GRAIN BOUNDARY SLIDING AND HETEROGENEITIES OF STRAIN DURING SUPERPLASTIC DEFORMATION

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TOPICS

1. Sliding behavior of individual grain boundaries in bicrystals.
2. The effect of intragranular slip on grain boundary sliding.
3. Relationship between grain boundary sliding and intragranular slip during superplasticity.
4. Deformation processes on the surface and in the bulk during superplasticity.
5. Peculiarities of strain localization during superplastic flow.
SLIDING AND MIGRATION OF 56°, 51° AND 48° <1010> SYMMETRIC TILT BOUNDARIES IN Zn BICRYSTALS

Geometry of specimens and schematic of slip. Lattice dislocations slip towards the boundary. Double arrows indicate the directions of shear stresses along basal planes and the boundary. \( \sigma \) is the applied stress.

Coincidence boundary  Near-coincidence boundary  General boundary
VARIATIONS OF VALUES OF GRAIN BOUNDARY SLIDING AND MIGRATION ALONG 54°, 51° AND 48° BOUNDARIES

Variation of the amounts of sliding and migration along 56° boundary of bicrystal tested at 553 K and \( \tau = 0.24 \) MPa (a) and along 54°, 51° and 48° boundaries, T=553K and \( \tau = 0.22 \) MPa (b).
GRAIN BOUNDARY SLIDING AND MIGRATION RATES AS FUNCTIONS OF BOUNDARY MISORIENTATION
THE EFFECT OF INTRAGRANULAR SLIP ON GRAIN BOUNDARY SLIDING IN PLASTICALLY INCOMPATIBLE BICRYSTALS WITH GENERAL BOUNDARY

Bicrystals with $48^\circ$ boundary

$\sigma=0.44$ MPa

$\sigma=0.48$ MPa

Sliding as a function of the distance along the boundary.
ATOMISTIC STRUCTURE OF $56^\circ<1010>\Sigma=9$ BOUNDARY CONTAINING GLISSILE DSC-DISLOCATION

MODEL OF $48^\circ$ BOUNDARY CONSISTING OF MIXTURE OF TWO STRUCTURAL UNITS THAT BELONG TO $\Sigma 9$ AND $\Sigma 15$ MISORIENTATIONS
CLASSIFICATION OF GRAIN BOUNDARY SLIDING

Original hypothetical bicrystal; (b) pure GBS provided by GBDs generated from boundary sources; (c) slip induced sliding provided entirely by GBDs generated as a result of interaction of lattice dislocations with boundary; (d) combination of pure sliding and slip induced sliding.
There are two contradictory concepts of structural superplasticity in view of relation between grain boundary sliding and intragranular slip:

According to the first one (see, for example, Kaibyshev, 1992) slip and sliding are closely related to each other during superplastic deformation: facilitation of slip increases the rate of sliding.

Following the other concept (see Nieh, Wadsworth and Sherby, 1996) sliding and slip are independent and concurrent processes of structural superplasticity.


ANISOTROPIC SUPERPLASTICITY IN Zn-1.1%wt.Ai ALLOY

Schematic of sample cutting from the rolled plate of Zn-1.1%Al alloy which allows to create a high fraction of incompatibly oriented grains.

Original pole figure and directions of deformations for different specimens.
SURFACE OBSERVATIONS AFTER SUPERPLASTIC DEFORMATION USING OPTICAL MICROSCOPY AND PROFILOMETRY

Optical micrographs taken from the surface after ~26% strain with initial strain rate of 7.3x10^{-5} s^{-1}.

3-D view of the surface relief after 26% deformation in the optimum region of superplasticity.

Roughness produced by grain boundary sliding
ANISOTROPY OF GRAIN BOUNDARY SLIDING IN Zn-1.1%wt.Al ALLOY DURING SUPERPLASTIC DEFORMATION

Definition of the vertical component, \(v\), of grain boundary sliding

Example showing the procedure used to determine the vertical component \(v\)

Number of boundaries vs sliding value, \(v\), for two specimens tested in different directions. Distribution functions for different orientations are superimposed.
ASSESSMENT OF CONTRIBUTION OF GRAIN BOUNDARY SLIDING TO TOTAL DEFORMATION

According to T.G. Langdon (1972) the contribution of GB sliding can be determined using the following equation:

\[ \varepsilon_{gbs} = \phi n \bar{v} \]  

(1)

where \( \phi \) is a coefficient equal to 1.4 for “annealed” surface, \( n \) - number of grains per unit length, \( \bar{v} \) – average vertical component of grain boundary sliding.

Our observations show that not each grain boundary can undergo grain boundary sliding. Therefore, in our calculations we use slightly modified formula (1):

\[ \varepsilon_{gbs} = \phi \frac{\sum v_i}{L} \]  

(2)

where \( L \) is the distance along which the measurements of \( v \) have been done.

