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POWER ASPECTS OF ENERGY DISSIPATION DURING PLASTIC DEFORMATION IN DIFFERENT STRESSED STATES. PART 1

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Work of plastic deformation defined as the area under deformation curve plotted on the «load-absolute elongation» coordinates for tension and on the «torque-turning angle» coordinates for torsion has been considered. To obtain adequate results the specific values of work determined by the «stresses-relative deformation» diagram have been compared. It is shown that for torsion the observed changes in values of specific work of the deformation are 3–5 times larger than for tension. This is connected with different activation of sliding systems during the deformation resulting in changes of the character of developing processes of generation, redistribution, accumulation and annihilation of crystalline structure defects of the material.

Introduction

The current methods used to describe the stressed and strained states by the continuum mechanics methods [1,2] are based on material presentation as a uniform elastic medium. The resulting was a strict classification of the stress-strain relationship for the elastic region and it has become possible to describe the like relationship in the plastic region. The description of real polycrystalline materials as uniform (isotropic) bodies is undoubtedly correct on a macrolevel (deformation of a body as a whole), but there occur difficulties when this approach is used to describe elementary processes of plastic deformation on a microlevel (the deformation as a consequence of motion of crystalline structure defects). The problem is that at this level the medium is no longer considered as the isotropic one and elementary acts of plastic deformation are just determined by the anisotropy of crystal lattice structure. The anisotropy present at the microlevel results in varying behavior of quasi-isotropic bodies under the plastic deformation at the macrolevel. A descriptive example of macroanisotropy developed under the deformation of polycrystals is the formation of regions of localized plastic deformation (the Luders–Chernov lines) during the uniaxial tension of the specimen. It is evident that the model of uniform medium does not imply that deformation is localized in certain regions and it is expected that the elementary traces of sliding will be equiprobably distributed in the bulk of material. But in practice we have the processes of quasi-isotropic medium self-organization and self-organization and structuring under the influence of power applied from outside.

On the other hand, the dependence of strength and plasticity characteristics of solids on the stressed-state type has been determined experimentally. It is evident that parameters of defect (dislocation) structure evolution in single crystallites depend on macrostressed state, however, model representations about the influence of stressed (and deformed) state of body as a whole on processes of dislocation motion and nucleation of failure have been insufficiently developed. In such a way, it becomes necessary to develop theoretical approaches to describe the interaction and mutual influence of the processes of deformation and failure nucleation at different structure (scale) levels.

Formulation of the problem

In the development of such approach one of the problems is the necessity of physically grounded distinction of structure levels in the structure of real deformable alloys. It has been shown [3–5] that processes of power accumulation and dissipation in the system result in structural and phase transformations followed by the formation of hierarchy structures in the originally uniform isotropic medium. In what follows we make use of the synergetic approach [3–5] considering the evolution of material structure under the action of power as a process of non-equilibrium phase transitions in open systems interchanging with fluxes of power and substance with the environment.

Relying upon the mentioned representations, let us specify the basic processes characterizing the accumulation, redistribution and reduction of the accumulated power in polycrystalline material during plastic deformation under the influence of external forces and power fluxes (Fig.).

Due to this scheme it can be assumed that a change in parameters of the A-type processes (including those resulting from changes in the stressed and strained state of the material) induces changes in the flow of the B-type processes, thus influencing the run of processes of type C and D. In this way, for subsequent analysis we propose to use the approach based on the estimation of balance between power fluxes in the material. Furthermore, according to the principles formulated, in particular, in papers [6–9], the system evolution is towards the attaining of a relative minimum of the accumulated power.

Discussion. Work of plastic deformation

Let us demonstrate the essence of the approach by means of simplest example. We evaluate power consumption for the uniaxial tension and torsion during the plastic deformation.

