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Stimulation of capillarity-driven grain boundary migration during sliding

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Abstract Zinc bicrystals with originally flat $\langle 10\bar{1}0\rangle$ 89° symmetric tilt boundary tilted at ~45° to the tensile direction were strained at high temperature. The operation of crystallographic slip in both grains was suppressed by orientation of basal planes parallel and perpendicular to the tensile axis. The boundary migrated under the action of curvature driving force making its inclination angle close to 70° with respect to the lateral free surface. In the case of annealing with no load applied, a small boundary migration was observed at the edges of the sample. Initiation of grain-boundary sliding significantly increases the amount of boundary migration. It has been established that sliding can increase the reduced boundary mobility by more than an order of magnitude.

Introduction

Grain-boundary sliding (GBS) is a major mode of deformation in superplasticity, high-temperature creep and high-temperature cyclic deformation [1–3]. In polycrystalline materials, GBS is always associated with grain boundary migration. In bicrystals with coincidence and near-coincidence boundaries, GBS and boundary migration operate in a coupled manner [4–6]. In this case, the elementary act of GBS and boundary migration is the motion of glissile grain boundary dislocation associated with grain boundary step. The migration of general or random boundaries in bicrystals is not always found to accompany GBS and can be induced by different factors. Often the boundary migration is observed only for the boundary portions adjacent to free surfaces for which original orientations are far different from the normal to those surfaces [7–9]. Usually the curvature of those boundary portions has been introduced prior creep. In some cases boundary migration can be driven by strain energy of lattice dislocations associated with the difference in dislocation density in neighboring grains [10]. Thus, it is still unclear whether GBS along general boundaries can promote grain boundary migration or whether they are concomitant and independent processes activated at high-temperature deformation. This report presents results on capillarity-driven boundary migration during sliding in Zn bicrystals, when intragranular basal slip is excluded or suppressed by the geometry of grains.

Experimental

Zinc bicrystal (99.995%) containing a 88.7 ± 0.5° $\langle 10\bar{1}0\rangle$ symmetrical tilt boundary were used (Fig. 1). A bicrystalline plate was grown by the horizontal Bridgman method from molten Zn in a boat consisting of a polished graphite plate and mica flanges in an argon atmosphere. Specimens were cut from a bicrystalline plate at an angle of 45° with respect to the boundary using electrical discharging machine (Fig. 1a). Basal planes were oriented either normally or in parallel to the tensile direction, thus preventing shear stresses along these planes when stress is applied (Fig. 1b). The damaged layer adjacent to the surfaces was removed by chemical polishing on the acid-resistant cloth. Final polishing was performed electrolytically. On the

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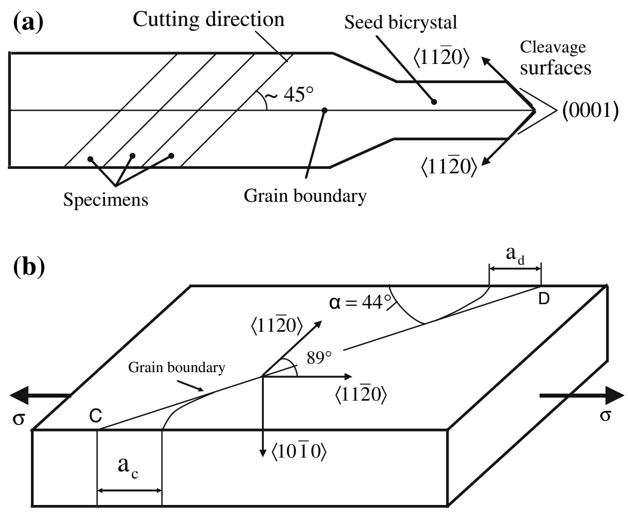

Fig. 1 Orientation of cutting the samples (**a**) and geometry of their deformation (**b**). a_c and a_d distances of migration of branches **C** and **D**, respectively

polished bicrystal surfaces, the families of marker lines parallel to the tensile direction to be used for measuring grain boundary sliding were scratched by a diamond tip using CSM Instruments scratch tester. The values of GBS and migration were determined, respectively, by the shift of marker lines and by spacing between the initial and subsequent boundary traces on the surface. Bicrystals were tensile strained at a constant load at 663 K (0.96 T_{melt}) during 5 min. They have been tested only once to avoid effects associated with different thermal expansion coefficients at asymmetrical portions of the boundary. Tests were performed in the range of tensile stress of 8×10^{-4}–8×10^{-1} MPa which corresponded to the range of shear stress along the boundary 4×10^{-4}–4×10^{-1} MPa. For comparison, bicrystals were annealed with no shear applied along the boundary by putting them on the horizontal support surface. One of these bicrystals was annealed for 100 h and test was interrupted for surface observations.

