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V.N. Varyukhin¹, Y.Y. Beygelzimer¹, B.M. Efros¹, O.V. Prokof'eva¹,
V.P. Pilyugin²

HIGH PRESSURE EFFECTS IN SEVERE PLASTIC DEFORMATION

¹Donetsk Physics & Technology Institute of NASU
72 R. Luxemburg Str., Donetsk 83114, Ukraine

²Institute of Metal Physics of the RAN
18 S. Kovalevskaya Str., Ekaterinburg 620219, Russia

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]).

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.

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

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 ($e \approx 1.2-1.4$) 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 $e \approx 0.15-0.3$ changes for a fragmented one, which is a population of fragments (subgrains) with a $5-10^\circ$ (and more) misorientation. For $e \approx 1.2-1.9$, the process of a more uniform grain refinement is genetically related to the process of evolution and branching of nonuniform banded substructure typical of $e \approx 0.4-1.0$ (Fig. 1).

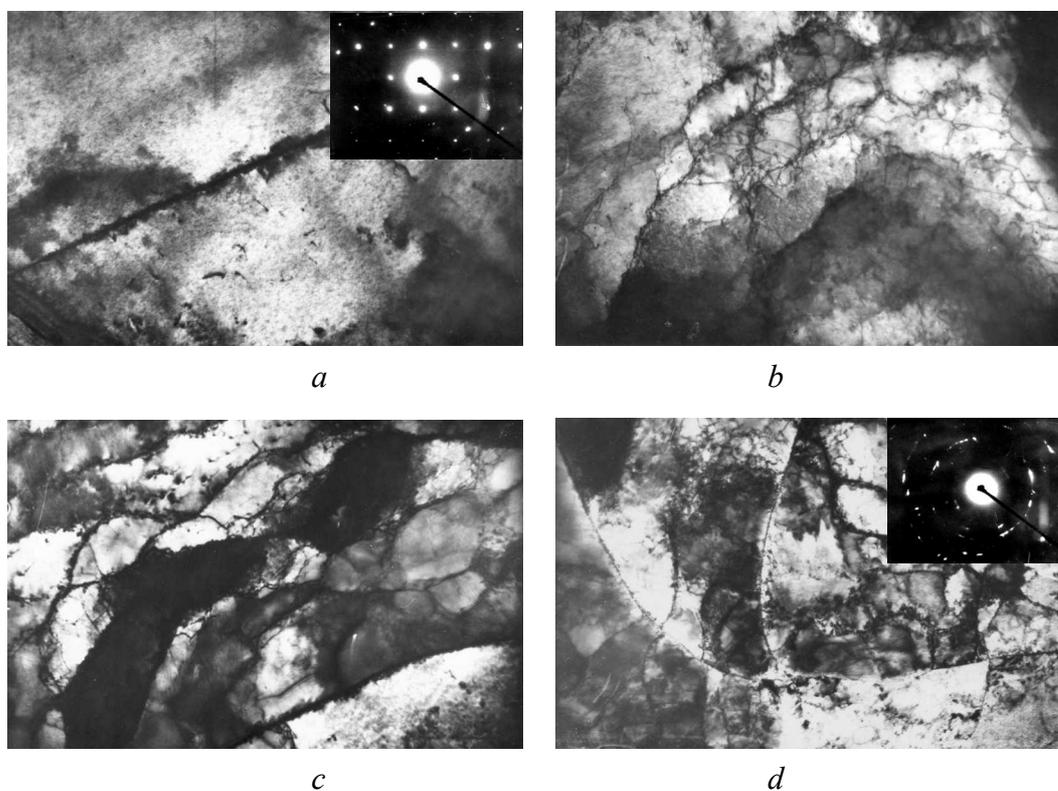


Fig. 1. Substructure of molybdenum as a function of direct extrusion parameters (cross-section, $\times 27000$): $a - e = 0$; $b - e = 1.2$, $P_{bp} \approx 0.1 \text{ MPa}$; $c - e = 1.2$, $P_{bp} \approx 800 \text{ MPa}$; $d - e = 1.4$, $P_{bp} \approx 800 \text{ MPa}$

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 .

