THE ROLE OF INTERNAL STRESSES IN THE REALISATION OF DISLOCATION-DIFFUSION VISCOUS FLOW OF EUTECTIC ALLOYS UNDER THE CONDITIONS OF SUPERPLASTICITY

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The eutectic alloys Sn-38wt.%Pb and Bi-43wt.%Sn are considered typical alloys exhibiting structural superplasticity. However, the studies conducted by the authors show that the superplastic flow in them is realized against the background of the decomposition of supersaturated solid solutions formed under crystallization conditions. Under superplastic conditions, the determining mechanism of deformation is diffusion-dislocation viscous flow, and not grain boundary sliding, as reported in the literature – Fig. 1–3.

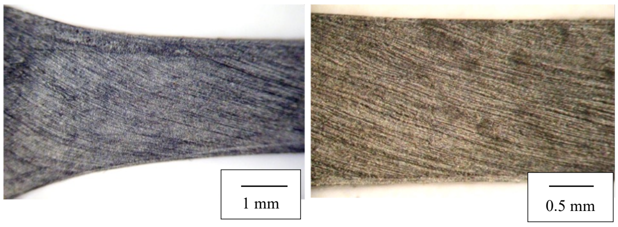

Fig. 1 Macrorelief of samples of Bi-43wt.%Sn alloy deformed under superplastic conditions.

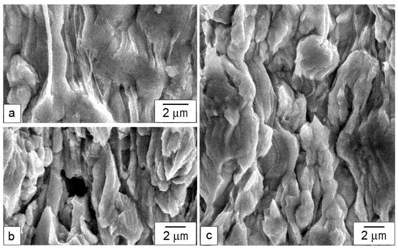

Fig. 2 SEM images of the surface of a superplastically deformed Bi-43wt.%Sn alloy sample at the initial stage of flow (a) and at different values of relative elongation (b, c). Secondary electron mode. The direction of elongation coincides with the vertical of the figure.

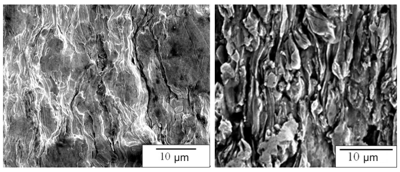

Fig. 3 Strain relief of Sn-38wt.%Pb alloy samples deformed under superplastic conditions. $T \approx 20$ °C. SEM image (in the secondary electron mode). The tensile direction coincides with the vertical.

The obtained results have actualized the question of the role of internal stresses in the manifestation of the superplasticity effect in the mentioned alloys [1–3].

The authors found that internal stresses arise in them as a result of preliminary deformation by compression in a press by 70–75%. This is evidenced by the observed decrease in the parameters of the crystal lattice of the β(Sn) phase (solid solution of lead in tin) in Sn-38wt.%Pb alloy and macroscopic cracking of Bi-43wt.%Sn alloy ingots, as well as an increase in the Young's moduli of both alloys as a result of compression. Superplastic flow is accompanied by relaxation of internal stresses, as indicated by an increase in the crystal lattice parameters of the β(Sn)-phase in the Sn-38 wt.% Pb alloy and a decrease in the Young's moduli of both alloys. The results obtained are presented in Table 1 and Fig. 4–8.

Table 1
Estimation of internal elastic stresses in the Sn-38wt.%Pb alloy from data on the change in the crystal lattice parameters of the β(Sn)-phase

Alloy series	Alloy condition	Crystal lattice period, Å		Change in crystal lattice parameters		Internal elastic stresses σ, MPa		Critical activation length of Frank – Reed dislocation sources, l_{cr}, nm
		β(Sn)-phase		β(Sn)-phase		β(Sn)-phase		β(Sn)-фаза
		a	c	$\Delta a/a_{st}$	$\Delta c/c_{st}$	σ_a	σ_c	
1 Casting on copper substrate	Cast	5.8333	3.1822					
	Deformed by compression	5.8228	3.1779	-1.7×10^{-3}	-1.0×10^{-3}	92	54	156; 266
1	Deformed under superplastic conditions	5.8337	3.1810					
2 Casting in a mold	Deformed by compression	5.8277	3.1798	-8.6×10^{-4}	-3.8×10^{-4}	46	20	313; 719
Standard	Sn	5.8327	3.1810					

The average grain size in the alloy is $d \approx 3$ μm.
The optimal stress of superplastic flow:
casting on a copper substrate – $\sigma = 7.5$ MPa; casting in a mold – $\sigma = 4.5$ MPa.

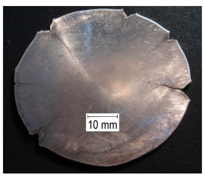

Fig. 4 Macroscopic cracking of a Bi-43wt.%Sn alloy ingot after preliminary plastic deformation by compression by 70%.

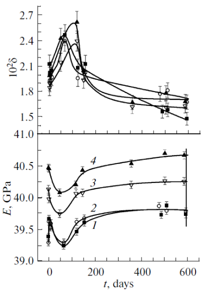

Fig. 5 Relationship between decrement δ and dynamic Young's modulus *E* for compressed (by hydraulic press) Sn-38wt.%Pb alloy subjected to an aging process of duration *t*. The duration of aging after compression is 18 days for samples 1 and 2 and 26 days for samples 3 and 4.

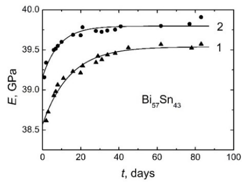

Fig. 6 Dependences of the dynamic Young's modulus *E* of the Bi-43wt.%Sn alloy on the aging time *t*. 1 – in the cast state; 2 - after plastic deformation by compression by ≈ 70%.

