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EFFECT OF ISOCHRONOUS ANNEALING ON THE FORMATION OF SHEAR BANDS IN THE VICINITY OF A STRESS CONCENTRATOR ON THE SURFACE OF IRON-BASED AMORPHOUS ALLOYS

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The effect of isochronous annealing on the formation of shear bands in the vicinity of a stress concentrator on the surface of an amorphous material is studied. Using the local deformation method, a parameter is introduced to determine the temperature interval in which amorphous and crystal phases coexist.

Key words: *shear bands, stress concentrator, isochronous annealing, amorphous alloys.*

In amorphous materials, the main channel of plastic deformation is shear bands [1, 2]. However, the microscopic structure of shear bands in metal glasses differs significantly from that in single crystals and polycrystals. The special features of the formation and development of shear bands in amorphous materials have been studied insufficiently. There is a lack of physical models for the formation of shear bands in amorphous condensed media subjected to various energy treatments. Therefore, the goal of the present study was to examine the formation of shear bands in amorphous iron-based alloys subjected to isochronous annealing. Investigation of the initiation of shear bands in materials under heating will contribute to a better understanding of fracture of amorphous alloys because crack propagation along shear bands is energetically favorable.

Experimental Method. The experiments were performed with Fe–Cr–Mo–Ni–C–Mg–Al, Fe–Ni–Co–Cr–Mo–B–Si, and Fe–P–C–Si–Al–B amorphous alloys produced by fast cooling of a melt on the outer surface of a copper crystallizer disk. The sample thickness was varied over 50–80 μm and the rate of sample cooling was $(8 \cdot 10^5)^\circ$C/sec.

X-ray structural and X-ray phase analyses were performed on a DRON-3 diffractometer using monochromatic $\mathrm{Cu}_{\mathrm{K}\alpha}$ radiation under the following conditions: a power of 30 kV, a current strength of 20 mA, and a gauge rate of 2 deg/min.

The structure was studied using a Neophot-21 optical microscope and a CamScan-4 scanning electron microscope.

Samples were subjected to isochronous annealing in air. Amorphous samples were held at a specified temperature for 20 min, after which they were tested. Annealing was then repeated at higher temperature. The maximum temperature was 700°C. The same samples were annealed at various temperatures because preliminary results show that the time of annealing has almost no effect on experimental results.

The rate of formation of shear bands in iron-based amorphous alloys was studied by the local deformation method. In this method, the surface of an amorphous material is deformed with the Vickers diamond pyramid of a PMT-3 device [3–5]. Then, the defects formed in the vicinity of the indentation are counted. The tests were performed on both surfaces of the amorphous samples: the surface in contact with the crystallizer disk and the surface exposed to the air during production of the amorphous bands. The indenter load was 1.5 N. The indentor penetration depth did not exceed 4 μm. The shear bands studied had the shape of semi-rings surrounding the indentation. At the same time, we recorded the average number N of these defects near the indentation. The measurement error did not exceed 3%.

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Fig. 1. Deformation pattern in the vicinity of an indentation on the surface of the starting amorphous alloys under an indentor load of 1.5 N.

Experimental Results and Discussion. X-ray structural analysis showed that the starting iron-based alloys are X-ray amorphous. Under an indenter load of a 1.5 N, the surface of the alloys in the vicinity of the indentation usually exhibits the deformation picture shown in Fig. 1. We observed only one type of defects — semicircular shear bands (in the vicinity of the indentor edges). The radial shear bands mentioned in [2, 6] were not observed. A few radial shear bands appeared only at temperatures close to 300°C. Therefore, a detailed study of these defects to reveal the special features of their formation at various temperatures was impossible.

An experimental curve of the average number N of semicircular bands versus isochronous annealing temperature t is shown in Fig. 2. The data obtained suggest that at the initial annealing stages, the number of semicircular bands varies versus the annealing temperature. Considering the measurement error, it can be concluded that the number of semicircular bands depends only slightly on the annealing temperature. At temperatures close to 600°C, the curve $N = f(t)$ decreases abruptly. This curve can be empirically described by a Fermi–Dirac distribution function

$$N = N_0/[\exp((t - t_0)/\alpha) + 1],$$

where N_0 is the number of semicircular bands calculated by extrapolation of the straight-line segment of the curve of $N = f(t)$ onto the N axis, t_0 is the temperature determined from the point of intersection of the straight line $N = N_0/2$, which is parallel to the t axis, with the curve $N = f(t)$, and α is a parameter that determines the rate of disappearance of shear bands with increase in the annealing temperature.

We note that the parameter α characterizes the range of isochronous annealing temperatures in which the fast-quenched alloys subjected to thermal treatment are in a state where amorphous and crystal phases coexist. The case in hand is a crystal phase with a grain size sufficient to affect the nature of formation of shear bands In this case, the method proposed can be used to control the transition from the amorphous state to the crystal state.

The rate of formation of shear bands depends directly on the number of sources of elementary carriers of plastic deformation of amorphous materials activated under deformation. According to the concepts of [1], dislocations can be considered as such carriers. In this case, dislocations are introduced to facilitate calculations and to visualize the processes considered. Unlike dislocations in single-crystal condensed media, in amorphous materials, these defects can be called quasidislocations because, in fact, they do not exist. Obviously, the formation and development of dislocations in amorphous materials differ from those in crystals. In amorphous materials, quasidislocations contain a larger number of jogs and kinks. The Burgers vector along such dislocation lines changes both its value and direction. As a rule, for amorphous materials, the value of the Burgers vector is taken to be equal to the Burgers vector averaged over all dislocations and the direction of this vector is assumed indefinite [1].