The quantitative analysis of histograms for distribution of structural elements in size has shown that during the direct extrusion of molybdenum, with the increase

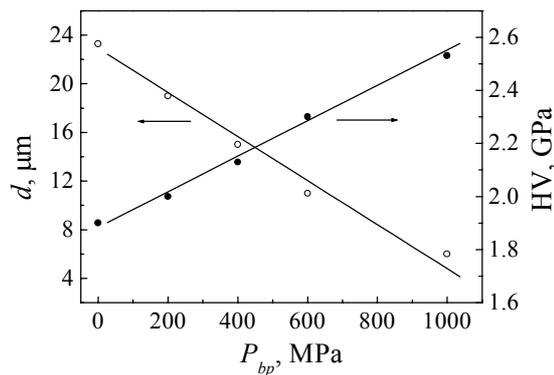


Fig. 2. Influence of backpressure P_{bp} on changes in the average size of structure elements d and on value of hardening HV of molybdenum ($e = 1.4$)

in backpressure and thus in extrusion pressure, the average size of structural elements of molybdenum is decreasing. At the same time, the hardening increases with the growth of P_{bp} (Fig. 2).

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 length of large-angle boundaries per unit of cross-section area of the material S . 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 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. 3.

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. 3I shows a comparison of direct and twist extrusion processes. A gradual descent of the both curves on the graph of a number of accumulative zones $N(e)$ is due to the formation of a considerable share of indivisible fragments. The introduction of the mechanism of mutual slippage results in the lowering of the intensity of internal-stress accumulation.

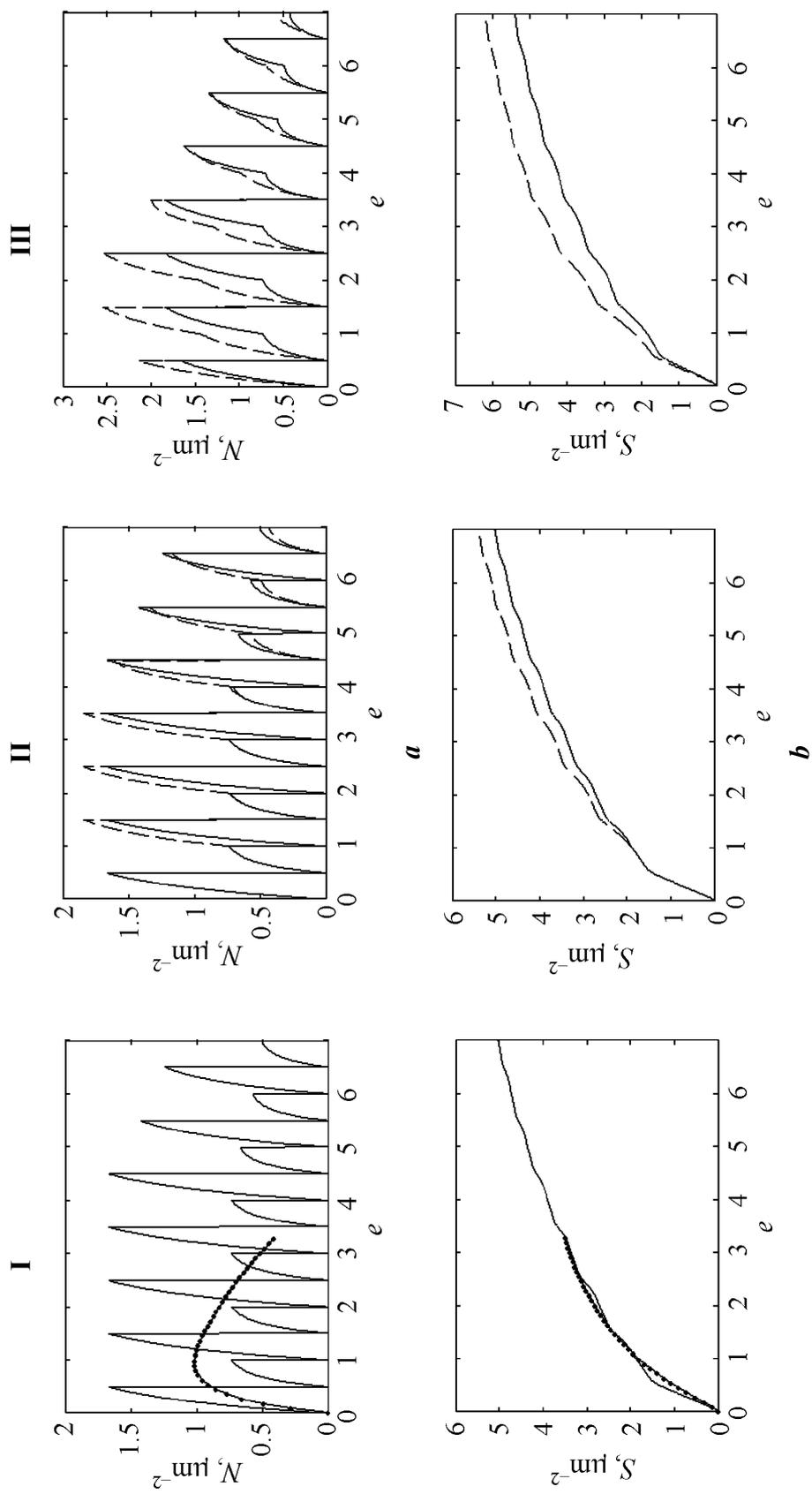
It follows from the graphs of $S(e)$ and $d(e)$, which illustrate the material structure grain refinement, that its intensity is practically the same for the processing methods under consideration. However, in the case of direct extrusion, $e \approx 3$ is a really attainable total deformation when sample 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 microvoids 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. 3II 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. So a greater quantity of accumulative zones is formed and curve $N(e)$ goes higher. The excess of those zones relaxes by the formation of additional large-angle boundaries and by increase of porosity, as illustrated by curves $S(e)$ and $\theta(e)$. As expected, we have some improvement of grain refinement, but structure failure has still increased. 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 S .

