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Dissociation of lattice dislocations in coincidence boundaries

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The possible dislocation reactions in coincidence boundaries with $\Sigma \leqq 19$ in f c c and b c c crystals were systematically analysed in consideration of energetics according to the coincidence site lattice theory. The elastic energy reduction during dissociation of lattice dislocations suggests to be more easily absorbed into coincidence boundaries with large Σ-values. Transmission electron microscopy showed a large difference in the absorption rate between coincidence and random boundaries in crept specimens. The absorption of the lattice dislocation depends strongly on its Burger's vector even in the same grain boundary. Experimental results showed that most of EGBDs observed in the coincidence boundaries were of the Burger's vectors which give rise to smaller energy reduction due to the dissociation reaction.

1. Introduction

Interaction of lattice dislocations with grain boundaries is one of the basic processes controlling various properties of polycrystalline materials. In plastic deformation, grain boundaries interrupt the motion of lattice dislocations on slip planes and give rise to grain size dependence of flow stress. During recrystallization migrating grain boundaries absorb the high density of the lattice dislocations to remove elastic strain in crystals. In the case of grain boundary sliding it has been accepted that the absorption of lattice dislocations into the grain boundary is the important elementary process [1–5]. Most recently the present authors have experimentally obtained direct evidence for the importance of the absorption in sliding [6].

Previous transmission electron microscopy (TEM) studies have suggested the following two possibilities of the absorption process of lattice dislocations at grain boundaries; the lattice dislocations can either spread their cores in the grain boundary [7–9] or dissociate into other dislocations [4, 5]. These models for the absorption mechanism are well reviewed by Gleiter [10]. The idea of the dissociation of a lattice dislocation into two or more partials in a grain boundary was first put forward by Crussard and Friedel in 1956 [11]. Such a dissociation of a lattice dislocation into partials was observed by transmission electron microscopy of a $\Sigma 29$ boundary in a creep tested austenite stainless steel bicrystal [12]. Recently the dissociation of lattice dislocations into grain boundary dislocations (GBDs) with DSC primitive lattice vectors has been discussed [4, 5, 13] on the basis of theoretical consideration of grain boundary structure [14, 15]. (The DSC lattice is composed of all relative translations between two grains that leave the structure of the periodic pattern unchanged [15].) Darby *et al.* [13] have shown that the absorption process can be formally described in terms of the dissociation into either perfect or partial GBDs for their experimental results on GBDs. Earlier TEM studies have revealed the details of the dissociation in aluminium [16] and austenitic stainless steel [17] boundaries. The energetics based on the dissociation model has suggested that the driving force of the absorption does depend on Σ-value (the reciprocal density of common lattice points) [4]

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and the Burger's vector of lattice dislocation [18]. However, there has not been much direct experimental evidence for those dependences. The present investigation has been made to systematically analyse the dissociation reactions in the grain boundary of f c c and b c c crystals according to the coincidence site lattice theory, and to examine the validity of the present analysis by transmission electron microscope observations of the interactions between the lattice dislocations and the grain boundary.

2. Energetics of dissociation reactions

Pond and Smith [4] have pointed out that the elastic energy reduction by the absorption reaction increases in general with the increasing Σ-value, but that not all absorption reactions lead to a reduction in elastic energy [18]. In this section, the Σ-dependence and the anisotropy of the elastic energy reduction were systematically analysed for discussion in the following section.

As one of the elementary processes of the absorption of lattice dislocations into the grain boundary, the dissociation process into the grain boundary dislocations having DSC primitive lattice vectors is examined. The possible dissociation reactions have been analysed for coincidence boundaries mainly with $\Sigma \leqq 19$ in f c c and b c c crystals, because the special properties of the coincidence boundary generally appear to be more significant. However, a Σ25 f c c coincidence boundary was also analysed to explain the TEM observation. The Burger's vectors of the typical lattice dislocations $a/2\langle 1\,1\,0\rangle$ and $a/2\langle 1\,1\,1\rangle$ were chosen for f c c and b c c respectively, and the GBDs calculated by Ishida and McLean [19, 20] were used.

Fig. 1 shows Σ-value dependence of the average number of GBDs into which one lattice dislocation dissociates in specific coincidence boundaries. In both f c c and b c c, the average number tends to increase with the Σ-value. The increase is the natural consequence of the magnitude of the Burger's vector of GBD which decreases with the increasing Σ-value [19, 20].

