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Phase transitions in metallic alloys driven by the high pressure torsion


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ABSTRACT

Severe plastic deformation can lead to the phase transformations in the materials. Even the severe plastic deformation at ambient temperature is frequently equivalent to the heat treatment at a certain elevated temperature (effective temperature). However, if the real annealing at the elevated temperature leads to the grain growth, the severe plastic deformation leads to strong grain refinement. In this review the methods of determination of effective temperature after high-pressure torsion of metallic alloys are discussed.

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1. Introduction

Severe plastic deformation (SPD) frequently leads to the phase transformations in the materials. Even the SPD-treatment at ambient temperature $T_{SPD}=300$ K is frequently equivalent to the heat treatment at a certain elevated temperature $T_{eff}>300$ K. It has been demonstrated recently that concept of effective temperature T_{eff} originally proposed for the materials under severe irradiation [1] is applicable also for severe plastic deformation (SPD) [2]. If the atomic movements driven by an external action (deformation or irradiation) are higher in comparison with the conventional thermal diffusion, the material is forced to undergo into a state which is equivalent to that at a certain increased (effective) temperature T_{eff} . One can estimate T_{eff} if the phases in a material after SPD treatment differ from those before SPD [2]. This method is quite

productive since SPD frequently leads to the phase transformations [3] e.g. the formation [4–12] or decomposition [13–15] of a supersaturated solid solution, dissolution of phases [16–28], disordering of ordered phases [19–31], amorphization of crystalline phases [32–40], synthesis of the low-temperature [21,28], high-temperature [41–43] or high-pressure [44–52] allotropic modifications, and nanocrystallization in the amorphous matrix [53–61]. For the determination of T_{eff} one can use also the phase diagrams at high pressures, if they are known [44–52]. However, the SPD-treatment at ambient temperature T_{SPD} usually leads to the very quick phase transformations, which is easy to understand if one considers the high density of defects, similar to an increased temperature. The increased pressure, oppositely, leads to the decrease of diffusivity and/or grain boundary mobility [62,63]. Some SPD-driven phase transformation needs only a small shift of atoms, for other

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ones the long-range mass transfer is needed. The results of such SPD-driven transitions cannot be explained by the bulk or even grain boundary diffusion at the SPD temperature (which usually remains slightly above ambient one). In this review the methods of T_{eff} determination of metallic alloys after high-pressure torsion are discussed. For the determination of T_{eff} we choose the alloys where the phases after HPT strongly differ from the ones before HPT. The alloys studied have also well investigated and unambiguously known equilibrium phase diagrams. These phase diagrams (in coordinates “temperature–composition” and/or “temperature–pressure”) allowed us the easy comparison with observed phases after SPD and, therefore, easy and reliable determination of T_{eff} .

2. Experimental

The Al–Zn, Al–Zn–Mg, Cu–Ni, Co–Cu, Ni–Y–Nb and Zr–Nb alloy systems of various compositions were investigated. The alloys were prepared of high purity components by the vacuum induction melting. The melts were poured in the vacuum into the water-cooled cylindrical copper crucible of 10 mm diameter. After sawing, grinding, and chemical etching, the 0.7 mm thick disks cut from the as cast cylinders were subjected to HPT in a Bridgman anvil type unit (room temperature, pressure 5 GPa, 5 torsions, 1 rotation-per-minute). After HPT, the central (low-deformed) part of each disk (about 3 mm in diameter) was excluded from further investigations. The samples for structural investigations and calorimetry were cut from the deformed disks at a distance of 4–5 mm from the sample centre. At this distance the shear strain is ~ 6 . The 2 mm thick slices were also cut from the cylindrical ingots, then divided into four parts. After quenching, samples were embedded in resin and then mechanically ground and polished, using 1 μm diamond paste in the last polishing step, for the metallographic study. After etching, samples were investigated by means of the light microscopy (LM) and by scanning electron microscopy (SEM). SEM investigations have been carried out in a Tescan Vega TS5130 MM microscope equipped with the LINK energy-dispersive spectrometer and on a Philips XL30 scanning microscope equipped with a LINK ISIS energy-dispersive spectrometer produced by Oxford Instruments. LM has been performed using a Neophot-32 light microscope equipped with a 10 Mpix Canon Digital Rebel XT camera. The samples for TEM investigations were prepared by ion milling on the PIPS machine. TEM investigations were carried out on a TECNAI F2 electron microscope with acceleration voltage of 200 kV. The dark field image was taken in the most bright reflection to which contribute both α and ω phases. X-ray diffraction (XRD) data were obtained on a Siemens diffractometer (CoK_{α} radiation). Grain size was estimated by the XRD line broadening and using the Scherer formula. Both the as-cast coarse-grained CG and fine-grained HPT-samples were studied with the aid of differential scanning calorimetry (DSC) using the NETZSCH Pegasus 404C and TA Instruments (models 910 and 1600) calorimeters in the dry argon atmosphere, Al_2O_3 crucibles and at the cooling and heating rates of 10 and 20 K/min.

