DIFFUSION IN THE Cu–Zn SYSTEM UNDER THE ACTION OF ALTERNATING DEFORMATIONS

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DIFFUSION IN THE Cu–Zn SYSTEM UNDER THE ACTION OF ALTERNATING DEFORMATIONS

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It is known that, in the process of continuous constant-sign plastic deformation, the self-diffusion in α-Fe is accelerated, increasing linearly with the deformation rate $\dot{\varepsilon}$ ([1]). Diffusion under the action of alternating deformations has also been investigated ([2,3]). In work ([2]), a Cd 99.99% specimen, coated with a layer of the isotope Cd^{115}, was placed in a bath with a liquid in which ultrasonic oscillations of frequency 22 kHz were excited. The coefficient of self-diffusion of Cd in these experiments did not change. When ultrasonic deformations were excited directly in rods of Zn and Ni with the aid of a conventional oscillatory system, transducer–concentrator, no change in the self-diffusion coefficient of Zn or in the diffusion coefficient of carbon in Ni was found either ([3]). Apparently, this is connected with the smallness of the alternating deformations.

We investigated the action of ultrasound of frequency 18.6 kHz on diffusion in the Cu–Zn system (polycrystalline Cu 99.9% and Zn 99.99%; the previously work-hardened copper rods were annealed for 3 hours at 700°). In particular, in this system a γ-phase is formed, containing about 59% Zn (a complex cubic cell of 52 atoms), and an ε-phase with 79% Zn (a close-packed hexagonal cell), readily observable with an optical microscope. As shown in work ([4]), the thickness x of these phases increases with the time of isothermal holding t as follows:

$$x = \sqrt{Dt}, \tag{1}$$

where D is the diffusion coefficient.

The experiments were carried out on copper rods 96 mm long, into which zinc cylinders 1.5 mm in diameter were pressed. The rods were held before the experiment at a temperature of 300—400° for 2.5–3.5 hours. As a result, rings of the ε-phase ($x = 15$—$50\,\mu$) and the γ-phase ($x = 60$—$150\,\mu$) formed around the zinc cylinder; these were photographed. The diffusion coefficients for these phases, found from expression (1), are respectively $7 \cdot 10^2$ and $7 \cdot 10^3\,\mu^2$/hour, which agrees well with the data of works ([4,5]).

The experimental scheme is shown in Fig. 1. Thermocouples are located at points I and II, and zinc cylinders at points a, b, c. The maximum values of the oscillatory displacements ξ_m in rod 3 were determined near point II with the aid of a microscope or a special probe ([6]).

The experiment lasts about 3 hours. During the experiment the rods heat up because of the dissipation in them of the energy of ultrasonic deformations, $\varepsilon_m = k\xi_m = (2.45 \div 6.2) \cdot 10^{-4}$. The loss coefficients in copper for such values of ε_m are $0.06 \div 0.1$. At the beginning of the experiment, at $\varepsilon_m \simeq 6.2 \cdot 10^{-4}$, the rod heats up to 300—400° in 4 min (the nonisothermal section). Then, owing to adjustment of the generator, the values of ε_m are reduced to $2.45 \cdot 10^{-4}$ and subsequently remain constant, as does the temperature reached in the nonisothermal section. The readings of the thermocouples differ from one another by

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Fig. 2. Growth of the γ-phase at temperature in the isothermal section $T = 350°$. **A** —initial phases obtained at $T = 350°$ and with a preliminary annealing time of 2 hours; —phases grown from these initial ones in the control experiment; —phases obtained under the action of ultrasonic deformations at point in Fig. 1.

by an amount not exceeding 30° only at the beginning of the nonisothermal section (up to 50 sec) and then coincide. Thus, the experiment is conducted under conditions isothermal in time and along the length of the rod at a constant value of ε_m. A check shows that the increase in the thickness of the phases in the nonisothermal section amounts to no more than 5% of the total increase over 3 hours.

In order to isolate the effect caused by ultrasonic deformations, control heating of the rods was carried out. To do this, during the experiments the readings of thermocouples I and II were recorded for each specimen and the dependences $T(t)$, including the initial nonisothermal section, were obtained. Then some of the rods with thermocouples sealed into them were subjected, after preliminary annealing, to control heating. For this purpose the rods, connected to the oscillatory system of Fig. 1, were lowered into the furnace. The heating regime of the control rods in the furnace was selected so that the readings of the thermocouples sealed into them reproduced the corresponding dependence $T(t)$ with an accuracy of $\pm 3°$ in the isothermal section. As for the rate of temperature rise of the control rods in the nonisothermal section, in all cases it was somewhat higher than during the experiments. The photographs of the phases on the control rods and on the rods subjected to ultrasonic deformations were then compared.

