

Hardening Viscous Failure and Strain Localization during Severe Plastic Deformation

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Abstract. The analysis is made of effect and physical mechanisms of the influence of pressure on metal materials that are in the state of plastic flow, as well as on characteristics of materials undergone severe plastic deformation under pressure.

Influence of Pressure on Deformation Behavior of Materials

Increasing the plasticity of solids under pressure has been the subject of numerous investigations starting from fundamental works [1,2]. It is currently shown that the effect is due to two interrelating processes: suppression of fracture and defect structure homogenization (DSH) during active deformation under high pressure [3,4].

For a wide class of solids there exist two levels of critical pressure: $P_c \sim \sigma_s \sim 10^{-3}K$ and $P_0 \sim 10^{-2}K$ (σ_s – yield stress, K – compression modulus). When $P = P_c$ the process of micro-inhomogeneities (pores and cracks) development is retarded under deformation, i.e. the solid plasticizes and the ultimate strain ε_p increases (ε_p – value of strain prior to fracture). For brittle bodies the value of P_c coincides with that of pressure of brittle – plastic transition. With further P growth, in the $P_c < P < P_0$ range, the process of suppression of nonuniformity origination becomes more intensive and for $P > P_0$ the solid can be ideally plastic (it deforms as a high-viscous liquid). Table lists values of P_0 calculated for various metals (see [4]).

Table Critical pressure for various metals [4]

Material	Lattice type	P_c , [GPa]	P_0 , [GPa]
Cr	BCC	0.07 – 0.72	7
Mo		0.11 – 1.13	11
W		0.18 – 1.69	18
Fe		0.08 – 0.84	8.5
Steel 1045		0.09 – 0.91	9.2
Be	HCP	0.17 – 1.72	17.1
Mg		0.16 – 1.67	16.2
Zn		0.05 – 0.54	5.1
Ti		0.04 – 0.43	4.2

Let us consider the process of DSH for a solid subjected to active deformation under high pressure at relatively low deformation velocities. The nucleation and the mobility of dislocations in solids are limited by thermally activated processes. The application of pressure results in decreasing thermal activation and, thus, in the grows of number of dislocation sources and, finally, in the increase of DSH.

It is known that during the deformation the formation of concentrators results in origination of micro – and meso-inhomogeneities favoring fracture. For $P > P_c$, in the deformed solid the relaxation processes tend to minimize the probability of nonuniformity origination, otherwise the work $\Delta A_p = P\Delta V$ (ΔV – change in volume due to nonuniformity origination) should be done, which increases with P . This results in deconcentration of stresses in volume samples and, thus, in DSH intensification.

In heterophase and noncubic polycrystalline systems, the process of DSH becomes more intense due to relaxation processes taking place at the expense of pressure – induced shearing stresses at inner interfaces or at elastic nonuniformities. It should be noted that processes of twinning and martensitic transformations during the deformation of metastable system under high pressure also favor the DSH.

In such a way, the main physical reasons of DSH and, thus, of plasticization of crystal solids under high pressure are the decreasing of thermal fluctuations, the suppression of generation and retardation of micro- and mesomicro-inhomogeneity development, as well as the intensification of effects of compression anisotropy in elastically nonuniform and noncubic polycrystals. For $P \geq P_c$, activation of the processes results in the intensification of plasticization effects in solids under pressure that are observed at different scale levels depending on nature of objects observed (mono- and polycrystals, metastable and heterophase systems, noncubic and porous solids) and on value of P realized in the experiment.

When DSH is high, the value of maximal internal stresses decreases and defects of crystal structure tend to distribute more uniformly in the volume of samples, which, as a rule, results in the improvement of physico-mechanical properties of different materials.

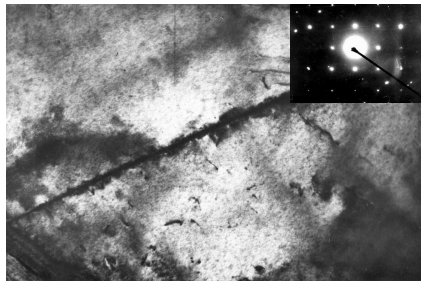
Experimental Results on the Influence of Pressure on Grain Refinement and Plasticity of Metals

The above assumptions concerning the role of hydrostatic pressure in deformation process are supported by the following experimental facts.