The work of plastic deformation can be estimated as the area under the deformation curve plotted on the «load-absolute elongation» coordinates for the case of

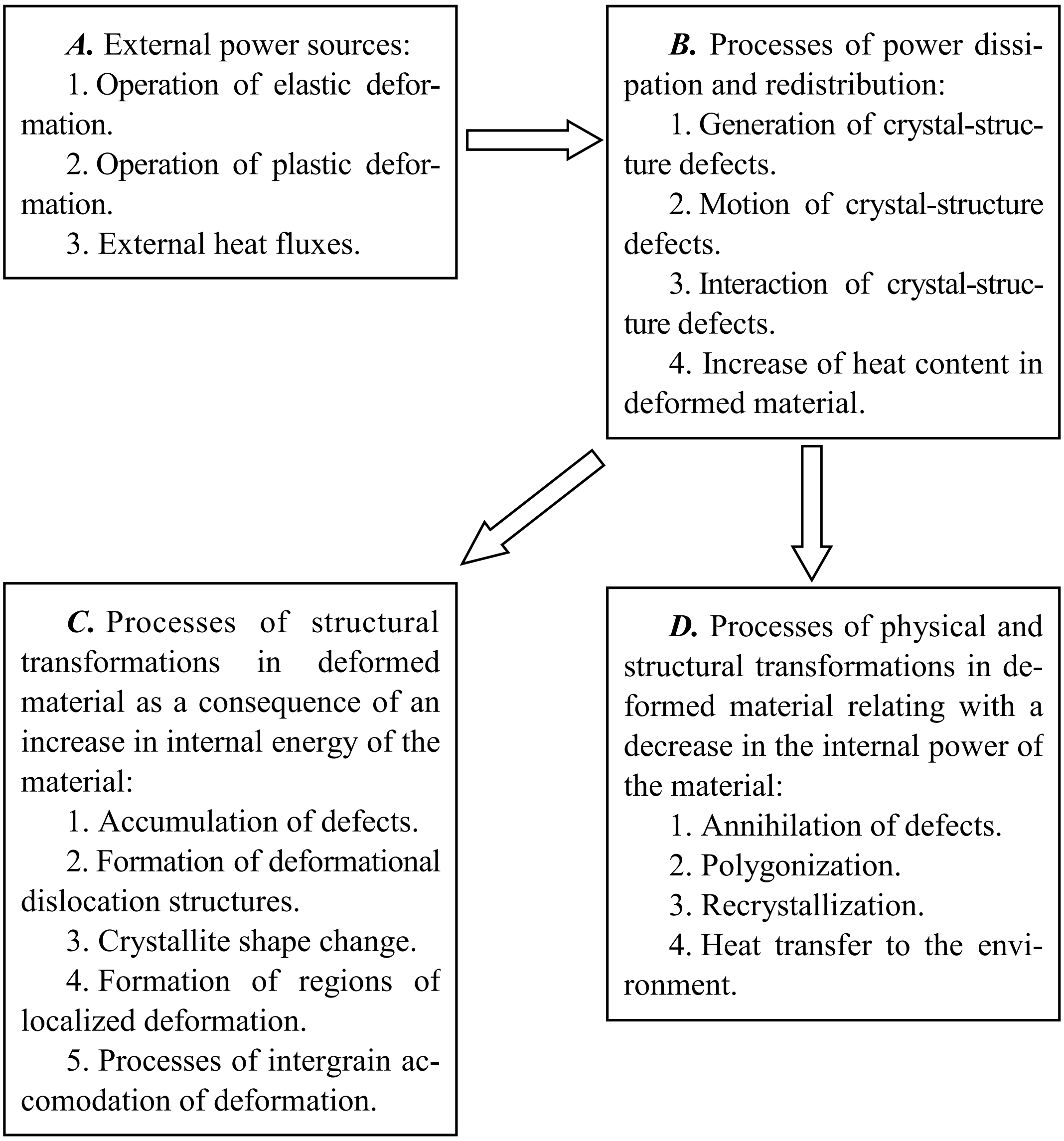

Fig. Scheme of relationship between the processes of power redistribution and transformation of structure under the plastic deformation.

specimen tension and on the «torque-turning angle» coordinates for the case of torsion. To obtain the comparable results we must take specific values determined by the «stress-relative deformation» diagram. It has been shown [10] that for different tests the primary diagrams can be transformed to generalized curve of the flow. The physical sense of quantitative value obtained by the integration of the flow curve can be interpreted as the work of deformation of materials unit volume.

Apart from physical arguments, this is confirmed by the analysis of dimensions of quantities: $J/m^3 = H{\cdot}m/m^3 = H/m^2$.