3. Results and discussion

Usually, the high applied pressure decreases the diffusivity and grain boundary mobility [62,63]. However, the atom movements caused by strong external forces can drive both accelerated diffusion and phase transformations in the material [64]. Historically, such unusual behaviour was first observed in materials under severe irradiation [1]. Martin proposed a simplified mean-field description of solid solutions subjected to irradiation-induced atomic mixing [1]. His main idea was that the forced mixing induced by irradiation emulates the increase of entropy and changes the thermodynamic potentials in the alloy. In a simple case of regular solution in the Bragg–Williams approximation, a law of corresponding states was formulated: The equilibrium configuration of the solid under irradiation flux φ at temperature T is identical to the configuration at $\varphi=0$ and a certain effective temperature

$$T_{\text{eff}} = T(1 + \Delta). \quad (1)$$

If the irradiation-driven movements of atoms are similar in amplitude to conventional diffusion jumps, they can be described by the “ballistic” diffusion coefficient D_{ball} and $\Delta = D_{\text{ball}}/D_{\text{b}}$, where D_{b} is conventional bulk diffusion coefficient, possibly increased due to the non-equilibrium defect concentration [1]. It means that one can use the equilibrium phase diagram for the description of the system under irradiation, but at T_{eff} instead of the actual temperature T . For example, if the liquid phase is present in the phase diagram at T_{eff} , the amorphous phase would appear under irradiation [1,65].

To check the applicability of the Martin's law (1) to the forced diffusion driven by pure shear deformation (D_{HPT}) instead of irradiation (D_{ball}), experiments where HPT leads to the phase transformations have to be analysed. We have chosen for the comparison the data where (i) the HPT-driven atomic movements are comparable with each other, i.e. HPT was performed at 4–6 GPa with 4–6 torsions and (ii) the phases appeared after HPT can be easily localized in the phase diagrams and are different from those present in the samples before HPT.

The composition of the phases after SPD allows to localize those phases in the respective equilibrium phase diagram and to estimate the effective temperature T_{eff} . Such a schematic diagram is shown in Fig. 1. In this figure the dashed vertical lines denote compositions of the various studied alloys. Figurative points corresponding to the effective temperature of the alloys are indicated by an open circle and numbered. Each star with a letter indicates the composition and temperature of an alloy's treatment (normal cooling, SPD or rapid quenching).

The supersaturated solid solution in the as-cast Al–30 wt % Zn alloy contained about 15 wt% Zn (Fig. 2) [13,14,67]. It corresponds to the point *b* in Fig. 1. The as-cast Al–20 wt% Zn and Al–10 wt% Zn alloy contained about 7 and 3 wt% Zn in the supersaturated solid solution (Fig. 2). The HPT at room temperature (point *a* in Fig. 1) produced nanograined pure Al (point 1) and pure Zn particles simultaneously leading to unusual softening [13,14]. In other two as-cast alloys the

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