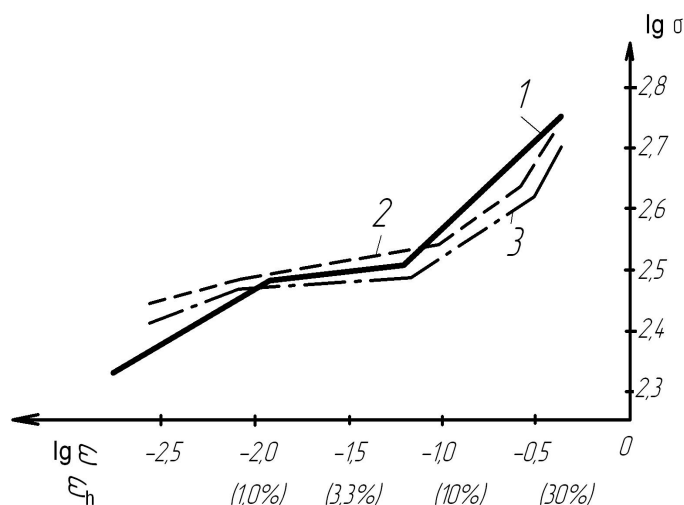


Fig. 2. Dependence of $\lg \sigma - \lg \varepsilon$ (1, 2, 3 - samples with a height to diameter ratio, accordingly 1:1; 2:1 and 3:1).

mation analogy with linear dependencies obtained in the description of topochemical reactions. As known, topochemical reactions are reactions taking place on a hard surface with the formation of a new phase with transition from kinetic flow to diffusion, and subsequently to termination of the reaction. These reactions can be described using equation of Avrami-Erofeev-Kolmogorov, having a form similar to the expression (1).

This analogy allows to conclude that the exponential character of the expression (1) is a manifestation of topochemical process of plastic deformation of metals occurring with the formation of a new “quasi-fluid state of metal in the zone of deformation and subsequent termination of this zone. Presumably, the deformation under tension or compression can be divided into the following areas:

- single acts of plastic deformation, located randomly throughout the length of the sample when “mini necks” or “mini barrels” visually are not yet identified (ε up to 1 %);
- with forming of «mini necks or mini barrels» (ε up to 7 %) - «running necks» according to A.A. Presnyakov;
- with forming of common neck or barrel (ε up to 30 %);
- destruction (ε more than 30 %).

Based on literature data and own experiments, both in laboratory and industrial conditions, the mechanism of plastic flow of metals is proposed, combining a number of different approaches to this problem. According to it, the elastic loading of the sample occurs before the moment, where in its cross-section, due to internal elastic distortion of the crystal structure in the weakest place there is an area with energy sufficient to move from being the original “low-temperature” phase in more “high-temperature”. The transition is accomplished by displacement of the atoms of the crystallite in the new position, and this transition is accompanied by a local loss of strength and a kind of “liquefaction - plasticization” of material. The formation of such microscopic (dot) weakening hearth leads to decrease of the effective cross-section of a nearby solid metal, and thus, to grow in it more stress, contributing ultimately to the distribution of “liquefaction” zone over the entire section of sample.

Under the influence of external in relation to the zone of liquefaction elastic forces occurs relaxation of loads in elastically deformed zones of the sample and develops viscous deformation in the weakening area

of metal. Deformation of this unit area is accompanied by an additional release of energy due to the work of deformation with formation of microneck.

The process of plastic deformation in the microvolume (microsection) is accompanied by heat removal in the neighboring area. The zone of plastic flow is rapidly cooled, the metal part does reverse transition from P_2 to P_1 , but part of it is fixed in a high-temperature condition of P_2 . Actually this is a kind of hardening of the material in the area of implementation of plasticity, while the metal is hardened, and the process of plastic flow is terminated.

It is the transition state (quasi-fluid), which is intermediate between the two stable states and responsible for the implementation of the plastic flow of the material without breaking its continuity. In a state of structural-phase transition $P_1 \rightarrow P_2$ in the field of plastic flow may be only a part of metal, but sufficient in number and location to ensure proper plastic flow.

According to the works of E.E. Zasimchuk [13], the formation of the zone of weakening occurs instantaneous. However, it would be more correct to assume that the propagation velocity of the weakening zone in the cross section of the sample is equal to the speed of propagation of longitudinal elastic waves in the material studied, i.e. the speed of sound in this material. The loss of strength in the zone of plasticity is accompanied by a dynamic reduction of the elastic part of the sample, plastic flow of weakening metal and wave of stress relaxation along the axis of the sample.