Fig. 1. Experimental setup. At the top is shown the distribution of longitudinal ultrasonic deformations $\varepsilon = k\xi$, where $k = 2\pi/\lambda$ is the wave number. 1 — magnetostrictive exciter of longitudinal vibrations; 2 —concentrator; 3 —copper rod of half-wave length $(\lambda/2)$, diameter 12 mm.

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Fig. 3

Figure 2: Fig. 3

Fig. 3. *A* —kinetics of growth of the γ-phase. Temperature in the isothermal section $T = 300^\circ$, amplitude $\varepsilon_m = 2.4 \cdot 10^{-4} = \text{const}$. Duration of the experiment 3 hours. Preliminary annealing at 300°, 2.5 hours. Straight line 1 —control; 2 — sound, point *b* in Fig. 1, $\varepsilon \simeq 0$; 3 —sound, point *b*, $\varepsilon \simeq 0.7\,\varepsilon_m$; 4 —sound, point *a*, $\varepsilon = \varepsilon_m$. Each point is the average for 2–4 specimens. *B* —dependence of the diffusion coefficient *D* for the γ-phase on the amplitude of the deformation rate $\dot{\varepsilon}$ at $T = 300^\circ$.

The increase in the γ-phase in the experiment as compared with the control is shown in Fig. 2 (see inset to p. 517). It is seen from the figure that, under the action of ultrasonic deformations, the phases increase more strongly than under control heating. From such photographs the dependences $x^2(t)$, characterizing the kinetics of growth of the γ-phase, were found (see Fig. 3A). On the basis of the data obtained, the dependence of the diffusion coefficient on the amplitude of the rate of deformation was constructed.

deformations $\varepsilon = \omega e$ (Fig. 3b); as can be seen from the graph, the diffusion coefficient increases almost linearly with increasing ε.

The experiments were carried out at three temperatures of isothermal holding (300, 350, and 395°). If, as is usually done, the dependences of $\ln D$ on $1/T$ are plotted for the control and for the experiment, it turns out that they are parallel to one another (see Fig. 4). Consequently, at the given temperatures and amplitude of alternating deformations, only the pre-exponential factor of the diffusion coefficient D_0 increases (an increase by a factor of 2.2). The growth of the ε-phase could be reliably determined only for $T = 395^\circ$, and the diffusion coefficient *D* at $\varepsilon_m = 1.5 \cdot 10^{-4}$ proved to be 5 times higher than for the control specimens.

Fig. 4

Figure 3: Fig. 4

Fig. 4. Dependences of $\lg D$ on $1/T$ for the γ-phase. Straight line 1—control; 2—sound at a deformation amplitude during the isothermal section $\varepsilon_m = 1.71 \cdot 10^{-4}$. Duration of the experiment: 3 hours.

Thus, an acceleration of diffusion in the Cu—Zn system under the action of alternating deformations of ultrasonic frequency has been established.

Considering the results obtained, we note that the Cu—phase—Zn system at points a and b in Fig. 1 experiences, throughout the entire experiment, ultrasonic alternating deformations with amplitudes $\sim 10^{-4}$ (at point c, $\varepsilon \simeq 0$), exceeding the values critical for Cu, and all the more for Zn, at which Frank-Read sources act ([7]). Consequently, copper and zinc should harden with time. Accumulation of hardening in copper rods was indeed observed by us; moreover, at times of exposure to alternating deformations close to the duration of the initial nonisothermal section of heating, hardening slows down.

Accumulation of hardening, i.e., an increase in the density of mobile dislocations, increases the probability of their interactions, leading to the appearance of a vacancy concentration in excess of the thermodynamically equilibrium one.

The fact that, at the given values of ε_m, hardening slows down apparently leads to the establishment of a stationary excess concentration of vacancies, as is assumed for sign-constant plastic deformation ([1]), although the mechanism by which a stationary excess vacancy concentration is created and the conditions for its existence must, in a number of essential features, differ from the case of sign-constant deformation. The observed dependence of the addition to the diffusion coefficient on the magnitude of ε makes it possible to assume that each value of ε corresponds to its own stationary concentration of excess vacancies.

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Note: Figure translations are in progress. See original paper for figures.