Results

Optical micrographs of bicrystals subjected to annealing and creep test are shown in Figs. 2 and 3. Testing conditions and parameters of boundary processes are presented in Table 1. The annealing of bicrystals with no load applied (Fig. 2) shows a weak migration at the boundary ends after the annealing during 5 min. No grain boundary sliding can be observed (Fig. 2b). The annealing of bicrystals during 100 h results in significant amount of boundary migration (Fig. 2c). In contrast, the short-term deformation of bicrystals in the range of stresses 8×10^{-4}–8×10^{-1} MPa results in a marked boundary migration. Loading of the specimen by its dead weight corresponding to $\sigma = 8 \times 10^{-4}$ MPa increases the amount of boundary migration in comparison with the specimen treated by annealing during the same period of time (Fig. 3). Small amount of grain-boundary sliding is detected in this case. Testing of bicrystals at higher stresses ($\sigma = 0.4$ and 0.8 MPa) results in a significantly larger amount of boundary migration and sliding (Fig. 3, Table 1). It is seen that at short period of annealing and low stress creep test there is a significant differences in the amount of boundary migration for different boundary branches. With increasing time or at high stresses this difference becomes much smaller. For the bicrystal annealed during 100 h with multiple interruptions for the surface observations the intense basal slip near the edges of the boundary is observed (Fig. 2c). Weak slip lines can be observed in some bicrystals tested once during 5 min.

Annealing of specimens on the horizontal support surface results in higher boundary migration at one edge of bicrystal and less at the other (Fig. 2a). Also, there is a difference in the amount of boundary migration for different boundary branches when bicrystal tested under its own weight. The velocity of migration of branch **D** is higher than that of branch **C**. After deformation at higher stresses, it is seen that the velocity of migration of branch **D** becomes smaller in comparison with branch **C.** The difference between velocities of different boundary branches decreases.

Discussion

Testing of bicrystals in the absence of intragranular slip demonstrates that GBS can significantly increase the velocity of boundary migration driven by its capillarity. It is obvious that the appearance of weak basal slip lines after short term testing is the consequence of the difference in thermal expansion coefficients at asymmetric portions of the boundary during cooling. Multiple annealing of one of the specimens (Specimen B5, Table 1) for the long time periods results in intense slip near boundary edges (Fig. 2 c). It is important that this slip does not affect boundary behavior during one time test. Depending on the boundary branch, the amount of migration can be different (Table 1). Annealing with no load during short time as well as straining under own weight of specimen result in a slower migration of the branch **C** in comparison with the branch **D**. At higher loads or long period of annealing the difference between velocities of migration decreases. Such relationship between the velocity of boundary migration and crystallography of the specimen cannot be explained easily. It seems that this can be a result of the difference in dislocation density and/or the lateral surface quality.

