

SINGLE-PHASE MODEL OF RECRYSTALLIZATION OF MOLYBDENUM ACTIVATED BY DIFFUSION OF NICKEL IMPURITIES

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A new model of the activated recrystallization of molybdenum under the diffusion action of a nickel coating is proposed. In the context of this model, dependences of the thickness of the recrystallized layer and of the velocity of motion of the recrystallization front on the annealing time have been derived analytically. It has been revealed that an increase in nickel concentration on the surface increases, whereas an increase in average size of recrystallized grains decreases the recrystallization velocity in molybdenum. A temperature dependence of the thickness of the recrystallized molybdenum layer has also been derived.

INTRODUCTION

The study of the evolution of the crystalline substructure of polycrystals and of the development of the recrystallization process is of critical importance in gaining an insight into the mechanical properties of these materials [1]. The mechanism of recrystallization under the action of diffusion flows is generally studied by way of annealing solid-phase-coated high-melting materials. A layer of recrystallized grains in the near-surface region of the metal is observed on the coating side. As time elapses, the recrystallization front propagates deeper and deeper into the metal [2, 3]. The development of recrystallization is related to the diffusion saturation of the material with activating impurities, and the position of the recrystallization front is determined by the depth of their penetration.

The phenomenon of activated recrystallization has been best studied for the Mo-Ni system [4-7]. Interest in the mechanism of the activated recrystallization in molybdenum and molybdenum-based alloys is related to the technological problem of producing composite materials from heat-proof and high-melting alloys. Such composite materials are reinforced with plates or fibers of alloys of refractory metals, molybdenum in particular. The activated recrystallization of the reinforcer, when it is in contact with the nickel matrix, has a detrimental effect on the strength properties of such composite materials [8].

In the systems under consideration, the impurity diffuses from the external medium, which is generally a thin coating. It has been established [4] that for all alloys the time dependence of the thickness of the recrystallized layer, that is, the law of motion of the recrystallization front, obeys the relationship $\xi(t) \propto t^{1/2}$. This paper offers a model in the context of which this relationship can be derived analytically.

THE MODEL OF ACTIVATED RECRYSTALLIZATION

Assume that the x -axis is normal to the surface of a semi-infinite molybdenum specimen. The thin nickel coating applied on the molybdenum surface lies in the yz -plane. Also assume that the diffusion of nickel impurities in molybdenum and the diffusion-activated recrystallization proceed from the surface ($x = 0$) to the bulk uniformly in volume. This allows the supposition that the recrystallization front is flat and that its motion obeys the law $x = \xi(t)$.

Since the solubility of nickel in molybdenum is very low, the penetration of nickel impurities into the bulk of the specimen occurs along the grain boundaries. Therefore, the diffusion of nickel impurities from the coating into the molybdenum specimen is grain-boundary diffusion.

In the case under consideration, the distribution of the nickel concentration C can be considered depending only on coordinate x and time t . Inside the recrystallized layer, in the region $0 < x < \xi(t)$, the nickel concentration distribution is determined as a solution of the diffusion equation

$$\frac{\partial C}{\partial t} = D_b \frac{\partial^2 C}{\partial x^2}, \quad 0 < x < \xi(t), \quad t > 0, \quad (1)$$

where D_b is the coefficient of grain-boundary diffusion of nickel in the recrystallized region.

Since the molybdenum surface is coated with a thin nickel film, the diffusion of nickel impurities proceeds from the surface on which the nickel concentration is a constant:

$$C(x, 0) = C_S, \quad (2)$$

where C_S is the nickel concentration on the surface of the molybdenum specimen.

Since the solubility of nickel in molybdenum is very low, it can be assumed that there is practically no nickel ahead of the moving recrystallization front. This implies that the nickel concentration at the moving boundary of the recrystallization front at $x = \xi(t)$ is equal to zero:

$$C(\xi(t), t) = 0. \quad (3)$$

The nickel diffusion flux through the recrystallization front is proportional to the velocity of motion of the front:

$$D_b \left. \frac{\partial C}{\partial x} \right|_{x=\xi(t)} = -\gamma \frac{d\xi}{dt}. \quad (4)$$

Here $\gamma = \gamma(d, T)$ is a coefficient of proportionality determined by the structure factors, in particular, by the average size of recrystallized grains, d , and by the annealing temperature.

Thus, the mathematical formulation of the suppositions made here is reduced to the diffusion equation (1) and to the boundary conditions on the surface, Eq. (2), and on the moving boundary, Eqs. (3) and (4).

The mathematical model of the recrystallization process, described by equations (1)–(4), represents a boundary value problem with a moving boundary whose law of motion is to be determined. This is the classical Stephen problem [9, 10]. The solution of the problem (1)–(4) is well known:

$$C(x, t) = C_S \left\{ 1 - \frac{\operatorname{erf}(x / 2\sqrt{D_b t})}{\operatorname{erf}(\beta)} \right\}, \quad (5)$$

$$\xi(t) = 2\beta\sqrt{D_b t}, \quad (6)$$

$$\beta \operatorname{erf}(\beta) e^{\beta^2} = \frac{C_S}{\gamma\sqrt{\pi}}, \quad (7)$$

where $\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2} dy$ is the error integral.

Expression (5) describes the distribution of the nickel impurity concentration in the recrystallized region of the molybdenum specimen. Expression (6) represents the law of motion of the recrystallization front, where the parameter β is