Materials Science Forum Vols. 357-359 (2001) pp. 393-398
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On the Independent Behavior of Grain Boundary Sliding and Intragranular Slip During Superplasticity

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Keywords: Grain Boundary Sliding, Intragranular Slip, Lattice Dislocations, Superplasticity

ABSTRACT

Operation of grain boundary sliding is examined for conditions of plastic strain incompatibility that is the most frequent case for deformation of polycrystals. Two coexisting components of grain boundary sliding: dependent and independent on intragranular slip are distinguished. Theoretical estimate of a ratio between slip induced sliding and intragranular slip is obtained. It is concluded that at the beginning of deformation intragranular slip and grain boundary sliding behave independently. However, at high strains they can be viewed to some extent as interdependent processes.

Introduction

Usual high-temperature deformation is associated with accumulation of lattice dislocations in grains that often induces processes of dynamic recovery and recrystallization. Structural superplasticity is a specific type of high-temperature deformation accompanied by insignificant accumulation of dislocations thus produces minor changes in microstructure. Such behavior is primarily attributed to the process of grain boundary sliding (GBS) that operates with intragranular (crystallographic) slip and diffusional creep in a favorable combination. Sliding and slip make their maximum contributions to total strain at the optimum and high strain rates respectively. There is a link between these processes. Under deformation with a constant strain rate the accumulation of lattice dislocations in grains is decreased by operation of GBS. Lattice dislocations entered grain boundaries are dissociated into extrinsic grain boundary dislocations (GBDs) that participating in the process of cooperative GBS [1, 2] can be carried out to the specimen surface. This makes possible further development of slip. At the same time giving a significant contribution to overall strain, GBS decreases the contribution of slip. Such complex interconnection between sliding and slip results in appearance of two different concepts of structural superplasticity. According to the first one [3] slip and sliding are interconnected in the optimum superplastic region: facilitation of intragranular slip increases the rate grain boundary sliding. Following the other concept [4] sliding and slip are independent and competing processes. In this paper, results that can support these different concepts are analyzed and relationship between slip and sliding is determined. To elucidate the problem experimental results obtained by different researchers on bicrystals and polycrystalline materials are considered.

Concept of Sliding Operating under Conditions of Incompatibility

Let us consider a hypothetical two-dimensional bicrystal containing a finite boundary with the ends designated as O and C (Fig. 1 (a)). If the applied shear stress is sufficient to initiate GBS but

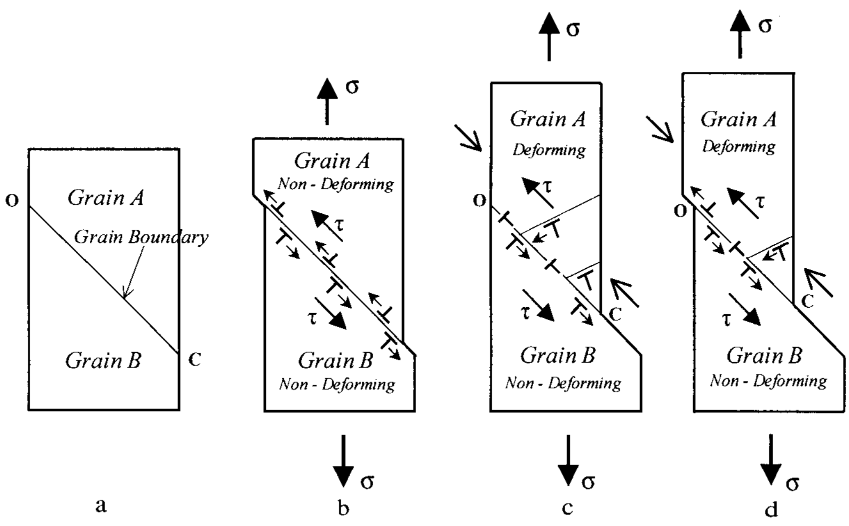

Fig. 1. (a) Original hypothetical bicrystal; (b) pure GBS provided by GBDs generated from boundary sources; (c) slip induced sliding provided entirely by GBDs generated as a result of interaction of lattice dislocations with boundary; (d) combination of pure sliding and slip induced sliding.

