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STUDY OF THE INFLUENCE OF VACANCIES AND VACANCY COMPLEXES ON THE YIELD LIMIT OF Al SUBJECTED TO STRAIN AGING

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Mechanical properties of metals are most sensitive to the presence of point defects. The influence of point defects on the kinetics of plastic deformation is highly diversified: the point defects can be the main carriers of plastic deformation (diffusion creep, crowdion plasticity, etc.), can imitate the velocity of nonconservative motion of dislocations, and can serve as centers of pinning of dislocations.

The course of microplastic deformation in real crystal bodies under loading in the macroelastic region has long been known [1–3]. The dislocation nature of this phenomenon is beyond question. Mechanisms of origin and evolution of microplastic deformation have been studied and substantiated scientifically; each mechanism does exist. Among them are the mechanisms of unlocking and motion of dislocations already existing in the initial material. The processes based on origin of new dislocations during microplastic deformation in the regions of stress concentrators are not excluded as well [4]. The structure of actual crystal bodies is always macro- or microinhomogeneous. Microinhomogeneity is manifested through the imperfect crystal structure that results in the inhomogeneous stressed state of the elastic material under loading.

Microplastic shears in a loaded sample can strongly affect the state of the stress concentrators. In most cases, they cause the concentrator relaxation. However, the reverse effect is also possible.

The knowledge of laws and mechanisms of microplastic deformation of the material under macroelastic loading, including the special features of the actual structure of the material and the character of stress distribution over the sample, is extremely important for understanding of the inelastic mechanisms, formation of the yield limit, fragile destruction, etc.

One of the possible methods of elucidating the influence of the point defects on the kinetics of plastic deformation can be quenching from high temperatures. Interest to this question arose in the study of the influence of the character of structural changes and properties of metals after a sharp temperature change. It is also caused by the possibility of obtaining valuable information on the interaction of the point defects with each other and their influence on the properties of metals.

For the metal to be investigated, we have chosen polycrystalline aluminum with a purity of 99.995% and grain sizes of ~0.22 mm.

A systematic study of the influence of the quenching rate on the concentration of vacancies being formed was carried out in [5–7].

The data for aluminum were calculated using the procedure of determining the concentration of quenched-in vacancies.

Table 1 tabulates the yield limits for annealed samples quenched in water from the indicated temperatures at a test temperature of 77 K.

The vacancy concentration increases with the heating temperature before quenching, and the yield limit

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TABLE 1

Serial number	T_q, K	Yield limit$\cdot 10^{-7}$, N/m^2 at 77 K	Quench hardening$\cdot 10^{-7}$, N/m^2	Calculated vacancy concentration $C_\upsilon \cdot 10^{-4}$
1	Annealed	0.35	–	–
2	673	0.53	0.18	2.0 ± 0.18
3	773	0.93	0.58	11.0 ± 0.19
4	823	1.1	0.75	20 ± 0.18
5	873	1.2	0.85	37.5 ± 0.18
6	923	1.35	1.00	120 ± 0.18

TABLE 2. Energies of Defect Formation (E_0, eV) and Migration (E_m, eV) in Aluminum

Energy type	E_{0V}	E_{mV}	E_{0bV}	E_{mbV}	$E_{0V} + E_{mV}$	E_q
Al	0.66	0.64	0.2	0.46	1.3	1.28

increases monotonically after quenching. The maximum initial hardening is reached after quenching from the premelting temperature in water cooled down to 273 K. Subsequent annealing at a temperature of 273 K is accompanied by further increase of microplastic deformation in the macroelastic region.

It is well known that in the FCC lattice it is energetically favorable to form complexes. Table 2 tabulates the energies of formation (E_0) and migration (E_m) of the point defects that were obtained in aluminum by the method of quenching [8, 9].

Taking into account that the energy of bivacancy migration is low in comparison with that of monovacancy migration, we can conclude that bivacancies contribute significantly to the diffusion processes. The trivacancies are even more mobile. It was found that a complex of four vacancies located in tetrahedron vertices is energetically more favorable for the FCC lattice. In principle, the examined complexes can serve as centers of condensation of other vacancies thereby forming large vacancy pileups [9]. Thus, the vacancy mechanism of diffusion is dominant, and the self-diffusion coefficient is written in the form [8]

$$D = D_0 e^{-E_q/kT}, \tag{1}$$

where D_0 is the independent pre-exponential temperature multiplier, and E_q is the self-diffusion activation energy equal to

$$E_q = E_{0V} + E_{mV}. \tag{2}$$

In other words, large clusters of point defects are formed in the material volume after subsequent temperature annealing. Because aluminum has the high degree of purity, the volume defects are formed after quenching and subsequent annealing mainly from vacancies being the main carriers of plastic deformation hindering the dislocation motion.

It is convenient to trace the kinetics of interaction of vacancy defects with dislocations for vacancy concentrations low but sufficient for redistribution of vacancies and their complexes deformed in the macroelastic region with residual strain up to 0.5% [10–12].

Repeated deformation differs from preceding one by the increment of the flow stress (Fig. 1). The increment $\Delta\sigma(t)$ is characterized by the presence of a maximum whose magnitude and observation time depend on the temperature at which the repeated deformation occurs and on the preliminary strain rate and degree (Fig. 2). The increase of the yield limit as a result of low-temperature aging under loading is more stable for subsequent heating to room temperature.