According to the recent theory of grain boundary structure, the grain boundary is considered to be several atoms wide, and conservation of the Burger's vector in the grain boundary is similarly considered as in the grain interior. The elastic energy change (ΔE) by the dissociation reaction can be estimated on a $\mathbf{b}^2$ criterion. The effect of shear modulus is discussed later. $-\Delta E/E$ (%) is the percentage of the elastic energy reduction due to the dissociation reaction of a lattice dislocation.

The absorption process of a lattice dislocation

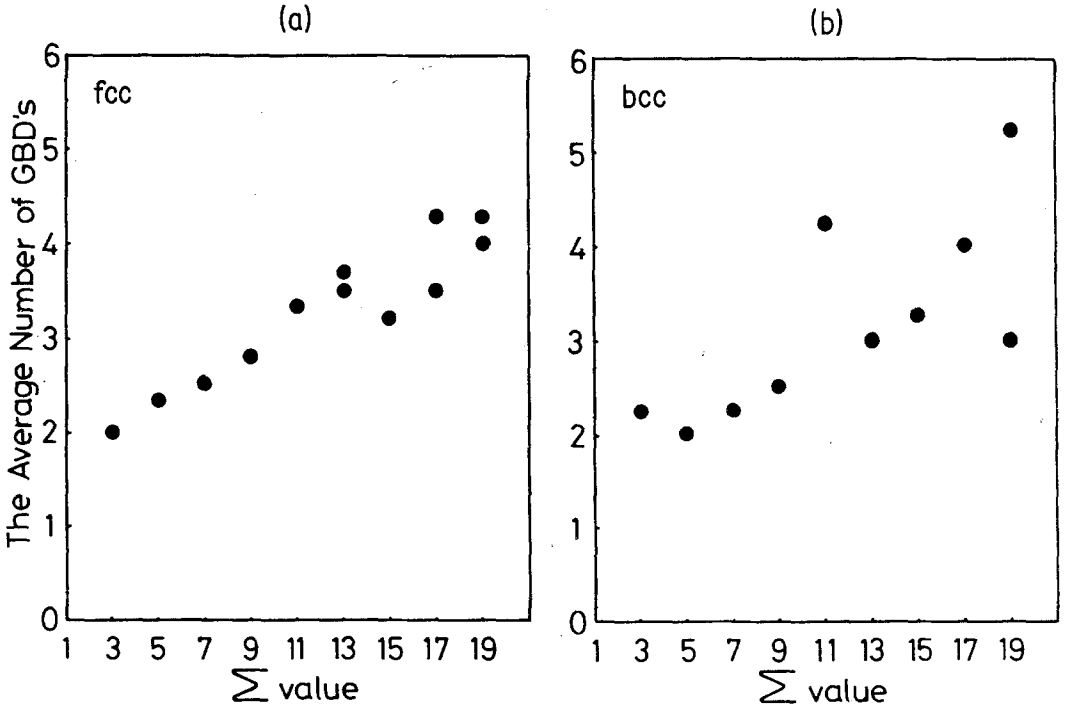


Figure 1 Σ dependence of the average number of GBDs.

is completed only when the dissociated products are incorporated into pre-existing structural dislocation arrays and all the GBDs restore the equal spacing for optimum cancelling of the long range elastic fields [4]. Therefore, the rate of the absorption process itself must be controlled by that of the rearrangement of the GBDs. The rearrangement generally involves climb motion because of the component of the Burger's vectors perpendicular to the boundary plane. The rate of the absorption is controlled mainly by the geometrical relationship between its Burger's vector and the grain boundary plane as well as the grain boundary diffusion. The elastic energy reduction ($-\Delta E/E$) of the reactions is assumed to be the major driving force of the dissociation process. Figs. 2a and b show the relationship between Σ-value and $-\Delta E/E$ for fcc and bcc crystals, respectively. In these figures the solid circle indicates the average value for each coincidence boundary. In both fcc and bcc crystals, the average value of $-\Delta E/E$ appears to increase as the Σ-value increases. Pond and Smith [4, 18] have suggested a similar tendency. The present result leads to the suggestion that a lattice dislocation will be absorbed more easily by a grain boundary as the Σ-value increases. A random high angle boundary would absorb a lattice dislocation quite easily, because the random boundary may be regarded as one with an extremely large Σ-value.