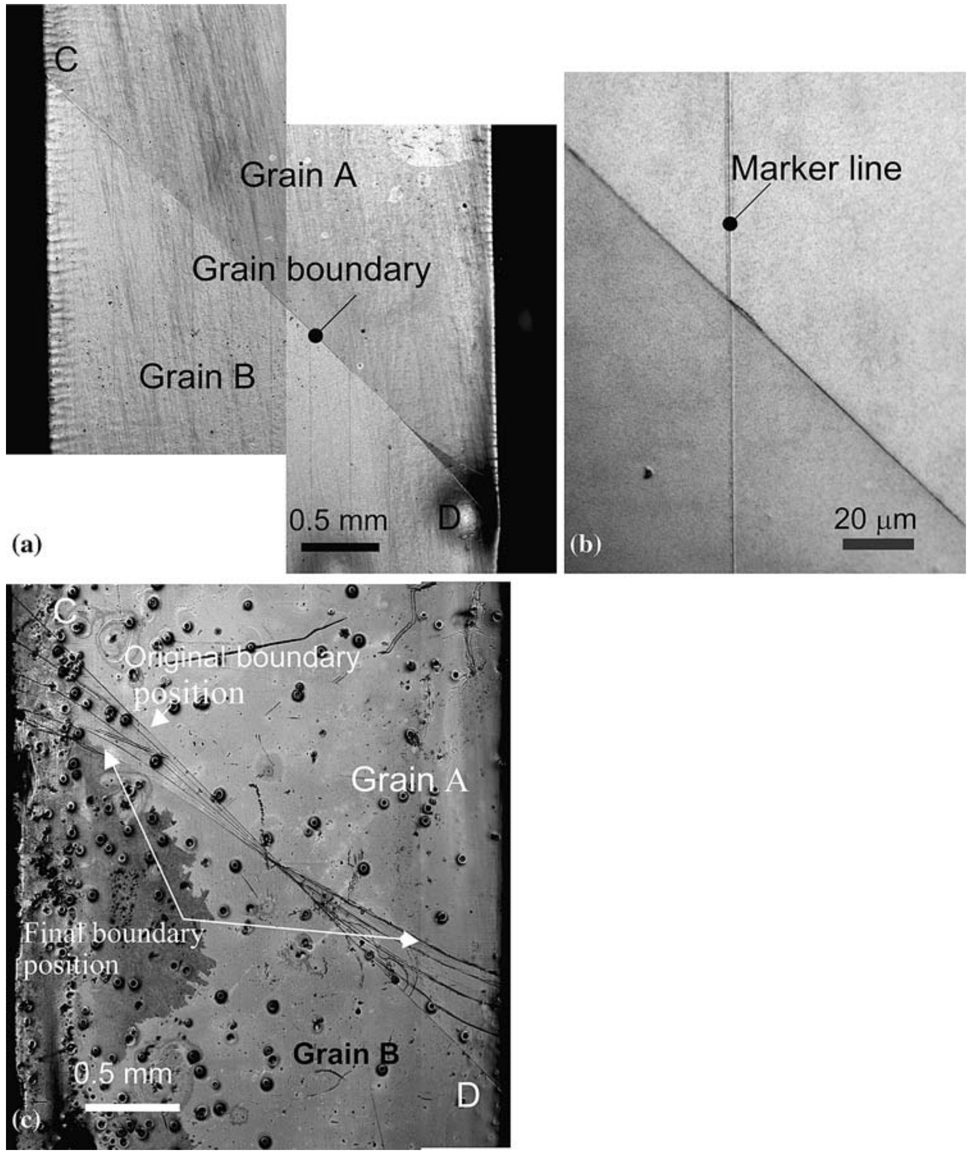

Fig. 2 Boundaries in bicrystals after stress-free annealing during 5 min (**a**, **b**) and 100 h (**c**)

A grain boundary moves with velocity v in response to the net pressure or driving force p on the boundary. It is generally assumed that the velocity v of migrating boundary is directly proportional to the driving force p and boundary mobility m which is the constant of proportionality as shown by equation:

$$v = m \cdot p \qquad (1)$$

The direction of v is normal to the boundary toward to the center of curvature. The driving force p is given by

$$p_c = \gamma_b \cdot \mathrm{k} = \frac{\gamma_b}{R} \qquad (2)$$

where γ_b is the surface tension of the grain boundary, k—the curvature, and R—the radius of curvature, the direction of v is normal to the boundary towards to the center of curvature. The motion of boundaries in bicrystals is provided by non-constant driving force. This case corresponds to the well-known reversed-capillary technique designed for measuring the grain boundary motion by applying the capillarity as the driving force for grain boundary migration [11–15]. The curvature of boundary in this case is inversely proportional to the distance a from the vertex of α in Fig. 1b. The mobility of the boundary can be determined from the distance of migration a at the lateral surface and the annealing time t according to the relationship:

$$a^2 = 2 \cdot A \cdot f(\alpha) \cdot t \qquad (3)$$

where $A = m \cdot \gamma_b$ is the reduced boundary mobility, $f(\alpha)$ is the geometric factor. Due to not exactly known value of grain boundary surface tension, γ_b, and the unknown influence of GBS on surface tension of the boundary only the reduced mobility can be obtained for the curved boundary subjected to GBS. The geometric factor reflects

