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Viscous grain-boundary sliding and grain rotation accommodated by grain-boundary diffusion

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Abstract

When the sliding of a viscous grain boundary is accommodated by grain-boundary diffusion, we evaluate the sliding rate and the stress distribution on the boundary, by employing the energy-balance method developed by Mori et al. [Mori T, Nakasone Y, Taya M, Wakashima K. Phil Mag Lett 1997;75:359 and Mori T, Koda M, Monzen R, Mura T. Acta Metall 1983;31:275]. The phenomena analyzed are the sliding of non-planar grain boundaries, the sliding of boundaries containing particles and the rotation of polygonal grains in two dimensions. For given grain-boundary configurations or grain shapes, we obtain respective analytical expressions for the sliding and rotation rates in a steady state, as a function of the viscosity for the boundary sliding. The obtained sliding and rotation rates are different from the existing ones. In particular, the sliding rates of non-planar grain boundaries have different expressions from the classical predictions by Raj and Ashby [Raj R, Ashby MF. Metall Trans 1971;2:1113]. The sliding/rotation rate and the normal stress on the grain boundary decrease with an increase in the boundary viscosity. As the boundary viscosity becomes sufficiently large, the deformation rate is dominated by viscous grain-boundary sliding, and the contribution of grain-boundary diffusion becomes negligible.
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1. Introduction

When a polycrystal is stressed at high temperatures, diffusional creep may occur through the cooperation of diffusion and grain-boundary sliding. The stress-directed diffusion, either in grains [1,2] or along grain boundaries [3,4], induces a shape change of the grains. Meanwhile, the grain overlap and separation that would have accompanied the shape change is accommodated by grain-boundary sliding to maintain microstructural coherency. Thus, both diffusion and grain-boundary sliding contribute to the macroscopic deformation of the polycrystal in diffusional creep, and their contributions can be separately evaluated [5,6].

To estimate the rate of diffusional creep, most studies [7–9] assumed that the shear stress against grain-boundary sliding is fully relaxed in a steady state, and that sliding can occur at any rate. However, this is not correct. Even an atomically flat grain boundary must be viscous in the same way that a liquid is viscous. The sliding resistance of the viscous grain boundary generally increases with the sliding rate. Hence, the rate of diffusional creep should correspondingly decrease with increasing grain-boundary viscosity. Lakki et al. [10] and Pezzotti et al. [11] measured the grain-boundary viscosity from the experiments of internal friction for ZrO_2 and SiO_2-glass, respectively. The measured boundary viscosity ranges between 10^7 and 10^{11} Pa s at 1000–1400 °C, and for

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ZrO_2 the value was found to be sufficiently large to control the rate of diffusional creep [12].

Raj and Ashby [13] considered that the viscous deformation of a polycrystal is a result of the sliding of non-planar grain boundaries accommodated by diffusion. They obtained an analytical solution for the sliding rate of a non-planar grain boundary the configuration of which is described by a Fourier series. According to their analysis, the apparent grain-boundary viscosity depends on the diffusivity and on the configuration of the grain boundary. Later, Schneibel and Hazzledine [14] obtained more accurate solutions for the sliding rates of the irregular grain boundaries consisting of discrete straight segments. Those sliding rates, however, were also obtained under the assumption of zero viscosity for a flat grain boundary.

The effect of viscous grain-boundary sliding on the overall strain rate was first formulated by Mori et al. [15]. By utilizing the energy-balance method, they analyzed the contributions to energy dissipation by both diffusion and viscous grain-boundary sliding, and predicted the overall strain rate. Despite its simplicity, the method gives an exact solution to the diffusional creep problem in a steady state. Using this method, we recently analyzed the diffusional deformation of hexagonal microstructures with viscous grain boundaries [12] and found, in the limit of zero boundary viscosity, the same result as that of Spingarn and Nix [9].

In the present study, we extend this approach to a number of related problems in two dimensions. We obtain analytical solutions for the sliding rates of grain boundaries corrugated due to either nanostructure or precipitates, when the sliding occurs on the viscous grain boundary and is accommodated by grain-boundary diffusion. We also consider grain rotation, which, as shown by Moldovan et al. [16], can be treated in the same spirit as grain-boundary sliding.

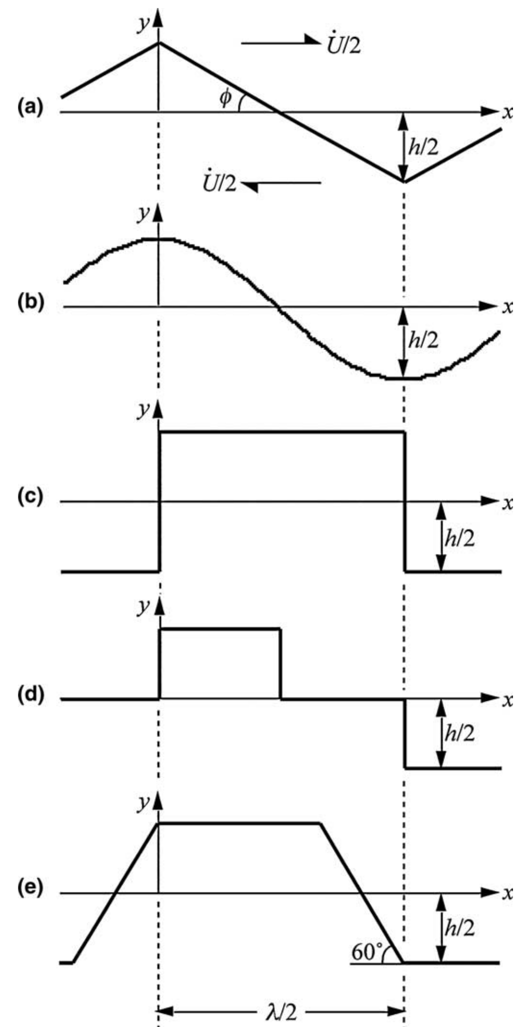

Fig. 1. Various non-planar grain boundaries: (a) saw-toothed, (b) sinusoidal, (c) single-stepped, (d) double-stepped, and (e) hexagonal boundaries.

2. Grain-boundary sliding

2.1. Saw-toothed boundary

We first analyze the sliding rate and the stress distribution of the various non-planar grain boundaries shown in Fig. 1. Analytical solutions are obtained in a steady state for respective two-dimensional boundaries and compared with each other. The detailed procedure for solving the problem of the saw-toothed boundary in Fig. 1(a) is described below, because the boundary has the simplest configuration among them shown in Fig. 1.

Consider a saw-toothed boundary of a height h and a period λ. Let the applied shear stress τ cause a relative displacement rate $\dot{U}$ between the two adjoining grains in a steady state. Then, the relative velocities, v_n and v_s, on the grain-boundary facet in tension, become

$$v_n = \dot{U}\sin\phi \quad \text{and} \quad v_s = \dot{U}\cos\phi, \tag{1}$$

where ϕ is the inclination of the boundary to the sliding direction, and the subscripts n and s denote the normal and tangential components, respectively. When lattice diffusion is ignored, the normal component of the relative velocity v_n is accommodated by grain-boundary diffusion, and the tangential component v_s by viscous grain-boundary sliding.

For grain-boundary diffusion, the volume-conservation of the diffused matter demands $v_n = -\Omega\, \mathrm{d}J/\mathrm{d}s$, where Ω is the atomic volume, s is the distance along the grain boundary from the center of the boundary facet, and J is the flux of matter, namely the number of atoms per unit time per unit thickness in the direction normal to the plane of the figure. If the thickness of the grain boundary is δ, then J is related to the velocity

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