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DEVELOPING OF SPD PROCESSING AND ENHANCED PROPERTIES IN BULK NANOSTRUCTURED METALS

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The present paper focuses on some recent achievements and problems in developing the SPD methods to enhance properties of metals and alloys by means of optimization of formed nanostructures.

Introduction

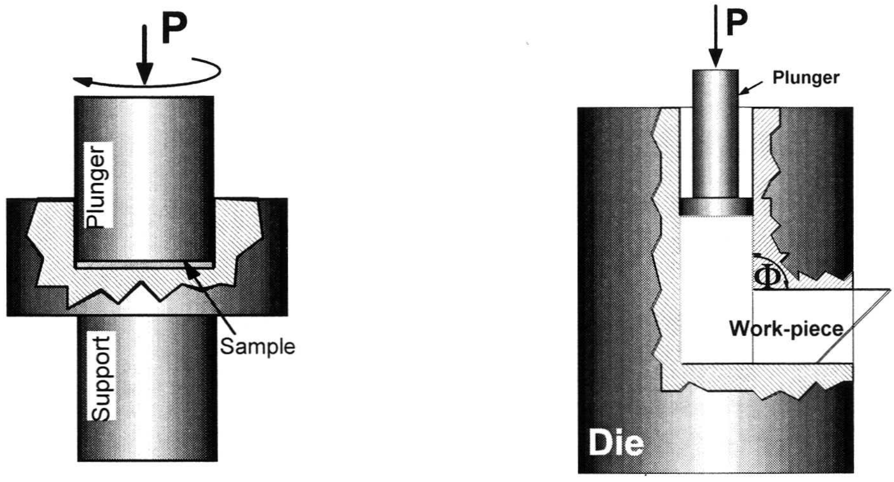
Since the first works [1] demonstrating a possibility to obtain bulk nanostructured metals and alloys by severe plastic deformation (SPD) techniques, i.e. intense plastic straining under high applied pressure there has been an increased interest in this field [2,3]. Within the last 2–3 years a significant progress has been made in obtaining advanced mechanical (high strength, superplasticity, fatigue) and physical-chemical (magnetic, corrosion) properties in SPD materials [2].

The present paper focuses on some recent achievements and problems in developing the SPD methods to enhance properties of metals and alloys by means of optimization of formed nanostructures.

SPD processing

The developed SPD techniques should meet several requirements, among which we would like to emphasize a possibility of obtaining high plastic strain (true strains greater than 6–8, as a rule) at low deformation temperatures under high applied pressure [2]. This requirement is important to get ultrafine-grained nanostructures with very small grains of about 100 nm possessing mostly high-angle grain boundaries. Till recently the developed and applied techniques were high-pressure torsion (HPT) (Fig. 1,*a*) and equal-channel angular (ECA) (Fig. 1,*b*) pressing [1–5].

In order to optimize the procedure of SPD and to develop bulk homogeneous nanostructured ingots the experimental and FEM approaches were developed and successfully used [4–7]. As a result, a character of plastic flow, distributions of normal and shear stresses and strains, contact pressures between the deformed ingot and the die are studied and the influence of the friction coefficient and die geometry on the above-mentioned characteristics is analyzed [7]. On this basis the optimal SPD conditions have been revealed and applied to process bulk nanostructured ingots of different metals and alloys. However, the main progress was achieved conformably to plastic materials (Cu, Ni, Al alloys) and the developing of techniques of treatment of hard-to-deform and low-ductile metals and alloys is urgent. An increase in dimensions of obtained ingots with ultrafine-grained structure is also important.



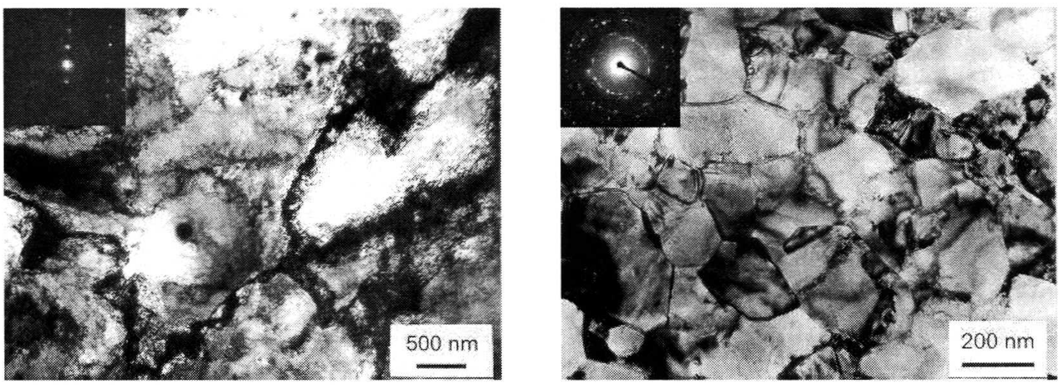
a *b*

Fig. 1. Principles of severe plastic deformation techniques: *a* – high-pressure torsion, *b* – equal-channel angular pressing

Structural characterization

The numerous investigations demonstrate that generally it is a quite effective ability to attain a microstructural refinement through SPD processing. However, the obtained nanostructures usually differ essentially and are characterized by different structural parameters. For example, the substructure with low-angle boundaries (Fig. 2,*a*) differs radically from ultrafine-grained nanostructure with high-angle grain boundaries processed by HPT (Fig. 2,*b*). It is worth mentioning that the development of SPD nanostructures with high-angle grain boundaries is a rather difficult task. The formation of nanostructures is determined by many factors such as strain and rate of SPD, temperature, the amount of the applied pressure, a die geometry and so on. That is why the investigation of microstructure evolution during SPD applying different techniques of structural analysis is a quite actual topic of works.