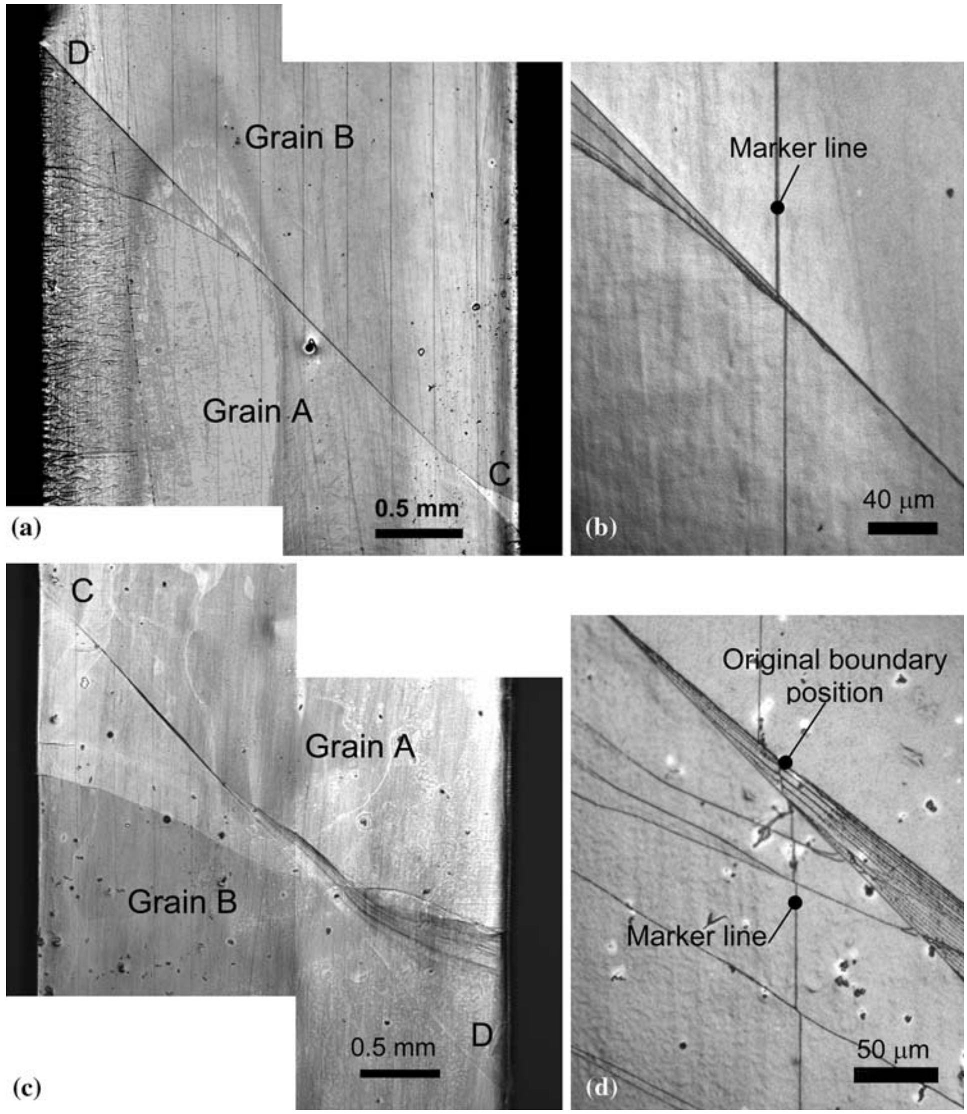

Fig. 3 Behavior of boundaries subjected to different applied stresses. Creep of bicrystals under own weight (**a**, **b**) and under tensile stress of 0.8 MPa (**c**, **d**) during 5 min