The contribution of grain boundary sliding to total strain:

\[ \gamma = \frac{\varepsilon_{gbs}}{\varepsilon_{tot}} \]  

(3)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L, mm</th>
<th>Number of sliding boundaries (v=0.5±11μm)</th>
<th>( \bar{v_i}, \mu m )</th>
<th>( \gamma % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen I</td>
<td>39</td>
<td>273</td>
<td>3.43</td>
<td>13±2</td>
</tr>
<tr>
<td>Specimen II</td>
<td>39</td>
<td>373</td>
<td>3.48</td>
<td>18±3</td>
</tr>
</tbody>
</table>
 CONTRIBUTIONS OF SLIP INDUCED SLIDING TO TOTAL ELONGATION

Undeformed hexagonal grains (a). Slip induced sliding with (b) and without (c) contribution to total elongation at two-dimensional deformation of the upper grain by shear along slip planes.

\[ \varepsilon_{SIS} = \varepsilon_{TOT} - \varepsilon_{IS} = \frac{l_2 - l_1}{l_0} \]

\[ \gamma_{SIS} = 1 - \gamma_{IS} = 1 - \frac{l_1}{l_2} \]

where \( \gamma_{SIS} \) and \( \gamma_{IS} \) is the contributions of slip induced sliding and intragranular slip to total strain, respectively.
CONTRIBUTION OF SLIP INDUCED SLIDING AS A FUNCTION OF ELONGATION IN THE ABSENCE OF PURE SLIDING

Contribution of slip induced sliding to total elongation as a function of strain for different inclination of slip planes to tensile axis. Thick curve designate average contribution of slip induced sliding.

CONTRIBUTIONS OF PURE SLIDING, INTRAGRANULAR SLIP AND SLIP INDUCED SLIDING TO TOTAL STRAIN

\[ \varepsilon_{\text{tot}} = \varepsilon_{\text{pure}} + [\varepsilon_{\text{IS}} + \varepsilon_{\text{SIS}}] \]

\( \varepsilon_{\text{pure}} \) — strain due to pure sliding, \( \varepsilon_{\text{IS}} \) — strain due intragranular slip and \( \varepsilon_{\text{SIS}} \) — strain due to slip induced sliding.
EVOLUTION OF CRYSTALLOGRAPHIC TEXTURE ON THE SURFACE AND IN THE BULK OF Zn-1.1%Al ALLOY

Fig. 1. Schematic of sample cutting from the rolled plate of Zn-1.1%Al alloy

Intensity of 0002 components of annealed sample vs. thickness position.

Pole figures of Zn-1.1%Al alloy after rolling (a), annealing (b) and 150% strain (c, d). Texture measurements are taken from the surface (c) and mid-layer (d).
Flow stress as a function of initial strain rate for 7475 (a) and 5083 (c) alloys. The effect of strain-rate on strain-rate sensitivity index, m, for 7475 (b) and 5083 (d) alloys.
HETEROGENEITY OF DEFORMATION IN 5083 ALLOY

The microgrid on the surface of sample before straining produced by using nanoscratch tester. The average distance between lines is 5 μm.

Optical micrographs of the 5083 specimens after 20% deformation at initial strain rates of (a) $5.2 \times 10^{-4} \text{ s}^{-1}$ (optimum region of superplasticity) and (b) $\dot{\epsilon} = 5.2 \times 10^{-4} \text{ s}^{-1}$, $\epsilon=0.12$.

Surface profilometry before (a) and after (b) deformation.
HETEROGENEITY OF DEFORMATION IN 7475 ALLOY

Optical micrographs of the 7475 specimens after 20% deformation at initial strain rates of (a) \(1.2 \times 10^{-3} \text{ s}^{-1}\) (optimum region of superplasticity) and (b) \(4.8 \times 10^{-2} \text{ s}^{-1}\) (region III) at 789K. Tensile direction is horizontal.

Surface profilometry after deformation in region II (a) and region III (b).
CONCLUSIONS

• It has been shown for the first time that grain boundary sliding along coincidence and near coincidence boundaries can be more rapid than along non-coincidence or general boundaries.

• Two different atomistic mechanisms of grain boundary sliding are distinguished: motion of glissile DSC dislocations having steps in their cores and motion of non-DSC dislocations without steps. In the first case, the regular boundary migration is observed whereas in the latter case there is no sliding related boundary migration. This fundamental knowledge can be applied for characterization of boundaries (coincidence, near coincidence or non-coincidence) through its sliding behavior.

• The effect of the increase in grain boundary sliding rate in the presence of intragranular slip has been observed at compatible and incompatible conditions of deformation. In each case different mechanisms are responsible for this effect.

• Analysis of deformation of bicrystals shows that at respectively low strain rates two components of grain boundary sliding, dependent and independent on intragranular slip, can coexist at the same boundary.
CONCLUSIONS
(Continuation)

- Deformation of superplastic Zn-1.1% wt. Al in the direction favorable for intragranular slip decreases contribution of sliding to total strain, whereas deformation in the direction unfavorable for slip increases the sliding contribution.

- The proposed concept of slip dependent and slip independent grain boundary sliding allows to explain the observed independent relationship between grain boundary sliding and intragranular slip at respectively low strains. At the same time the concept predicts a complex relationship between grain boundary sliding and intragranular slip at high strains.

- It has been established for the first time that with straining the intensity of crystallographic texture on the surface during superplastic deformations remains stable whereas in the interior of the specimen the intensity decreases significantly.

- Surface observations of superplastically deformed specimens of 5083 and 7475 alloys did not reveal neither cooperative grain boundary sliding directed parallel to the surface nor heterogeneity of strain. A few large steps (~4÷8 mm) attributed to deformation has been found coexisting with a large number of small steps (<0.5 mm). The nature of the large steps needs further investigation.