It should be noted that the driving force, $-\Delta E/E$, for the dissociation of lattice dislocations with different Burger's vectors is quite different even in the same boundary. For example, Table I shows the dissociation reactions and the energy reduction for the Σ13a fcc boundary. Table I demonstrates that the $-\Delta E/E$ is 31% for a lattice dislocation with $\mathbf{b}_{L1}$, but that it is 62% for a $\mathbf{b}_{L3}$ dislocation; this fact suggests that the $\mathbf{b}_{L3}$ dislocation is absorbed more easily than the $\mathbf{b}_{L1}$ dislocation into the boundary. This type of anisotropy of the absorption reactions similarly occurs in other boundaries. For a grain boundary with a specific Σ-value $-\Delta E/E$ takes the maximum and minimum values indicated by open circles in Fig. 2 (in the case of bcc boundaries with ⟨1 0 0⟩ rotation axis, Σ5, 13a and 17a, there is no variation in the driving force with the difference

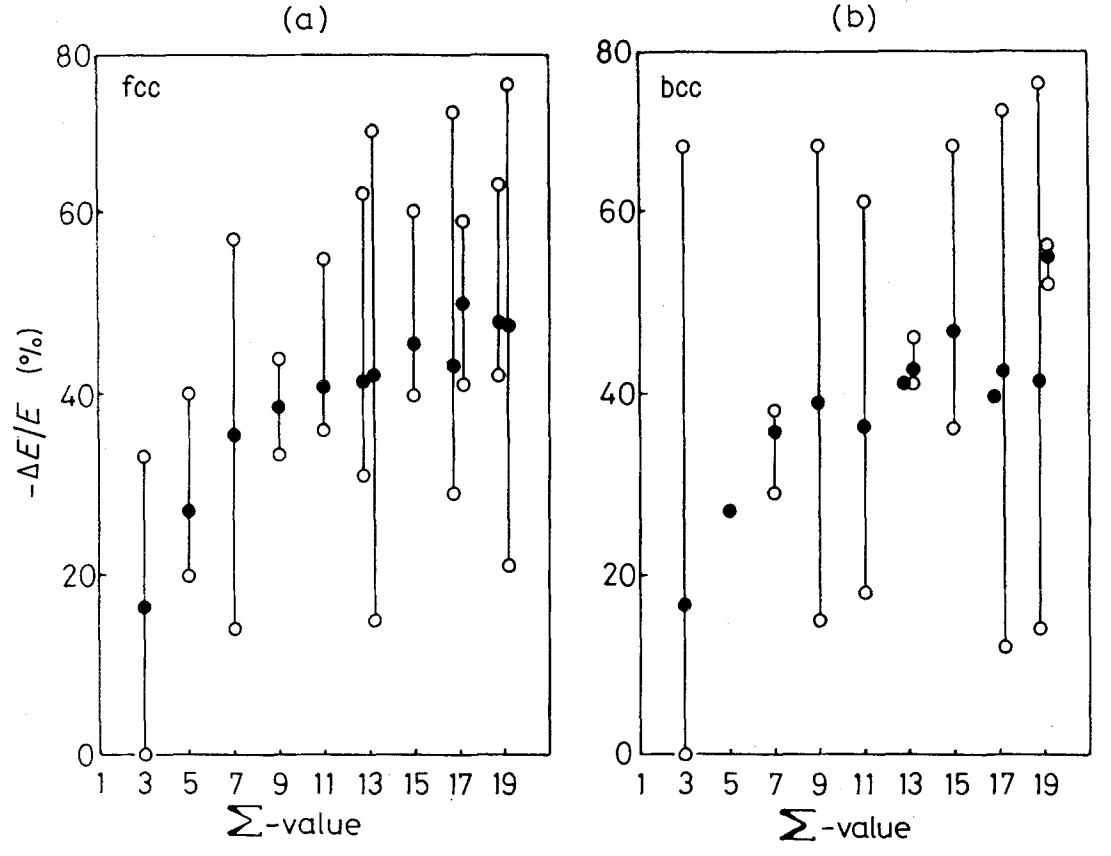


Figure 2 The relationship between Σ-values and $-\Delta E/E$ (a) for fcc (b) for bcc.