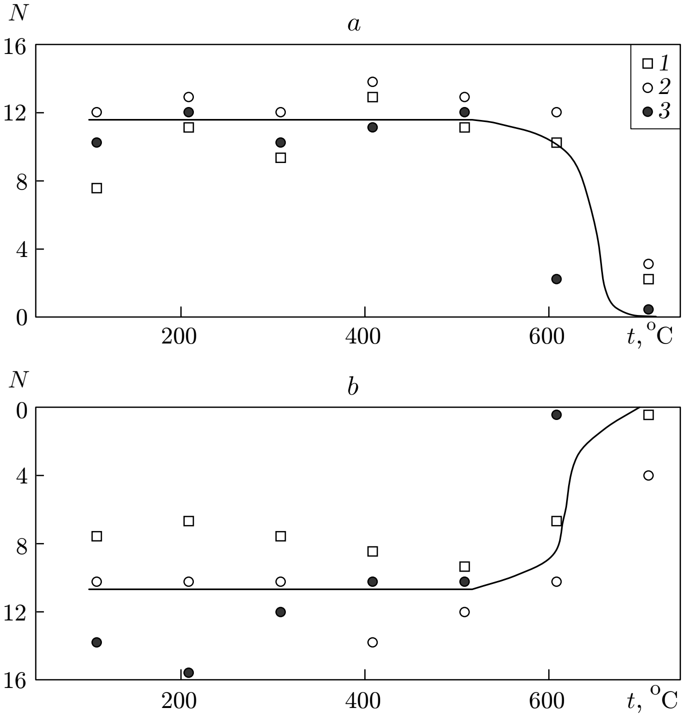

Fig. 2. Average number of semicircular shear bands versus isochronous annealing temperature for the surface exposed to the air (a) and the surface in contact with the copper crystallizer disk (b); the points refer to experimental data for Fe–Cr–Mo–Ni–C–Mg–Al (1), Fe–Ni–Co–Cr–Mo–B–Si (2), and Fe–P–C–Si–Al–B alloys (3); the curves are the averaged experimental data for all the alloys examined.

In studying the formation of shear bands, we assume that these defects are of a dislocation nature [1] and the sources of shear band dislocations are Frank–Read sources. Under these assumptions, as a criterion for activation of shear band sources, we can use the following well-known relation for calculating the critical stress of dislocation generation:

$$\tau_{\rm cr} = \alpha b G/l. \tag{1}$$

Here G is the shear modulus of the amorphous material, b is the averaged Burgers vector of dislocations that constitute the shear band, l is the source dimensions, and $\alpha \approx 0.5$ is a constant.

With increase in temperature in relation (1), the parameters G [7] and l change significantly, the amorphous material is embrittled [1], and its microhardness increases, thus leading to an increase in the shear modulus G, which is related linearly to $\tau_{\rm cr}$. Therefore, a change in the elastic properties of the amorphous material is mainly due to an increase in $\tau_{\rm cr}$ upon heating and leads to a decrease in the rate of formation of shear bands in the vicinity of the stress concentrator, as was observed in the experiments (Fig. 2). This is clearly manifested in the temperature range of 500–700°C, in which the structure of the materials examined is nearly crystalline.

The dimension l of dislocation sources depends largely on the average distance between the stress concentrators distributed in a composite material [7]. As such a composite material, one can use an amorphous alloy subjected to heating. In such materials, the concentrators are inclusions of composite grains in the amorphous material, whose size and number depend on heating. With increase in heating temperature, the number and size of crystalline (in particular, nanocrystalline) inclusions in the matrix of the amorphous material increase. This, in turn, leads to a decrease in l and an increase in $\tau_{\rm cr}$. At 500–700°C the volume of crystalline inclusions in the materials studied exceeds the volume of the amorphous matrix [1], which is also responsible for a decrease in the rate of shear band formation as the heating temperature of the amorphous material increases.

The total critical stress required to form N shear bands is

$$\tau = \sum_{i=1}^{N} \tau_{{\rm cr},i}, \tag{2}$$

where $\tau_{{\rm cr},i}$ is the critical stress of formation of the ith band.

If we assume that all stresses $\tau_{\text{cr},i}$ are equal in magnitude, relation (2) can be written as

$$\tau = N\tau_{\text{cr}}. \tag{3}$$

In this case, the Burgers vectors of dislocations are assumed to be equal as well as the dimensions of their sources. In (3), τ_{cr} is obviously determined by formula (1).

It easily can be proved that

$$\tau = \alpha N_0 Gb/[(\exp((t - t_0)/\alpha) + 1)l].$$

Below, we assume that the following relation is satisfied:

$$\tau = E\varepsilon = E\rho bL/2. \tag{4}$$

Here E is Young's modulus, ε is the relative strain, ρ is the dislocation density in the shear band, and L is the total length of shear bands determined experimentally.

Taking relation (4) into account, we have

$$l = 2\alpha N_0 G/[(\exp((t - t_0)/\alpha) + 1)EL\rho].$$

The meaning of this relation is that in the dislocation approach, the dependence of the dimension of shear band sources on temperature is similar to the dependence $N = f(t)$ if a certain critical temperature $l \to 0$ is reached. This situation is possible in the case of transition of a fast-quenched material from the amorphous state to the fine-crystalline state. In particular, this is supported by X-ray structure studies and the fact that the microhardness of annealed amorphous alloys increases [2, 6].

Conclusions. Thus, a method for studying the special features of shear band formation in the vicinity of a stress concentrator is proposed. The method involves local deformation of the material surface with subsequent counting of the number of shear bands in the plastic deformation region.

A parameter for determining the temperature interval of coexistence of the amorphous and crystal phases is introduced for the first time. In this case, the crystal-phase grain size affects significantly the formation of the shear bands.

Using the dislocation approach, an assumption is made on the small grain size in the stable state of a fast-quenched material subjected to annealing.

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