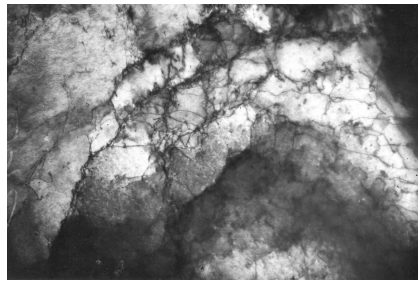
When molybdenum is deformed under pressure, on the structural level the polyhedral grain structure of the annealed material ($d \approx 22 \mu\text{m}$) starts showing a local instability to the origination of rotational structure of the «vortex» type during direct extrusion with $e > 0.3$. With e increase, the growing instabilities result in a cardinal rearrangement of the initial structure ($e \approx 1.2\text{--}1.4$) to a rotational structure of the «vortex» type. With further increase in the extrusion ratio up to $e \approx 1.9$, in sample cross-section the «vortex» character of the structure becomes more pronounced, while in the longitudinal section the fibrous structure is observed.

At the level of substructure, the low-misoriented cellular structure existing with $e \approx 0.15\text{--}0.3$

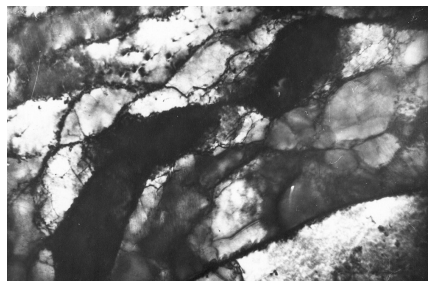
changes for a fragmented one, which is a population of fragments (subgrains) with a $5\text{--}10^\circ$ (and more) misorientation. For $e \approx 1.2\text{--}1.9$, the process of a more uniform grain refinement is genetically related to the process of evolution and branching of nonuniform banded substructure typical of $e \approx 0.4\text{--}1.0$ (Fig. 1).



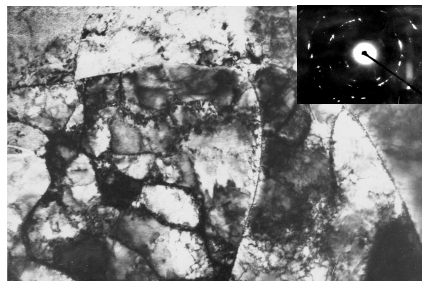
a



b



c



d

Fig. 1 Substructure of molybdenum as a function of direct extrusion parameters (cross-section, $\times 27000$);

a - $e = 0$;

b - $e = 1.2$, $P_{bp} \approx 0.1$ MPa;

c - $e = 1.2$, $P_{bp} \approx 800$ MPa;

d - $e = 1.4$, $P_{bp} \approx 800$ MPa.

During the direct extrusion of molybdenum, the increase in pressure level at the expense of backpressure P_{bp} results in shifting the range of deformation ratios, necessary for the origination of rotational structures of the «vortex» type, to lower values of e .

Mathematical Modeling of the Effects Resulting from the Influence of Pressure on Plastic Deformation of Solids

The development of the SPD technologies should be based on the mathematical models describing fracture and grain refinement of solids and taking into account the pressure effect on this process.

We have proposed a continual model of the deformation of solids describing the fracture of the material under deformation as well as the effect of pressure on the process [5]. The model [5] did not take into account the interrelation between the formation of micro-inhomogeneities and the grain refinement in solids under severe plastic deformation. Another model has been developed to describe the above – mentioned effects [6].

In order to incorporate the structure of polycrystals into a continual model of plasticity, two scalar parameters have been introduced [6]: *the total volume of micropores* θ per unit volume of the material and the *total area of large-angle boundaries* S per unit of cross-section of the area of the material. Using the assumption of self-similarity of the structure changes during quasi-monotone loading and the complementarity of grain refinement and fracture, we obtain a

system of kinetic equations for these parameters. We show that the proposed model not only explains a number of known effects, but also suggests new ones. In particular, it turned out that the loading processes that most intensely fragment the metal should be processes which lead to the highest decrease of plasticity of the given metal (among all processes with the same level of hydrostatic pressure in the strain center). To obtain submicro- and nanostructures, these processes need be carried out under high hydrostatic pressure in the strain center. In this case, the relaxation of internal strain will follow the path of crystal grain refinement, not of the emergence of micropores.