TABLE I Possible dislocation reactions and the energy reduction, $-\Delta E/E$, for a $\Sigma 13a$ f c c boundary in the grain A. The Burger's vectors of lattice dislocations are $\mathbf{b}_{L_1} = a/2[1\,1\,0]$, $\mathbf{b}_{L_2} = a/2[1\,0\,1]$, $\mathbf{b}_{L_3} = a/2[0\,1\,1]$, $\mathbf{b}_{L_4} = a/2[1\,\bar{1}\,0]$, $\mathbf{b}_{L_5} = a/2[1\,0\,\bar{1}]$ and $\mathbf{b}_{L_6} = a/2[0\,1\,\bar{1}]$

Rotation angle/axis	Rotation matrix	Burger's vector of GBD	Dissociation reaction	$-\Delta E/E$ (%)
22.62°/[1 0 0]	$\frac{1}{13}\begin{pmatrix} 13 & 0 & 0 \\ 0 & 12 & -5 \\ 0 & 5 & 12 \end{pmatrix}$	$\mathbf{b}_1 = \frac{a}{26}[0\,5\,\bar{1}]_A = \frac{a}{26}[0\,5\,1]_B$	$\mathbf{b}_{L_1} = 2\mathbf{b}_1 + \mathbf{b}_{31}$	31
		$\mathbf{b}_2 = \frac{a}{26}[0\,1\,5]_A = \frac{a}{26}[0\,\bar{1}\,5]_B$	$\mathbf{b}_{L_2} = 2\mathbf{b}_2 + \mathbf{b}_{33}$	31
		$\mathbf{b}_{31} = \frac{a}{26}[13\,3\,2]_A = \frac{a}{26}[13\,2\,3]_B$	$\mathbf{b}_{L_3} = 2\mathbf{b}_1 + 3\mathbf{b}_2$	62
		$\mathbf{b}_{32} = \frac{a}{26}[13\,2\,\bar{3}]_A = \frac{a}{26}[13\,3\,\bar{2}]_B = -\mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L_4} = -2\mathbf{b}_1 + \mathbf{b}_{34}$	31
		$\mathbf{b}_{33} = \frac{a}{26}[13\,\bar{2}\,3]_A = \frac{a}{26}[13\,\bar{3}\,2]_B = -\mathbf{b}_1 + \mathbf{b}_{31}$	$\mathbf{b}_{L_5} = -2\mathbf{b}_2 + \mathbf{b}_{32}$	31
		$\mathbf{b}_{34} = \frac{a}{26}[13\,\bar{3}\,\bar{2}]_A = \frac{a}{26}[13\,\bar{2}\,\bar{3}]_B = -\mathbf{b}_1 - \mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L_6} = 3\mathbf{b}_1 - 2\mathbf{b}_2$	62

in Burger's vector). Therefore, it seems very possible that the difference in the Burger's vector of the lattice dislocation affects the difficulty of the absorption in the same boundary. The Burger's vector of the lattice dislocation depends on the slip system activated during crystal deformation. Therefore, the possible effect of the stress direction on the absorption process should also be remembered. The present authors have observed grain boundaries in crept specimens of aluminium by transmission electron microscopy. The result has shown that the absorption process does play an important role in the grain boundary sliding [6]. If the absorption process of the lattice dislocation by a grain boundary is an essential process of grain boundary sliding [1–3], the grain boundary which absorbs less lattice dislocations will produce a smaller amount of grain boundary sliding. The anisotropy of the absorption reaction may cause some anisotropy of grain boundary sliding. Biscondi and Goux [21] have reported that the grain boundary sliding took place much more easily in the direction perpendicular rather than parallel to the rotation axis in ⟨1 0 0⟩ tilt aluminium bicrystals with the same misorientation. The anisotropy of the absorption is suggested to be one of the possible reasons for the anisotropy of sliding. This has yet to be verified by experiments in the near future.

The preceding discussions were made for grain boundaries with the exact coincidence orientation relationships. General boundaries deviate from the exact coincidence orientations by the superposition of GBD nets on the exact coincidence boundaries. However, similar reactions to those in the exact coincidence orientations are also expected to occur in slightly off-coincidence boundaries. The superposition of GBDs may also increase the grain boundary diffusion rate, and accelerate the absorption process [4]. For this reason the absorption reactions in slightly off-coincidence boundaries are considered to occur more easily than in grain boundaries of the exact coincidence orientations.