TEM investigations revealed step-by-step refinement of the coarse-grained microstructures and their transformation to the cell ones with low-angle interfaces, which



a *b*

Fig. 2. TEM micrographs of cell (*a*) and grain (*b*) microstructures in Cu subjected to HPT, 1 revolution (*a*) and 5 revolutions (*b*)

finally develops to the grain nanostructures with high-angle grain boundaries at certain SPD-regimes [2]. High-angle grain boundaries in SPD nanostructures are in a non-equilibrium state and possess extrinsic defects of a high density [2].

X-ray analysis revealed that evolution of microstructure during SPD has rather complex character. A decrease in the coherently scattering domain size as well as an increase in elastic crystal lattice microdistortions, the Debye–Waller parameter, static and dynamic atomic displacements take place at SPD [8,9].

As follows from the observed growth of the ratio of edge to screw dislocations the prevailing dislocation type is changing in pure Cu with the progress of SPD [9,10]. Combining these X-ray results with the above-mentioned TEM observations one can draw a conclusion that the majority of dislocations in SPD nanostructures are situated at grain boundaries. These dislocations being screw extrinsic grain boundary dislocations are responsible for their high-angle character.

At the same time, a certain limit in the grain size under which the dislocation density decreases was observed [10]. That could mean a high importance of the dynamic recovery processes happening at SPD processing.

In spite of the evident progress in the structural characterization of the SPD nanostructured materials some problems still should be scrutinized by investigators. One can refer to them the issues concerned with deep understanding of structure refinement mechanisms, attaining a minimal grain size, modelling of nanostructures in different SPD materials and others.

Probably, modern conception [11] of high plastic deformations should be developed with reference to severe deformations at low temperatures and high pressures.

Mechanical properties

It follows from recent results [2] that for enhanced mechanical properties (high strength and ductility, superplasticity) it is principally important to optimize SPD processed nanostructures, including a grain size and shape, structure of grain boundaries, defect density and crystallographic texture. For example, in Fig. 3 tensile true stress–strain curves for different structural states of pure Cu are represented. One can see that its deformation behaviour is changed dramatically depending on the prehistory of the samples.

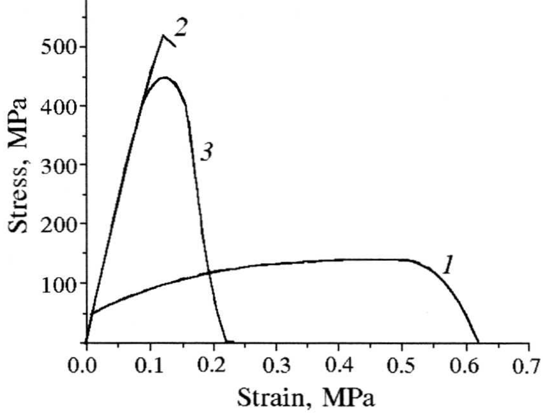


Fig. 3. Tensile stress–strain curves of Cu samples: coarse-grained (*1*), consolidated from powder by HPT [10] (*2*), HPT strained, 5 revolutions (*3*). Room-temperature tests. Strain rate 10^{-3} s^{-1}

The bulk sample with a mean grain size of about 100 nm consolidated from powder by HPT exhibits very high strength and limited ductility (Fig. 3) [12]. The sample had no any residual porosity, but it possessed high internal stresses. Simultaneously the HPT strained bulk Cu sample having also a mean grain size of about 100 nm exhibited both high strength and sufficient ductility in comparison with the coarse-grained Cu sample (Fig. 3).

The recent computer simulation conducted within the framework of the 3D deformation-based model [13] shows that unusual behaviour of nanostructured Cu with high-angle grain boundaries is a result of considerable activation of processes of mutual dislocation annihilation and lattice dislocations absorption by grain boundaries [14]. Low-temperature superplasticity revealed in a number of nanostructured SPD alloys [15] confirms the important role in this phenomena and defect structure of grain boundaries.

Thus, the recent results from experimental and modeling work enable one to conclude that:

1. SPD techniques can greatly refine the microstructure in metals and alloys up to nanometer range, however, character of the nanostructures formed (a grain size and shape, structure of interfaces, density and distribution of lattice defects, crystallographic texture, etc.) strongly depends on applied SPD techniques and regimes.

2. There are examples when very high properties (strength, ductility, superplasticity) were obtained in nanostructured SPD materials, however, these properties are very sensitive to structural parameters and require, as a rule, ultrafine-grained nanostructures with mostly high-angle grain boundaries.

3. The problems of optimization of SPD parameters to obtain enhanced properties, developing of new SPD techniques, which allow the obtaining of bulk nanostructured samples and ingots of larger size are rather urgent nowadays.

Acknowledgements

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