not enough to deform grains this is the case of pure sliding (Fig. 1(b)). It is worth noting that Horton et al. [5] used the term of pure sliding when it was accommodated by a small slip. At microscopic scale pure sliding can be considered as the motion of glissile GBDs of opposite signs generated in the boundary plane by numerous grain boundary sources distributed along the whole boundary including points O and C (Fig. 1(b)). When initiation of grain boundary shear or generation of GBDs by grain boundary sources is inhibited, sliding can be produced purely by the difference of deformation between neighboring grains [6]. In the case of incompatible deformation shown in Fig. 1(c) the upper grain A deforms and the lower grain B does not. Only GBDs of one sign are produced as a result of interaction of lattice dislocations with the boundary. If motion of GBDs is governed mainly by applied stresses the amount of sliding increases from zero at point O to some value at point C. Often, sliding is a combination of pure sliding and sliding induced by intragranular deformation (Fig. 1(d)). Assuming that these processes are independent the total amount of sliding is a sum of two kinds of sliding:

$$S = S_{pure} + S_{SIS}, \tag{1}$$

where S is total amount of sliding, S_{pure} is a value of pure sliding and S_{SIS} is a value of slip induced sliding. Due to non-uniform distribution of sliding induced by slip the overall sliding is also non-uniform. However in this case, some amount of sliding is reached at point O and this is a pure sliding whereas sliding at point C is a sum of the amounts of pure sliding and sliding induced by slip. At dislocation level the independence of different types of sliding means the non-interacting and independent operation of two different kinds of GBD sources: lattice dislocations impinged into the boundary and grain boundary sources of GBDs. The interaction between GBDs of different origin results in remaining of glissile GBDs of one sign (Fig. 1(d)).

Published in 'Superplasticity in Advanced Materials', Year: 2001, pp: 393-398
Periodical: Materials Science Forum Vols. 357-359
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Interaction Between Sliding and Slip in Incompatible Bicrystals

In the case of incompatible bicrystals the activation of intragranular slip results in gradual changing of the amount of GBS from one end of the boundary to the other [7]. It is shown that at respectively small intragranular strain (less than 1%), intragranular slip increases the magnitude of sliding more than twice in comparison with the case when intragranular slip is negligible. At the same time, the amount of sliding at point O remains the same [8]. Therefore, according to the concept described in previous section lattice dislocations and/or GBDs appeared as a result of LD-GB interaction obstruct neither the generation of glissile GBDs from boundary sources nor their motion along the boundary. Thus, a combination of two types of sliding obeys an additive (linear) law at respectively small strains. It is important noting that incompatible deformation is the most frequent case in polycrystalline materials.

Relation Between Slip and Sliding under Superplastic Conditions

Experimental Results

The study of anisotropic behavior of Zn-0.4%Al sheet alloy during superplastic flow have shown that straining in the direction favorable for basal slip reduces the strain-rate sensitivity exponent m [9] (Fig. 2). The analogous results have been obtained for fine-grained cadmium and magnesium alloy [10, 11]. The value of m correlates with contribution of sliding to overall strain [12, 13]. Therefore, these results may indicate on concurrent and independent character of sliding and slip during superplastic deformation: the greater contribution of GBS to total strain, the lower contribution of slip and vice versa.

The notion of the two independent processes contradicts to the results obtained by Matsuki et al. [14, 15] on Al-10.8%Zn-0.85%Mg-0.29%Zr and Zn-0.92%Cu-0.60%Mn alloys. For these alloys the stress exponents for GBS and slip were measured separately. Fig. 3 demonstrates that the stress exponents for sliding and slip are similar in the optimum region of superplasticity (n_{GBS}=2.0 and n_{IS}=2.2 for both alloys) and dissimilar in the region of the higher strain rates (n_{GBS}=2.0 and n_{IS}=4.9 for aluminum alloy, n_{GBS}=2.0 and n_{IS}=4.2 for zinc alloy). These results show that in the optimum region of superplasticity GBS and slip are interdependent processes whereas in the region of high strain rates they can be considered as independent.