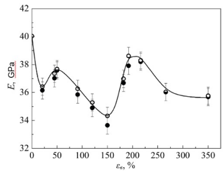

Fig. 7 The dependence of Young's modulus *E* of the Sn-38wt.%Pb alloy on the relative elongation ε under conditions of superplasticity. represents E values in 1 hour after unloading. corresponds to the values of E obtained by the extrapolation of the curve *E=f(t)* to the time *t*=0.

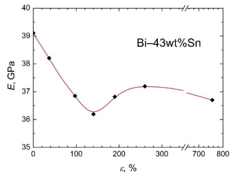

Fig. 8 Dependence of Young's modulus *E* of Bi-43wt.%Sn alloy on relative elongation ε under superplasticity conditions.

Moreover, the performed estimations indicate that the level of the indicated stresses is sufficient to activate the Frank-Read dislocation sources inside the grains and to ensure a significant increase in the dislocation density during the process of superplastic deformation – see Table 1.

Internal stresses associated with the volumetric effect of phase transformation

Internal stresses associated with the volumetric effect of phase transformation in the Sn-38 wt.%Pb alloy were estimated from data on volumetric changes accompanied by the decomposition of supersaturated solid solutions of tin in lead and lead in tin in the case when the phase composition of the alloy in the crystallized ingot corresponds to the eutectic temperature. Under such conditions, the alloy consists of solid solutions with a concentration of 19 wt. % Sn (α(Pb)-phase) and 2.5 wt. % Pb (β(Sn)-phase.

The estimation of the volume changes that occur in each of the above-mentioned supersaturated solid solutions as a result of the transition to a state corresponding to equilibrium at room temperature was performed based on data on the X-ray density ρx-ray of the two-phase mixture resulting from the decomposition and the relative number of phases.

The data on the value of ρx-ray were obtained by calculations using the formula:

$$\rho_{рентг} = \frac{100\rho^{\alpha}\rho^{\beta}}{x\rho^{\alpha} + (100 - x)\rho^{\beta}}.$$

Here x is the relative amount of β(Sn)-phase in the alloy, which was determined by the lever rule; ρα and ρβ are the X-ray density of the α(Pb)-phase and β(Sn)-phase – Table 2.

Table 2
X-ray density of α(Pb)-phase and β(Sn)-phase in Sn-38wt.%Pb alloy for equilibrium states at temperatures T

T, ºC	Concentration of elements, %, (wt./at.)				Periods of crystal lattices, Å			X-ray density of phases, g/cm³	
	in the α(Pb)-phase		in the β(Sn)-phase		α(Pb)-phase	β(Sn)-phase		α(Pb)-phase	β(Sn)-phase
	Pb	Sn	Pb	Sn	a_α	a_β	c_β	ρ^α	ρ^β
22.5	98.1 96.7	1.9 3.3	0.35 0.20	99.65 99.80	4.9450	5.8325	3.1816	11.2153	7.2914
183	81 71	19 29	2.5 1.45	97.5 98.55	4.9093	5.8378	3.1837	10.1855	7.3411

The results of calculations of the density of the mixture of phases formed as a result of the decomposition of the supersaturated α(Pb)-solid solution and β(Sn)-solid solution in the Sn-38 wt.% Pb alloy are given in Table 3.

Table 3
Data on the X-ray density of the phase mixture after decomposition of a supersaturated solid solution in the Sn-38 wt.%Pb alloy

Supersaturated solid solution	Relative number of phases after decomposition of supersaturated solid solution		Density of supersaturated solid solution	Density of phase mixture after decomposition of supersaturated solid solution	Relative change in specific volume of material
	α(Pb)	β(Sn)			
$\alpha(Pb)_{eut}$	0.8251	0.1749	10.1855	10.2505	0.0064
$\beta(Sn)_{eut}$	0.0220	0.9780	7.3411	7.3480	0.0009

As can be seen from Table 3, the volumetric effect of the transformation caused by the decomposition of the supersaturated solid solution in the α(Pb)-phase is an order of magnitude greater than in the β(Sn)-phase, so the continuous framework of the β(Sn)-phase grains will begin to compress the α(Pb)-phase at a certain stage. The difference in the relative volume change, which is about 6×10-3, leads to the emergence of internal elastic stresses of a rather high level. The relaxation of these stresses under the action of an external tensile stress can also be accompanied by the appearance of additional dislocations.

In the Bi-43 wt.%Sn alloy, the X-ray density of the solid solution based on tin, the α(Sn)-phase, with a concentration corresponding to the eutectic temperature, is 7.7719 g/cm3. According to the phase equilibrium diagram of the Sn-Bi system, at room temperature this solution decomposes into a mixture of a solid solution based on tin with a bismuth concentration of 1.3 wt. % and practically pure bismuth in the ratio 80.04:19.96. The X-ray density of this mixture, calculated by formula (1), is 7.7032 g/cm3. The decomposition of the α(Sn)-phase is thus accompanied by an increase in the specific volume of the material. Of course, the rigid framework of the β(Bi)-phase grains causes the appearance of compressive stresses in the α(Sn)- phase.

The kinetic correspondence of the processes of deformation and structural-phase transformations, determined by the nonequilibrium of the phase composition and the occurrence and relaxation of internal stresses, ensures the possibility of the active development of dislocation-diffusion viscous flow of eutectic alloys under conditions of superplasticity.

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