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. 3III illustrates the results of calculations showing the role of backpressure in twist extrusion by the scheme of different interchanging dies. $S(e)$ and $d(e)$ curves illustrate a more intensive grain refinement and, thus, the smallest size of fragments corresponds to processing with the backpressure. The run of $\theta(e)$ curve



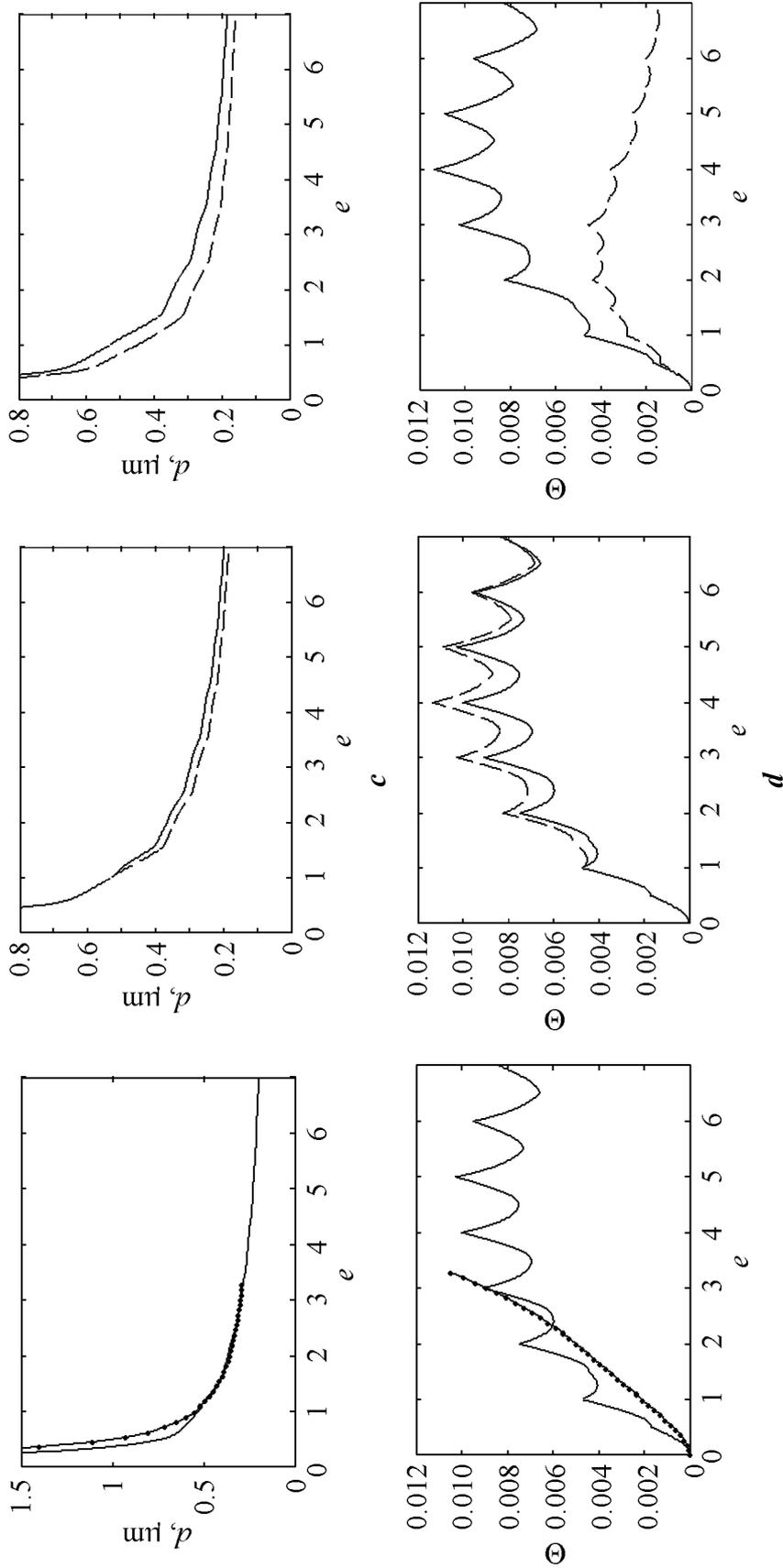


Fig. 3. Dependence of steel (0.45% C) structure characteristics on equivalent deformation e : a – numbers of accumulative zones per unit of cross-section area N ; b – lengths of large-angle boundaries per unit of cross-section area S ; c – average size of fragment d ; d – average size of fragment θ ; I – twist extrusion through the right-orientation die R (—) and hydroextrusion 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 $R \rightarrow L \rightarrow R \rightarrow L \rightarrow R \rightarrow L \rightarrow R \rightarrow L \rightarrow R \rightarrow L \dots$ with no backpressure (—) and with backpressure $P_{bp} = 600$ MPa (---)

evidences the positive influence of backpressure on healing the microvoids 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 that the last deformation scheme is optimal according to characteristics of material structure obtained.

Influence of the formed nanocrystalline state in metals on phase stability under pressure

It is known that the formation of nanocrystalline (NC) structure by SPD techniques can essentially influence the kinetics and completeness of phase transformations in metastable materials.

The objects of investigation were Fe–Mn alloys with manganese concentration $C_{Mn} = 0\text{--}55$ wt% and of different phase composition in the initial state.