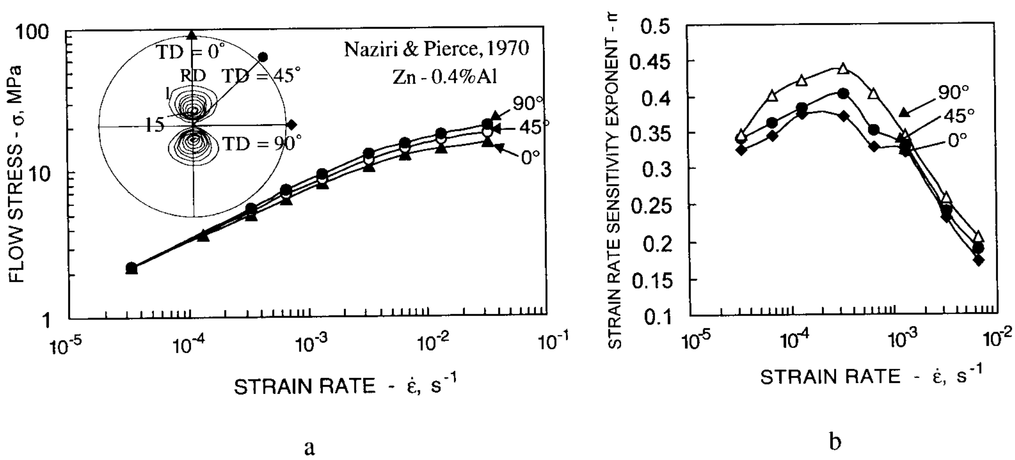

Fig. 2. Anisotropic superplasticity in Zn-0.4%Al [9]. (a) Flow stress-strain rate relations for specimens cut at 0, 45 and 90° to the rolling direction and (b) variation of m with strain-rate and with direction of straining.

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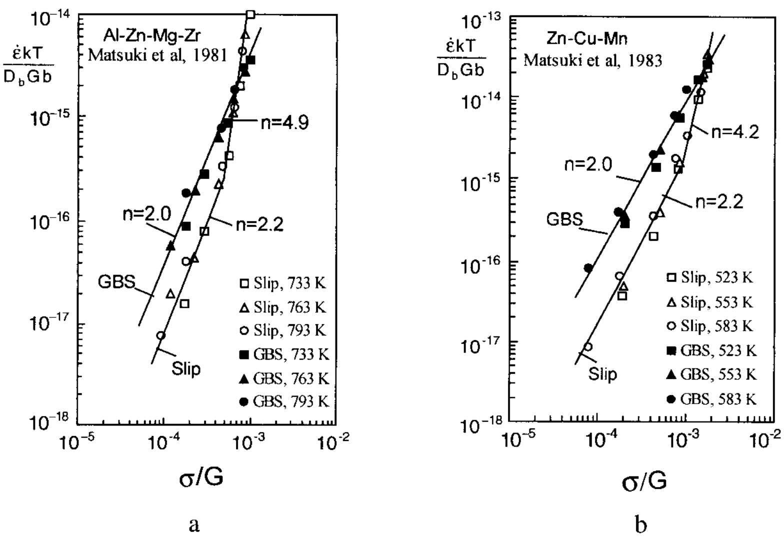

Fig. 3. Relation between individual strain rates of grain boundary sliding and intragranular slip and flow stress in dimensionless plots: $D_b=D_o\exp(-Q/RT)$ for Al (a) and Zn (b) alloys [14, 15].