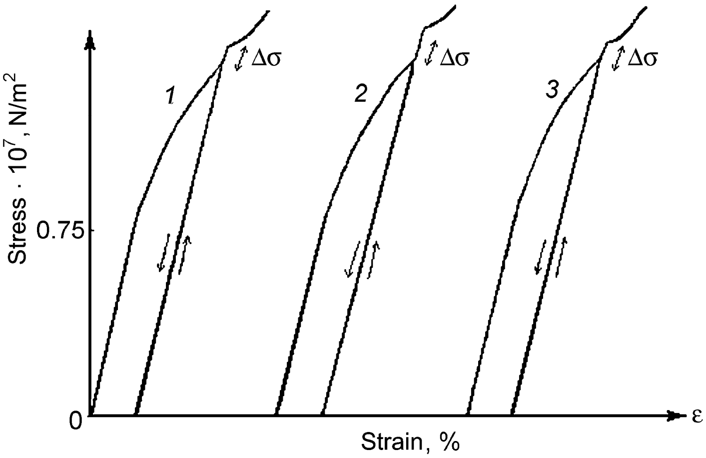

Fig. 1. Dependence of the increment of the flow stress for pure (99.995%) aluminum on the aging time (t_{ag}) at 77 K after quenching from 823 K for residual strain of ~0.5% at 77 K. Here t_{ag} = 600 (curve *1*), 1800 (curve *2*), and 4200 s (curve *3*).

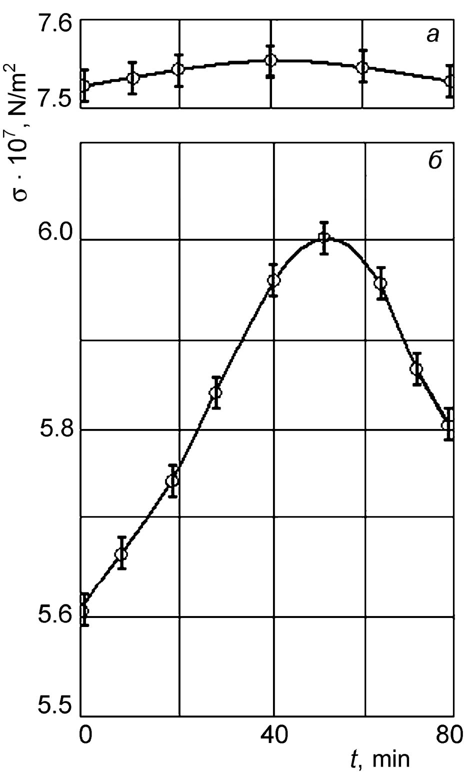

Fig. 2. Dependence of the flow stress increment for quenched aluminum on the aging time at 77 K after fast (*a*) and slow loading (*b*) to $\varepsilon = 0.5\%$.

The increase of the flow stress in the initial stage of aging of aluminum deformed after quenching is a consequence of occurrence of vacancy atmospheres formed around the dislocation due to an excess of the number of vacancies approaching to dislocations over the number of their annihilation on jogs and other sinks. A decrease in $\Delta\sigma$ with time of low-temperature aging testifies to a decrease in the density of centers of dislocation pinning. This is due to a decrease in the vacancy concentration in the grain volume; as a result, the diffusion flux toward dislocations becomes lower than the diffusion flux along dislocations to sinks. It seems likely that the maximum of the flow stress increment corresponds to the condition of equal rates of formation and annihilation of the centers pinned on dislocations.

REFERENCES

1. J. Friedel, Dislocations, Pergamon Press, Oxford (1967).
2. N. Brown, Observations of Microplasticity, in: Microplasticity, Ed. by C. J. McMahon, Jr., Wiley, New York, 1968.
3. M. A. Krishtal and R. A. Golovin, Internal Friction and Structure of Metals [in Russian], Metallurgiya, Moscow (1976).
4. E. F. Dudarev, Izv. Vyssh. Uchebn. Zaved., Fiz., No. 8, 118–132 (1976).
5. P. Tzanetakis, J. Aillairet, and G. Revel, Phys. Status Solidi, **B75**, No. 2, 433–439 (1976).
6. H. Wolluberger, Nucl. Mater., **68–70**, 362–371 (1978).
7. S. P. Flin, J. Bess, and D. Lasarus, in: Defects in Quenched Metals, A. A. Tsvetaeva, ed. [Russian translation] (1969), pp. 44–57.
8. A. N. Orlov and Yu. V. Trushin, Energy of Point Defects in Metals [in Russian], Energoatomizdat, Moscow (1983).
9. N. V. Kamyshanchenko, Influence of Mechanical and Thermal Treatment on the Structure and Property of Pure Quenched Metals, Deposited at VINITI, No. 5979-84 Dep (August 23, 1984).
10. A. A. Tsvetaeva, ed., Materials of Int. Conf. on Defects in Quenched Metals, Atomizdat, Moscow (1969).
11. P. Coulomb and J. Friedel, in: Dislocations and Mechanical Properties of Crystals, Ed. by J. C. Fisher, Wiley, New York, 1957.
12. I. A. Gindin, I. M. Neklyudov, I. I. Bobonets, and N. V. Kamyshanchenko, Izv. Vuz., Fiz., No. 12, 77–81 (1971).