The elastic energy of a dislocation is considered to be proportional to $\mu \mathbf{b}^2$, where the shear modulus was taken to be constant for both the grain interior and the grain boundary. However, the shear modulus of the grain boundary has been supposed to be lower than that of the grain interior [4,22], so that the driving force of the absorption may become larger due to the reduction of the shear modulus. Provan and Bamiro [23] have calculated the shear modulus of ⟨0 0 1⟩ symmetric tilt boundaries of copper and aluminium by computer simulation. Their result showed that the shear modulus of the perfect crystal lattice is an upper bound for all the simulated high angle boundaries, and that the boundary shear modulus is significantly dependent on the misorientation. It is also shown that the shorter period boundary, which has a smaller Σ-value (high regularity), has the higher shear modulus. According to their results a lattice dislocation can reduce the elastic energy by running into a grain boundary, and the reduction is larger for the grain boundary with lower regularity. Considering the elastic energy reduction due to that of the shear modulus, it is expected that the driving force of the absorption reaction may be larger than those considered previously, in particular in grain boundary of larger Σ-value. However, the qualitative behaviour of absorption reaction would not differ much from that shown in Fig. 2.

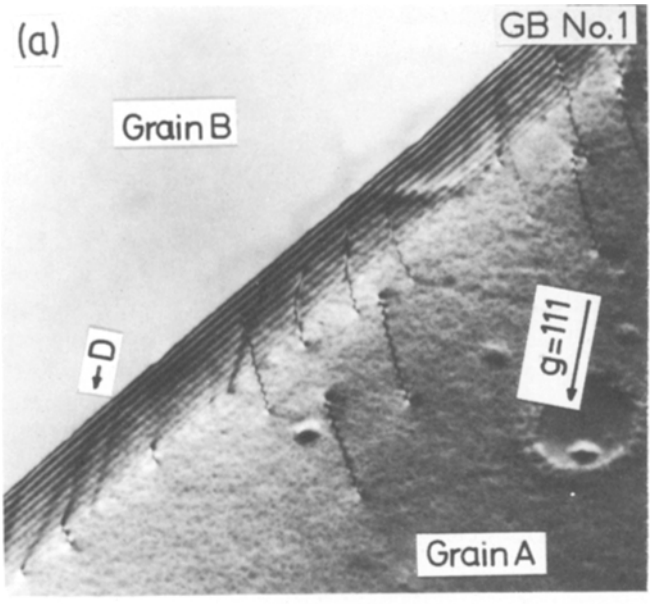
3. Transmission electron microscope observations

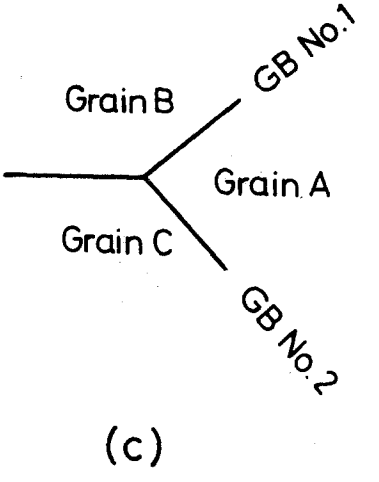
3.1. Interactions of the lattice dislocations with grain boundaries of different types

The elastic energy change calculated in Section 2 shows that the dissociation of a lattice dislocation occurs rather easily in the grain boundary of large Σ-value. This suggests that the absorption may occur much more easily in random boundaries than in coincidence boundaries. This is supported by recent TEM studies on the spreading process of EGBDs in grain boundaries [7, 24–28], which show that EGBDs are much more stable on ordered boundaries in comparison to random boundaries [27]. In the present study, in order to prove this suggestion more directly, the image changes of lattice dislocations running into grain boundaries of different types were continuously observed.

A tensile specimen (50 mm × 8 mm × 1 mm in gauge size) of 99.999% pure aluminium cut from cold-rolled sheet were annealed at 600 K for 12 h, resulting in a mean grain size of about 50 μm in diameter. The specimen was crept up to 1.3% elongation at tensile stress of 5 MPa and at 600 K in an argon atmosphere.