Theoretical Consideration

Consideration of sliding in a hypothetical bicrystal shows that there is a component of sliding dependent on intragranular slip called slip induced sliding. Contribution of slip induced sliding to total strain without operation of pure GBS can be assessed assuming that accommodation processes are rapid in triple boundary junctions and glissile GBDs disappear easily. Fig. 4 (a) illustrates two hexagonal grains having a common boundary. The upper grain is subjected to uniform elongation, the other is non-deforming (Fig. 4 (b, c)). The upper grain is allowed to slide when it deforms. In general, there are two different cases of sliding induced by slip. In the first case illustrated in Fig. 4 (b), slip induced sliding accommodates grain deformation without contribution to total strain and all strain is provided by intragranular deformation. It happens when there is no applied shear stress along boundary or its value is small. Under internal stresses grain boundary dislocations move in the opposite directions and appear in both triple boundary junctions creating facets. In the second case, slip induced sliding makes a direct contribution to strain and simultaneously accommodates intragranular deformation (Fig. 4 (c)). In this case, applied shear stress is sufficient to effect on slip induced sliding pushing GBDs in one direction and creating facet in the triple junction. Apparently, this type of sliding occurs in the optimal superplastic region being a part of cooperative GBS. The difference between strains in two different cases gives the strain produced purely by slip induced sliding:

$$\varepsilon_{SIS} = \varepsilon_{TOT} - \varepsilon_{IS} = \frac{l_2 - l_1}{l_0}, \quad (2)$$

Here l_0 - length between marker points in grains before deformation, l_1, l_2 - distances between the same points in two different cases of deformation.

Dividing equation (2) on ε_{TOT} we obtain the contribution of slip induced sliding to overall strain:

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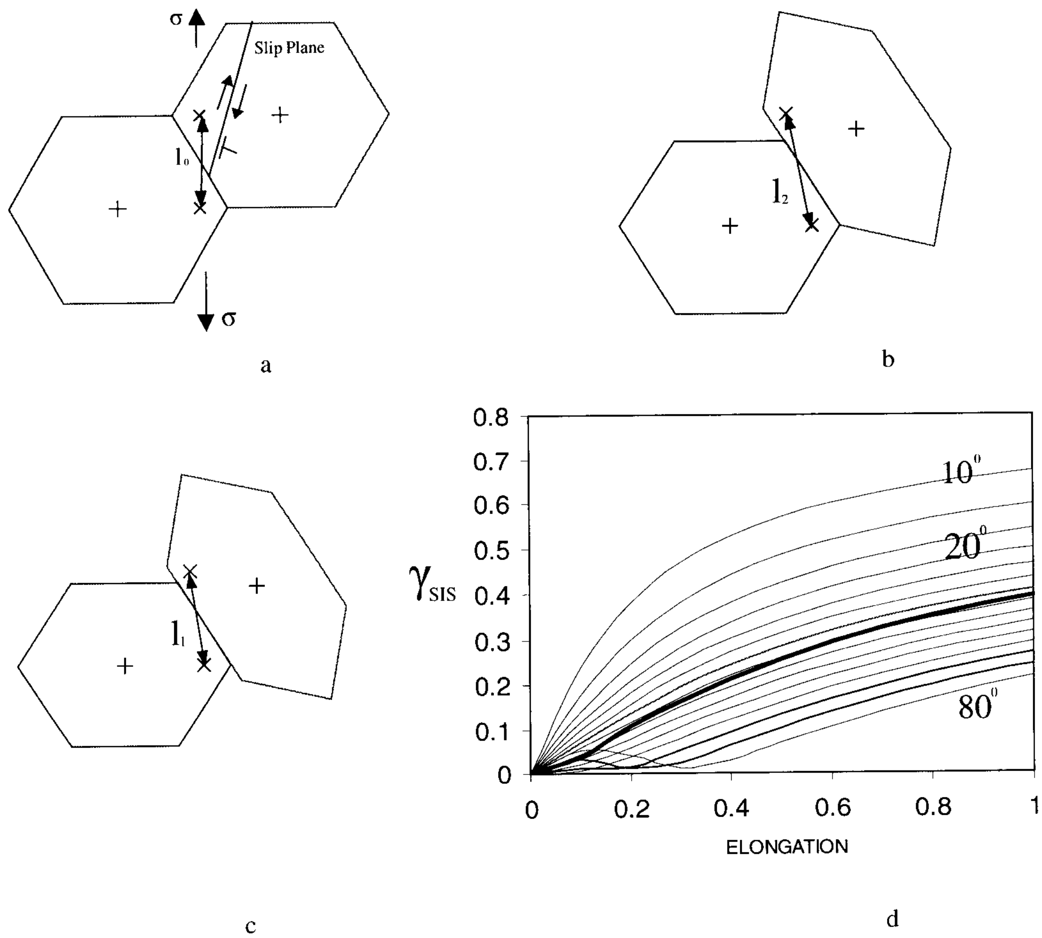