Table 1 Testing conditions and parameters of boundary migration

Specimen, No	σ, MPa	Time, min	a_c, mm	a_d, mm	Reduced mobility, branch **C**, m^2/s	Reduced mobility, branch **D**, m^2/s
B3	0	5	0.06	0.30	4.3×10^{-11}	1.1×10^{-9}
B5	0	32	0.22	0.26	9.0×10^{-11}	1.3×10^{-10}
B5	0	6000	0.61	0.58	3.7×10^{-12}	3.3×10^{-12}
B2	8×10^{-4}	5	0.18	0.75	3.9×10^{-10}	6.7×10^{-9}
B4	0.4	5	0.96	0.90	1.1×10^{-8}	9.6×10^{-9}
B1	0.8	5	1.29	1.03	2.0×10^{-8}	1.3×10^{-8}

the shape of the migrating boundary. The assumption of the circular arc shape of the boundary results in the expression $f(\alpha) = \frac{1}{\sin\alpha}(1 - \cos(\vartheta - \alpha))$ [15], which provides the value of $f = 0.14$ for the angles $\alpha = 44°$ and $\vartheta = 69°$ (where ϑ is the angle formed by the grain boundary and the lateral free surface). Under the assumption of shape invariance it is possible to determine the effect of GBS on the reduced boundary mobility. The effect of GBS on the reduced mobility can be estimated in the case of migration of branch **D**. For this branch the increase in the reduced boundary mobility is much closer to the increase in the amount of GBS than that for the branch **C** (Fig. 3, Table 1). For the branch **D** GBS enhances the reduced boundary mobility by approximately an order of magnitude whereas for the other branch the increase in the reduced mobility exceeds two orders of magnitude. Following the literature, the reduced mobility of the curved 86° $\langle 10\bar{1}0\rangle$ tilt boundary at 673 K was measured to be $A_{\mathrm{Zn}}^{673\mathrm{K}} = 3.2 \cdot 10^{-8}\,\mathrm{m}^2/\mathrm{s}$ [16]. The discrepancy between literature and our results can be explained by the differences in testing temperature, material purity, and dislocation density. Remarkably, the reduced mobility of the specimen annealed for 100 h significantly decreases with time of annealing. Because tests have been interrupted many times for surface observations it is reasonable to suppose that this is the effect of the increased dislocation density. The results are in a good agreement with the results of previous investigations [17, 18] showing that lattice dislocations reduce boundary mobility. The investigated 89° $\langle 10\bar{1}0\rangle$ tilt boundary cannot be considered as a special despite of its location in the vicinity of coincidence misorientation of 86° $\langle 10\bar{1}0\rangle$ $\sum = 15$. The sliding along this boundary is not accompanied by regular boundary migration. Namely, coupling of GBS and boundary migration with a fixed ratio between these processes is one of the important criteria of boundary specialty [19]. Existence of coincidence misorientation with sufficiently small value of $\sum$ does not necessarily mean that the boundary is favored, i.e., consists of structural units of one type which cannot be broken down into units from other boundaries [20]. GBS along favored boundaries is provided by the motion grain boundary dislocations, which preserves the atomic structure of the boundary. GBS along non-favored or general boundaries occurs without coupling between boundary sliding and migration. In this case, the boundary continuously changes its atomic structure. It is reasonable to suppose that such behavior facilitates atomic motion across the boundary and, hence, increases boundary mobility. Strong effect of GBS on the reduced boundary mobility may indicate that the boundary breaks away from an impurity cloud. Although drastic change of the reduced mobility in a narrow temperature range is observed only for special boundaries in zinc [21], the increase in the amount of the reduced mobility is comparable to the case of sliding-enhanced migration of general 89° $\langle 10\bar{1}0\rangle$ tilt boundary.

Concluding remarks

Zinc bicrystals with originally flat 89° symmetric tilt boundary tilted at $\sim$45° to the tensile direction have been strained at high temperature. Crystallographic slip in grains is suppressed by special geometry of bicrystals. Grain boundary sliding significantly increases the amount of capillarity-driven boundary migration which tend to turn the boundary normal to the free surfaces. The results are explained by the increase in the reduced boundary mobility during grain boundary sliding. The sliding can increase the reduced mobility by more than an order of magnitude.

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