For Fe, the NC state was reached by high-pressure torsion (HPT). It has been shown that the formation of NC state in Fe ($d \approx 80$ nm) in the process of preliminary HPT with $e = 6\text{--}7$ and $P = 10$ GPa increases critical points $P^{\alpha \leftarrow \varepsilon}$ of direct transformation and decreases $P^{\varepsilon \leftarrow \alpha}$ of reverse transformation by ~ 4 GPa as compared to coarse-grained (CG) state ($d_3 \sim 400$ μm), as determined by *in situ* investigations in high-pressure chamber (see Fig. 4,*a*). This fact is explained by the stabilizing action of the NC state in Fe, which is the restraining force for the basic $\gamma \rightarrow \varepsilon$ transformation (the ratio of the volume fraction of the microcrystallite boundaries to the «defect-free» portion in NC Fe is 2–3 orders of magnitude larger than the same ratio in CG Fe). HPT with parameters $e \approx 6.4$ and $P = 10$ GPa does not result in α -Fe–Mn alloys ($C_{Mn} < 10\%$).

Under SPD by HPT of $(\gamma + \varepsilon)$ - and γ -alloys based on Fe–Mn solid solution a banded-type structure originates consisting of twins and stacking-fault twins. When degree of deformation increases ($e \geq 4$), the NC state is formed with the average size of microcrystallites ~ 80 nm ($e \sim 7\text{--}8$) (it should be stated that NC state is characterized by 3–4 fold hardening as compared to the initial one).

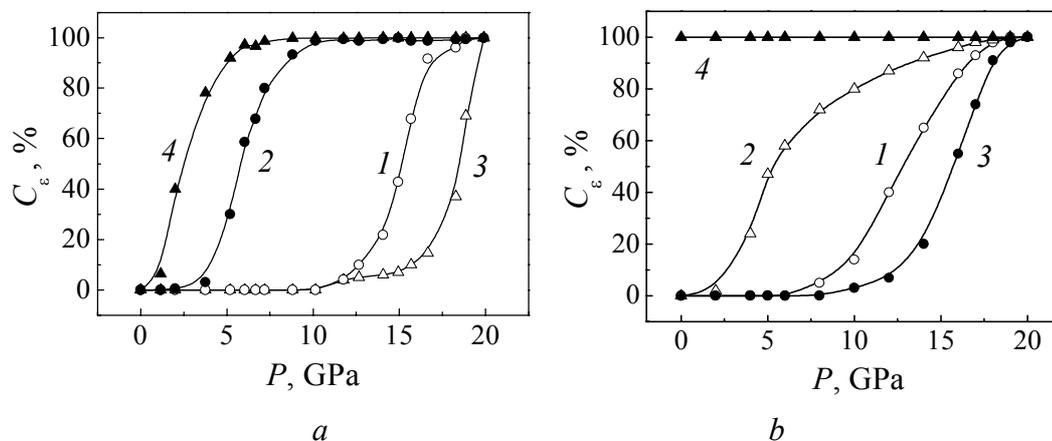


Fig. 4. Pressure dependence of HCP high-pressure ε -phase concentration C_ε in α -Fe (a) and γ -Fe₅₅Mn₄₅ alloys (b) in CG and NC states: 1, 2 – CG structure ($d \approx 400$ μm); 3, 4 – NC structure ($d \approx 80$ nm); 1, 3 – loading; 2, 4 – unloading

