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A MULTISCALE RHEOLOGICAL MODEL OF SUPERELASTIC METAL ALLOYS: FROM NANO TO MACRO SCALE

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Some crystalline materials at high temperatures demonstrate superplasticity that is a state at which the material deforms well beyond its usual breaking point (~200%). In this state any treatment of the material like stamping, cutting, extension or rolling is easy and the constructions with lightweight design can be built. During the cycling of the materials around their phase transformation, the superplastic behaviour develops due to the internal stress produced. Among the mechanisms of superplasticity are the atomic diffusion and sliding of grains past each other [1].

Many metal alloys demonstrate the superplastic behavior after being treated by the high-current relativistic electron beams (HCREB) [2]. Titanium alloy VT1-0 can be modified by HCREB with energy E=0.35 MeV with Δt=5 μs impulse duration and power density PD=60 MW/cm^2. The intense electron exposure significantly increased both hardness (~30%) and elastic modulus (~12%) within a subsurface layer h~100 μm [2]. The superelasticity has also been obtained by pulsed HCREB irradiation (PD=109 W/cm^2, E~0.5MeV, Δt=0.5 μs) on mesoscopic structure of Al-Cu-Mg-Mn alloy (92.9%,4.8%, 1.5%, 0.8% accordingly). The samples have been formed as plates 4x10 mm with 3 mm height, and one impulse has been applied at each side of the sample. The surfaces of the samples have been studied by Scanning Electron Microscope SEM JEOL JSM-840. The ultrafine structures with grains of d=2-3 μm have been detected (Fig.1b) on the microphotographs of the alloys after the HCREB irradiation. The structure is much finer in comparison to the images of the untreated samples (Fig.1a). It is clearly visible that the surface layer s~60-80 μm of the sample plate has been melted and is composed of grains with d~40 μm. Fracture of the samples was supplied by development of numerous large defects (pores) at the interfaces of the grains and matrix followed by their conjugation into cracks.

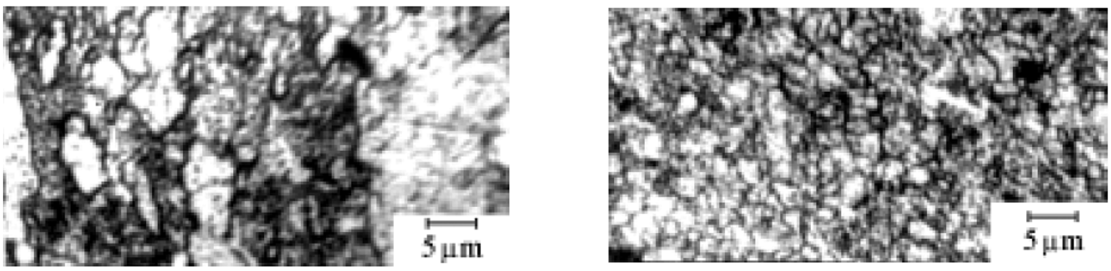

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Fig.1. SEM microphotographs of Al-Cu-Mg-Mn alloy before (a) and after (b) HCREB treatment.

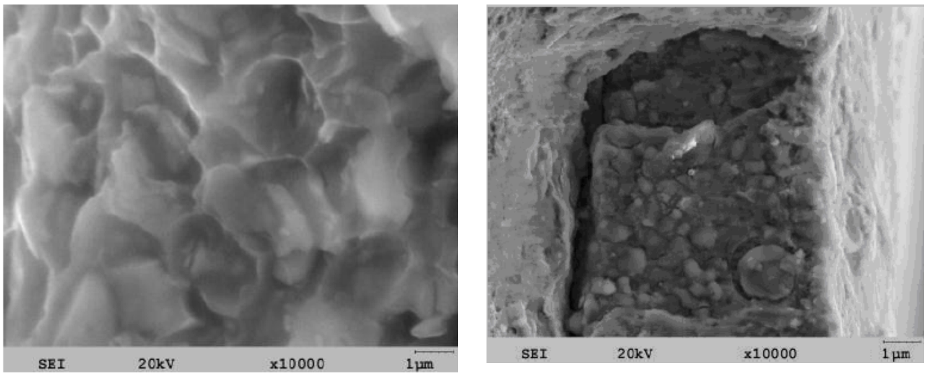

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Fig.2. SEM images of the fractured Al surface before (a) and after (b) the HCEB.

In that way, irradiation by HCEB changes the nanostructure of the treated materials by:

- heating of the material;
- development of numerous point defects;
- generation of the shock waves and fragmentation of the larger grains;
- atomization, fluidization and sedimentation of the matter at the surface of the inclusions;
- melting of the surface of the inclusions.

The fractal dimensions on the grayscale SEM microphotographs of the fractured surfaces have been statistically analyzed by divisor step methods with the sliding square window of varying size [3]. It was found, the microstructure of the fractures has also been significantly refined by the treatment. The much smaller grains with melted surfaces are detected in the treated samples (Fig.2b) in comparison with the non-treated ones (Fig.2b).

In this paper a novel multiscale rheological model of the superplastic material is proposed.

- At the microscale (I) the shear deformations of the smaller grains on the surface of the greater ones have been modeled by rotations of the grains governed by the shear stress, adsorption, nanoscale friction and sliding within the discrete four-field micropolar model [1]. The computed surface forces and deformations have been averaged over the grains;
- At the mesoscale (II) the dislocation model has been applied to describe the dislocations and agglomerations of the generalized grains with gradual development of the microstructure without or with defects;
- At the macroscale (III) the obtained mesoscopic relations have been averaged over the representative sample volume and the resulting rheological relationships for the superplastic material have been obtained.

The dependencies $\delta(\sigma)$ for the stretched loads (Fig.3a) and $\sigma(\dot{\varepsilon})$ for the tensile loads (Fig.3b) have been computed on the model and compared to the experimental curves for the treated samples. Quite a good agreement between the theoretical and experimental data has been found.

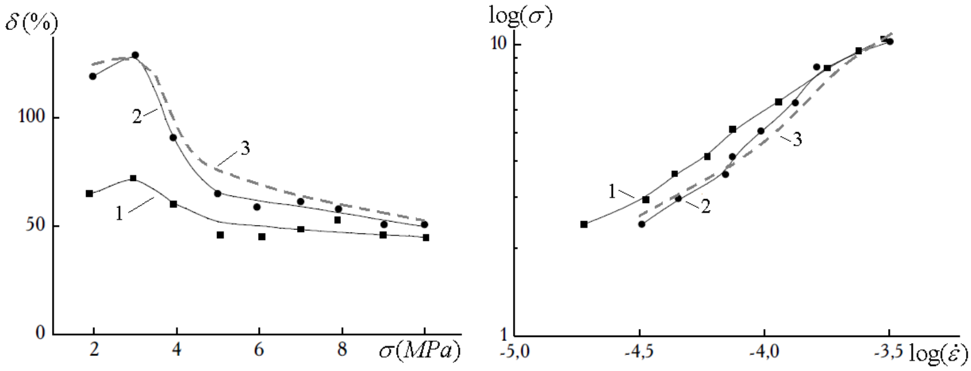

Fig. 3. Dependence of the elongation δ on the applied extension σ (a) and the strass-strain rate curve for the tensile experiment (b) for the untreated (squares, lines 1) and treated (circles, line 2) samples; 3 - computed curves.

The developed model will be useful for *in silico* planning of stamping and other types of mechanical processing of the superelastic materials.

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