However, the wave of relaxation with relation to the primary (longitudinal) acting perpendicularly or at an angle to the axis of the sample, is the transverse which velocity is equal to the product of the material speed of sound multiplied by the Poisson's ratio (0.2 to 0.3 for metals). This is the reason as registered by V.E. Panin et al. [14], the speed of the stress relaxation waves is several times less than the speed of sound in the test material. Indirect confirmation of this fact is the experimental evidence that under the additional imposition on the deformation during tensile of various waves - from sound to high-frequency ranges - the most accurate results are always obtained by superposition of waves across the action of tensile forces [15].

Since the “solid” areas of sample (non-deformable), boundary with area of a single strain, are the surfaces of the heat removal, occur heat transfer from the zone

of plasticity in these zones, which are in direct contact with them. The reverse transition of metal in the zone of deformation from “quasi-liquid” - plastically deformed state in solid - occurs as a result of structural-phase transformations with corresponding recrystallization of the original structure. Moreover, the crystallization centers are border crystallites of the solid phase.

In work [16] is shown experimentally that during upsetting of the metal samples are formed crystallites with size close to the value of the elastic deformation in the direction of the force and with sizes close to the size of the original crystallites in the plane transverse to the action of a deforming force. The increase of the grain surface of the substance and partial quenching of the high-temperature phase leads to hardening of the zone of plastic deformation in comparison with the initial state (deformation-phase hardening).

The actual value of total change of sample size Δl_a in the process of a single act is determined by the elastic deformation outside the zone of plasticity Δl_o , the elastic deformation of the tool and deforming machine Δl_m , as well as the amount of movement of the working tool during a single act of deformation Δl_t :

$$\Delta l_a = \Delta l_o + \Delta l_m + \Delta l_t. \quad (2)$$

The ratio of the values included in this expression defines a single change of the sample size for a single act of deformation.

In the laboratory tests, under conditions where the rigidity of the deforming device and tools much more than rigidity of test sample at low loading rates, the basic quantity that determines the movement of metal in the area of weakening is the elastic deformation of the sample parts out of plasticity area Δl_o . This value is determined by the modulus of elasticity of the sample material and the yield strength, and for most metals is approximately equal $l_o \cdot 10^{-3}$.

For most technological machines (presses, rolling mills, etc.) the components of equation significantly affect on the total displacement in a single cycle of deformation. This is due to the fact that technological machines are designed for large volume of production of metal and they are made to limit the total load (including safety margin). The characteristics included in equation (2) become comparable. But then the change of “rigidity” parameter of deforming machine and tool

will change the size of the zone recrystallization with appropriate changes in the structure, strength and ductility of a deformable metal.

It should be kept in mind that the rigidity, on one hand, characterizes the amount of elastic load per unit displacement, but on the other hand - stress relaxation time of load shedding. For low rigidity of machines, the speed of the elastic displacement of the parts of the machine lower at the weakening point of the stroke of the deforming tool at the same time will be less, and accordingly, less will be the component Δl_m .

The frequency of deformation pulses uniquely associated with the loading rate, with the rigidity of the system “sample - deforming machine” and physical-chemical properties of the sample material. At the moment of the beginning of weakening, the full development of this process and the time until formation of hardened structures are determined by the properties of the deformable material. At the same time, the value of deformation per cycle and the time of load accumulation to the maximum value before a new pulse of weakening determined by the mechanical rigidity of the system and the loading rate.

Since the deformation of the sample by machine goes on continuously, then occurs repeated elastic loading with the formation of the next area of plastic deformation, but with some higher strength characteristics than the previous single act. From the areas of plasticity (“quasiliquid”) through the boundary surfaces in the form of heat and waves of relaxation on the rest of the metal is transferred additional energy. But, as a rule, at the initial stage of deformation it is not enough that subsequent area of a single cycle of deformation formed next to the previous area with a minimum strength of cross section, in which the most likely development of plastic deformation are randomly placed along the axis of action of the loading force.

However, gradually the weakest areas (sections) as the result of structure-deformation recrystallization, strengthened and the overall strength properties between the individual sections are aligned so that the additional energy in the form of heat or elastic waves enough for a subsequent act of weakening occurred near the previous one. Consistent flow of plastic deformation in a restricted zone leads to the formation of macro-regions of centered form, changing with a noticeable reduction the cross section compared to the original, i.e. to the formation

of the common neck during tensile or common barrels during upsetting.