Fig. 4. Contribution of slip induced sliding to total elongation. Initial hexagonal grains (a). Slip induced sliding (b) with and (c) without contribution to total elongation at two-dimensional deformation of the upper grain by shear along slip planes. Contribution of slip induced sliding to total elongation as a function of strain for different inclination of slip planes to tensile axis (d). Thick curve designate average contribution of slip induced sliding.

$$\gamma_{SIS} = 1 - \gamma_{IS} = 1 - \frac{l_1}{l_2}, \tag{3}$$

where γ_{SIS} and γ_{IS} is the contributions of slip induced sliding and intragranular slip to total strain, respectively.

Fig. 4 (d) represents the dependencies of γ_{SIS} on total strain at different angles between direction of tension and slip planes. With increasing strain it increases from zero up to significant values. Depending on inclination of slip planes to deformation axis γ_{SIS} can vary in a wide range.

From comparison of theory and experimental results obtained on bicrystals, it follows that pure and slip induced sliding obey an additive law. In other words, these two types of sliding can operate

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as independent and concurrent processes at the same boundary. In polycrystalline materials pure sliding is a rare event. Nevertheless, we use the term "pure" to designate the component of sliding that is produced from grain boundary dislocation sources. This component is independent on slip. Slip induced sliding is directly connected with intragranular deformation. The latter makes a contribution to overall strain if motion of GBDs is governed by applied stresses. Hence, GBS along the same boundary can be separated into two components: dependent and independent on slip, each of them can make a contribution to total strain. We denote processes which are interdependent by including the appropriate strains in square brackets and processes which are independent, including the resultants of sequential pairs, just by addition signs. Thus, the total strain ε_{TOT} can be expressed in terms of strains due to pure GBS ε_{GBS} , intragranular slip ε_{IS} and slip induced sliding ε_{SIS} :

$$\varepsilon_{TOT} = \varepsilon_{GBS} + [\varepsilon_{IS} + \varepsilon_{SIS}] \qquad (4)$$

With changing strain and strain rate, the contributions of pure GBS, intragranular slip and slip induced sliding are varied. The increase of intragranular strain always results in decrease of total sliding composed of pure and slip induced sliding and vice versa. It means that competing character of slip and sliding does not mean that these processes are entirely independent. Fig. 4 (d) shows that with straining the contribution of slip induced sliding can exceed the contribution of intragranular slip. However, these results obtained from simplistic model. All experimental results on contribution of intragranular slip to total strain have been obtained at respectively small strains. Therefore, the exact relationship between slip and sliding at high strains is still unclear.

SUMMARY

Grain boundary sliding along the same boundary can be separated into two components that are dependent and independent on intragranular slip. Each of them can make own contribution to total strain during superplastic deformation in the optimum superplastic region. Theoretical assessment of ratio between intragranular slip and slip induced sliding shows that straining can increase the contribution of slip induced sliding to total strain from zero to more than half of that. Therefore, at small strains intragranular slip and grain boundary sliding can be considered as independent processes. At high strains the relationship between these processes is complex due to coexistence of slip dependent and slip independent components of sliding.

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