To illustrate conclusions following from the model, a study was done of the evolution of metal structure in two processes differing in deformation scheme. The deformation scheme was accounted for by value of materials ductility when the hydrostatic component of the stress tensor is zero [6]. The characteristics of carbon steel (0.45% C) were taken for calculation. The results of calculation are represented in Fig. 2.

The curve of the average grain size d (inverse value of S) is given below for comparison of the results as this structure parameter is the most frequently met in literature. Let us analyze the model curves.

Fig. 2I shows a comparison of direct and twist extrusion processes. It follows from the graph of $d(e)$, which illustrates the material structure grain refinement, that its intensity is practically the same for the processing methods under consideration. However, in the case of direct extrusion, $e \approx 3$ is a really attainable total deformation when sample is still considered to be three-dimensional. Indeed, as a rule, under direct extrusion, diameter of the billet is not larger than $D_0 = 50$ mm. While under the logarithmic deformation ($e \approx 3$), extrudate diameter $D = 10$ mm, and a high degree of deformation already gives extrudates which can hardly be considered three-dimensional. The graph of relative porosity $\theta(e)$ shows that twist extrusion ensures a higher plasticity of the deformed material.

As compared to direct extrusion, the twist extrusion is a cyclic (highly non-monotonic) process of loading, as during one pass, inside the twist channel the direction of deformation is changed [7]. Thus, there occur favorable conditions for healing micropores of the material as shown by peaks on porosity curve. Cyclic deformation results in a high plasticity of the deformed material, however the grain refinement is less intensive as compared to monotonic deformation. One of the ways of increasing the intensity of substructure grain refinement is the increase of its amplitude [6]. This is shown by twist extrusion.

In fig. 2II there is a comparison of two schemes of the twist extrusion: a sequence of twist dies of the same orientation and a sequence of interchanging dies oriented clockwise and anti-clockwise. In the case of scheme with different interchanging dies the dislocation charges do not discharge, when the one twist die is changed by another. As expected, we have some improvement of grain refinement (curve $d(e)$), but structure failure has still increased (curve $\theta(e)$). With e increase, the non-monotonicity of deformation process less adversely influences the porosity and for $e \geq 7$ the both curves $\theta(e)$ merge, while there is still "a gain" in the length of large-angle boundaries.

As it has been already said, the processing types resulting in a considerable decrease of plasticity should activate the formation of fine-grained structure under pressure.