The processing of the flow curves [10] for copper (the fcc lattice) and iron (the bcc lattice) in the annealed state and subjected to cold prestraining gave the results listed in Table.

Table

Specific work of deformation prior to materials failure

Material	State	Specific work upon tension, J/mm^3	Specific work upon torsion, J/mm^3
Copper	Cold-work	0.01–0.02	0.30–0.35
	Annealing	0.08–0.10	0.35–0.40
Iron	Cold-work	0.02–0.03	0.50–0.55
	Annealing	0.10–0.12	0.80–0.90

The analyzed results show that values of power absorbed under realization of the *B*-type processes (see Fig.) much (1–2 orders of magnitude) differ for one and the same material depending on the initial state and loading type. At the same time, for identical states and loading types the differences (2–2.5 times) in the first approximation correspond to differences in moduli of elasticity and in values of materials strength.

We can qualitatively explain the influence of the original state by a high level of power preaccumulated by specimens subjected to cold drawing and, as a result, the material is less capable of dissipating power applied later on. At the same time, the changes in specific work of the deformation observed at the tension-torsion stage have no trivial explanation and should be analyzed in detail. Of special importance is the fact that upon twisting the work of deformation is less respondent to the cold-work in the case of cold predrawing as compared to that during tension, especially in the material with fcc lattice. Within the above-formulated approach it can be postulated that such a significant difference in power parameters of the deformation process should be associated with different character of developed processes of generation, redistribution, accumulation and annihilation of crystal structure defects.

First we assume that the main mechanism of power accumulation is the increase of the dislocation density under disordered (chaotic) distribution thereof in the bulk of material. Basing on values of the specific work of deformation that are listed in the Table we can evaluate the increase in density of crystal structure defects. Power of chaotically arranged dislocations can be estimated from the relation

$$A_{\mathrm{dis}} = 2\rho\alpha G b^2,$$

where ρ – dislocation density, α – structural factor, G – shear modulus, b – Burgers vector.

Let us specify values of parameters: $\alpha = 1$; Burgers vector – of $2.5\cdot10^{-10}$ m, shear modulus – of the order of 40 GPa for copper and $2\cdot10^{-10}$ m, 80 GPa for iron, respectively.

It follows from the equation that for the absorption of deformation work of the order of 0.01-1 J/mm^3 the dislocation density should be increased by 10^{11}–10^{13} m^{-2}. Taking into account that in highly annealed metal the original dislocation density is at a level of 10^7–10^8 m^{-2}, the total density (10^{18}–10^{21} m^{-2}) is much larger than the experimentally observed values for metals before failure (10^{14}–10^{15} m^{-2}). In the case of metal after the cold-work the discrepancy is even more prominent. Thus, it can be concluded that during the cold plastic deformation, in the metal there are active processes of motion, redistribution and annihilation of generated defects of the crystal structure, to provide the dissipation of mechanical energy applied from outside. This topic will be discussed in the second part of the paper. It should be noted that the process of dislocation motion is the definitive one as a possibility of dislocation redistribution and annihilation depends on it.

Conclusion

In plastic materials the macroscopic plastic deformation is the sum of multiple acts of shear, which, in turn, results from the sliding of dislocations in sliding systems activated with the stressed state. Therefore, the following statement can be formulated: during the deformation the stressed state effect on plasticity reserve is through different activation of sliding systems. Upon torsion, the deformation scheme is evidently of simple shear type when the direction of action of the maximum tangential stresses is constant and the state of direction of the largest elongation with respect to the line of stress action is continuously changed. Therefore, during the torsion more and more new sliding systems are involved. In the case of tension, the angle between the direction of action of the maximum tangential stresses remains constant, which does not favour the activation of new sliding systems. Upon torsion of the predrawn specimens the dislocation motion develops in systems that were not activated before because of changes in direction of action of the maximum tangential stresses and in direction of the maximum elongation, so the influence of pretreatment in the case of torsion is weaker than in the case of tension. Upon the tension of drawn specimens, position of the both directions is preserved, thus leading to exhaustion of plasticity reserve in the limited number of sliding systems activated before.

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