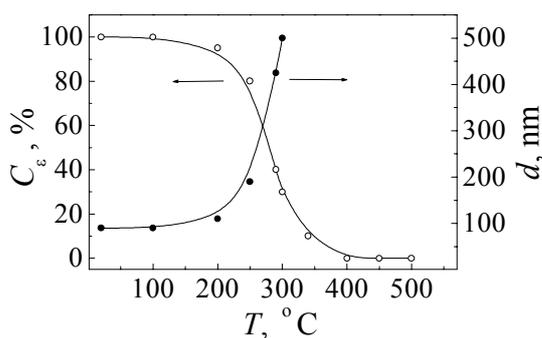


Fig. 5. Tempering temperature dependence of the C_ϵ and average size of crystallites (grains) d for γ -Fe₅₅Mn₄₅ alloy

(Fe₅₅Mn₄₅ alloy) of high-pressure HCP ϵ -phase has been conserved after treatment (the quantity of ϵ -phase decreases with the increase of stacking-fault energy in γ -phase) HPT with parameters $e \approx 4-5$ and $P = 19-20$ GPa has induced $\gamma \rightarrow \epsilon$ transformation. After the treatment the high-pressure HCP ϵ -phase has been conserved completely (the *in situ* investigation in Fe–Mn alloys, $C_{Mn} = 40-55\%$, is reversible). Analysis of the results has shown that the increase in hysteresis of the reverse $\epsilon \rightarrow \gamma$ transformation due to stabilization of high-pressure phase in NC state of γ -Fe–Mn alloys subjected to preliminary HPT is the mechanism of HCP high-pressure ϵ -phase stabilization under the decompression (Fig. 4,*b*).

Investigation of the temperature stability of HCP high-pressure ϵ -phase in NC γ -Fe–Mn alloys has shown that the heating to $T \geq 250^\circ\text{C}$ initiates the reverse $\epsilon \rightarrow \gamma$ -transformation (single-phase γ -state needs a 5 min holding at $T \approx 340-390^\circ\text{C}$), Fig. 5.

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.

The obtained results of complex investigation of alloys based on Fe–Mn solid solution have shown that their structural-phase state depends on parameters of SPD under pressure as well as on the initial phase and concentration composition which, in the end, determines the level of mechanical and service properties of this class of materials.

HPT of $(\gamma + \epsilon)$ -Fe–Mn alloys results in the increase of high-pressure HCP ϵ -phase as compared to other types of pressure treatment (direct extrusion, shock waves). This is confirmed by investigation of changes in phase composition of Fe₈₀Mn₂₀ alloy, placed into high-pressure chamber, depending on value of stressed-state indices.

HPT with parameters $e = 6.4$ and $P = 10$ GPa induces $\gamma \rightarrow \epsilon$ transformation in γ -Fe–Mn alloys. In this case, from 70 (Fe₆₀Mn₄₀ alloy) to 10%

1. *P.V. Bridgman*, Investigation of high plastic deformations and rupture, Foreign Liter. Publ. House, Moscow (1955).
2. *B.I. Beresnev, L.F. Vereshchagin, Yu.I. Ryabinin, L.D. Livshits*, Some problems relating to severe plastic deformation of metals under high pressures, Izd. AN USSR, Moscow (1960).
3. *B. Beresnev, B. Efros, V. Streltsov*, High Pressure Research **13**, 281 (1995).
4. *Y.E. Beygelzimer, V.N. Varyukhin, B.M. Efros*, Physical mechanics of the hydrostatic treatment of materials, Don PTI NAS of Ukraine, Donetsk (2000).
5. *Y. Beygelzimer, B. Efros, V. Varyukhin, A. Khokhlov*, Eng. Fract. Mech. **48**, 629 (1994).
6. *Y. Beygelzimer*, Mechanics of Materials (2005) (in press).
7. *Y. Beygelzimer, D. Orlov, V. Varyukhin*, Ultrafine Grained Materials II, Y.T. Zhu, T.G. Langdon, R.S. Mishra, S.L. Semiatin, M.J. Saran, T.C. Lowe (eds.). TMS (The Minerals, Metals & Materials Society) (2002), p. 297–304.