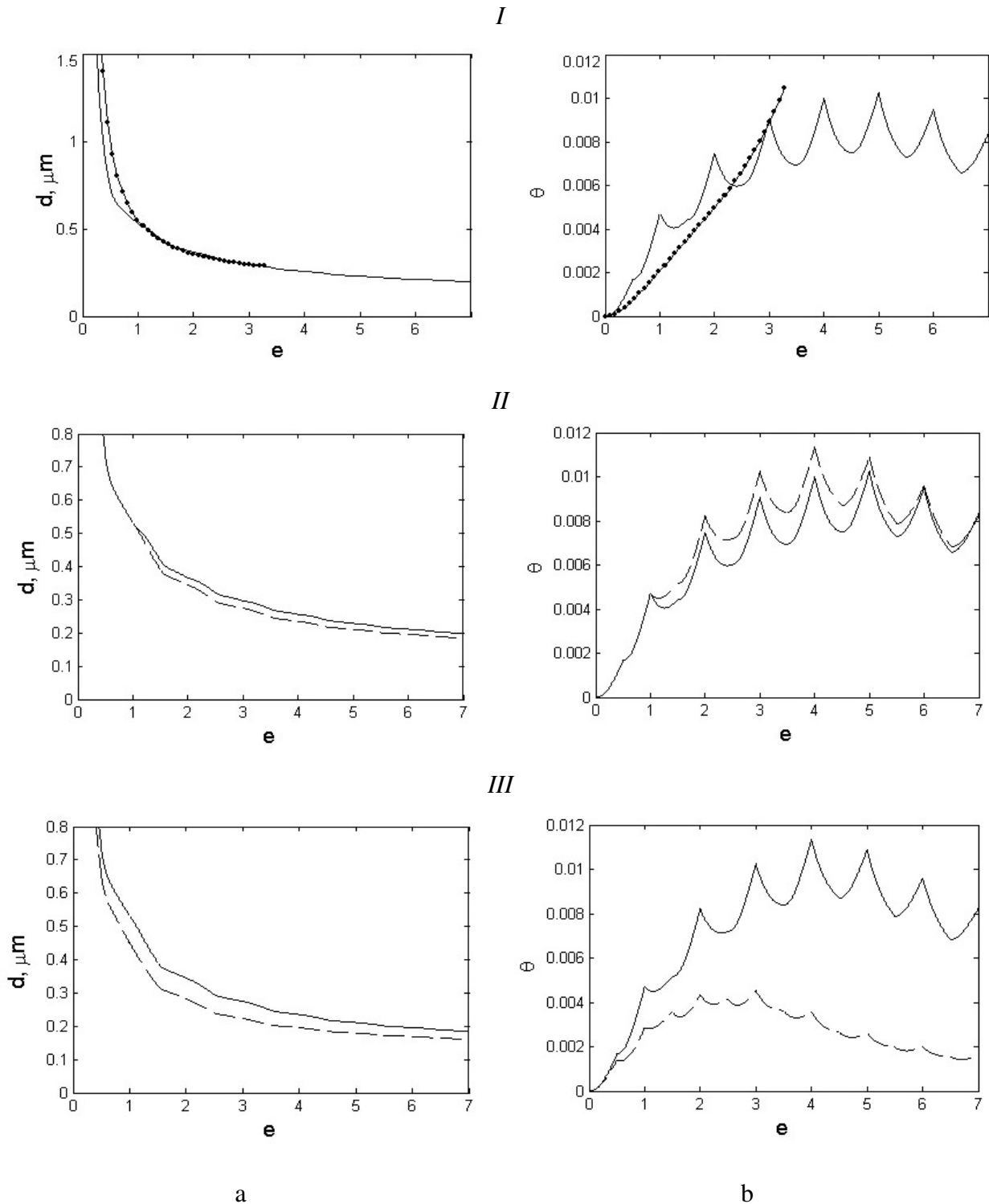


Fig. 2 Dependence of steel (0.45% C) structure characteristics on equivalent deformation e : a - average size of fragment d ; b - porosity θ ; I - twist extrusion through the right-orientation die R (—) and direct extrusion in three passes with drawing $\lambda = 3$ at each pass (....); II - twist extrusion through die R (—) and dies R and L (of the left orientation) by route R→L→R→L... (---); III - twist extrusion by route R→L→R→L... with no backpressure (—) and with backpressure $P_{bp} = 600$ MPa (---).

Fig. 2III illustrates the results of calculations showing the role of backpressure in twist extrusion by the scheme of different interchanging dies. Curve $d(e)$ illustrates the more intensive grain refinement and, thus, the smallest size of fragments corresponds to processing with the backpressure material. The run of $\theta(e)$ curve evidences the positive influence of backpressure on healing the micro-voids of the material that are the basic cause of its fracture. In such a way, the backpressure makes it possible to increase plasticity of the metal, the preferences from the grain refinement being preserved. It can be concluded the last deformation scheme is optimal according to characteristics of material structure obtained.

Conclusions

- The experiments show that in metals the intensity of grain refinement under severe plastic deformation increases with pressure. As a result, the hardening of metals becomes higher than the hardening under atmospheric pressure.
- The results of modeling have shown the twist extrusion to be an effective scheme of deformation accumulation, which gives the improved characteristics of material structure. In the case of the scheme with different interchanging twist dies and application of backpressure to the process of deformation make it possible to produce fine-grained low-damage materials possessing a high plasticity.

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