Further deformation process, registered on the indicator curves until reaching the maximum value of the load, consists of sequential formation of running necks (during tensile) or barrels (during upsetting) along the length of the sample. And only after a significant hardening of the metal, leading to averaging its mechanical properties establishes conditions when in the process of sequential deformation comes such a huge part of metal that formed a single neck (during tensile) or single barrel (during upsetting), in which the most notable change of section occurs until fracture.

Elementary calculations show that during deformation of the standard steel samples with a diameter of 10 mm and a tensile speed of 1 mm/min, the residence time of the metal in a plastic state is just 0.0013% of the total time, and the rest of the time samples are in solid state and deforming elastically. Therefore, the reason that the rheological calculation methods of plasticity of metals do not give data close to the experimental ones is the fact that during defining the viscosity characteristics of the metal are applied methods, in which metal is mostly in elastic state.

In the regular processes, which include rolling, drawing and pressing through the die, metal alternately passes through all degrees of deformation. At sufficiently high speeds in the area of the instrument may form a single zone of plasticity.

One of the factors that decisively determine the state of the material in the zone of deformation is rigidity of the system "machine - tool - deformed sample". It is the elastic deformation of this system that determines the work done in the area of weakening during the single cycle. The existence of metal in a plastic state is determined by the heat removal out of this area, and the amount of heat depends on the work of deformation. Therefore, the lesser deformation in a single cycle, the lesser the time for metal stay in a plastic state and the lesser secondary grain.

Since displacement in weakening zone carries elastic deformation determined by the rigidity of the system, then, the lesser the rigidity of the system, the lesser the elastic displacement during a single act, the work of deformation and the size of the secondary grains of crystallites. Another effect during reducing the rigidity of the system is increasing the intensity of hardening

of metal as a result of refinement of the crystallites and the residue of the high-temperature phase. During the experiment, this is manifested as increased deformation loads with decreasing rigidity of the system and the immutability of the other conditions of the experiments.

The above position [16] allows to refuse from notions about the deformation zone as a consequence of the mechanical movements of parts of the crystallites relative to each other, from the theories of lattice defects as carriers of plasticity (theory of dislocations and disclinations) and to recognize the physical-chemical nature of the plastic deformation. This mechanism is inherent to all types of metal forming and cutting. These same patterns are evident during deformation of non-metallic crystal structures, i.e. it is the same for the plasticity of all solid crystalline systems [17].

CONCLUSIONS

1. Plastic flow of metals (solid crystalline materials) occurs in very localized areas where the metal is in a non-equilibrium transition state. Localization can occur cyclically in different parts of a deformable material or, under certain conditions, to unite in one common deformation zone.

2. The formation of localized deformation area is accompanied by local heat, deformation waves, sound manifestation, electromagnetic effects, exoemission of electrons and other particles, up to neutron radiation, which indicates the underlying physical-chemical phenomena in metals during plastic deformation.

3. Deformation mechanism passes through the transition phase with the liquefied metal in the zone of plasticity and as a result we observe a structure obtained by recrystallization. Because during a single pulse occurs direct and inverse phase transitions, some of the material remains in the form of high-temperature phase. The decrease in grain size during recrystallization and the presence in the material of a certain amount of high-temperature phase leads to the strengthening of this area, and in general - to the work hardening. The mechanism of plastic deformation is topochemical and described by equation of I. I. Frenkel and Avrami-Erofeev-Kolmogorov.

4. The change in the rigidity factor of the system with any method of deformation changes the nature of the metal flow. This is reflected in the structure of

the cross-section of the processed metal, in location of zones of active and difficult to deform, the change in the structure of the metal, especially in the zone of active deformation.

5. All factors affecting on a deformable metal, contributing to the growth of the work of deformation for a single cycle and to increase of the temperature in the zone of plasticity contribute to a longer residence time of the metal in the transition (plastic) state and to increase the size of the crystallites observed as a result of plastic flow. All factors contributing to the reduction of the deformation in a single cycle of weakening and lowering the temperature in the zone of weakening will lead to reduction of the sizes of the secondary crystallites.

6. Based on the earlier proposed ideas about the mechanism of plastic deformation of metals, it is theoretically developed and experimentally verified a fundamentally new way to control the properties of the processed metal by changing the rigidity factor of the system processed material - deforming tool that allows to change the grain size of the processed metal in a wide range, and therefore its properties. The process can be easily implemented in any production, as it requires minimal changes in the existing production machines.

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