Fig. 3 shows the grain boundary structure in the crept specimen. As schematically illustrated in Fig. 3c, the two grain boundaries observed bordered the grain A. Kikuchi line analysis demonstrated that grain boundary (GB) 1 was a random boundary





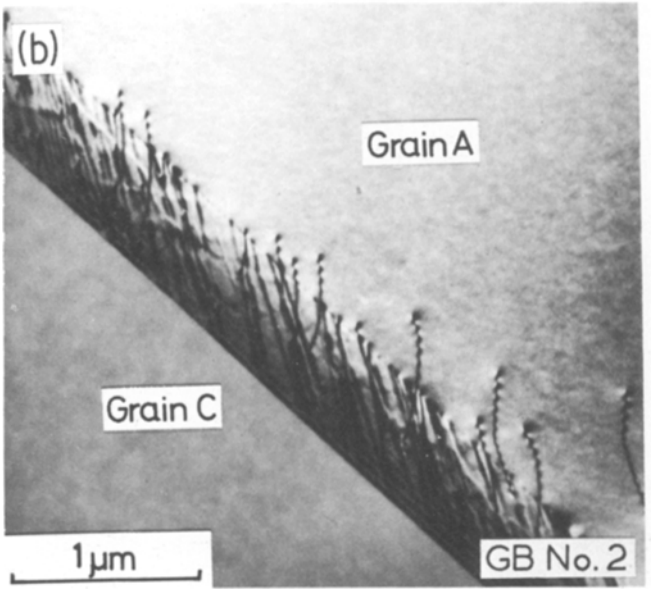


Figure 3 Interactions of lattice dislocations with grain boundaries of different types; (a) a random boundary (grain boundary 1), (b) a slightly off-Σ13b coincidence boundary (grain boundary 2) in the specimen crept up to 1.3% elongation at a tensile stress of 5 MPa and 600 K.

and grain boundary (GB) 2 slightly deviated from the Σ13b orientation relationship by 2.68° ($\Delta\theta = 2.68°$). After creep deformation, no extrinsic grain boundary dislocation (EGBD) was observed in the random boundary (GB 1), while many EGBDs were observed in the coincidence boundary (GB 2). During observation for a rather long time, motion of some lattice dislocations which would have been of the same Burger's vector took place in grain A, probably because of thermal stress by electron beam irradiation. They moved from the right hand side to the left in Fig. 3 to impinge on the two grain boundaries. Those which impinged on the random boundary (GB 1) rapidly spread their images (see D in Fig. 3a), and decreased their image contrast until they became invisible. The lattice dislocation at the position D partly lies in the grain boundary and partly within the grain A. The spreading of the dislocation image took place in the grain boundary. On the other

hand, the lattice dislocations impinged on the slightly off-coincidence boundary (GB 2) remained almost the same image contrast in the boundary as in the grain A.* These observations suggest that there is a significant difference in the absorption rate between a random boundary and a coincidence boundary, as expected from the analysis in Section 2. EGBDs in GB 2 would have been lattice dislocations introduced by creep deformation but not absorbed for the grain boundary structural reason as also reported by others [29].

3.2. Determination of the Burger's vectors of extrinsic grain boundary dislocations

According to the analysis in Section 2 the difficulty of absorption of a lattice dislocation into a boundary depends on the Burger's vector. The EGBDs observed after deformation could be the lattice dislocations of small reaction energies ($-\Delta E/E$). Pond and Smith [4] pointed out that the absorption process requires climb motion of dissociation products (GBDs). During high temperature creep deformation, lattice dislocations impinge on a grain boundary and climb in order to relax their strain fields in or near the grain boundary. It has been considered that the absorption of lattice dislocations is requisite for grain boundary sliding [6]. It is interesting, therefore, to determine the Burger's vector of EGBDs in grain boundaries whose sliding behaviour has been investigated by high temperature creep tests.

Three tensile specimens (20 mm × 8 mm × 1 mm in gauge size) cut from the cold-rolled sheet were pre-annealed at 773 K for 5 h and annealed at 923 K for 100 h after 2% straining, resulting in a grain size of 5 to 10 mm in diameter. The specimen surfaces were electrolytically polished and marker lines almost perpendicular to the grain boundary were scribed for sliding measurement on the specimen surface with a spacing of about 0.5 mm. These coarse-grained specimens were crept up to 10 to 15% elongation at tensile stress of 1.0 MPa and at 800 K in an argon atmosphere with a specially designed testing machine equipped with a high-temperature stage microscope, with which the amount of sliding was continuously measured at a magnification of × 75.

On the assumption that the Burger's vector of the EGBDs is one of the possible lattice vectors of the neighbouring grains, the visibilities of the EGBD images on three grain boundaries in the crept specimens were examined by operating several different two-beam diffraction conditions in each grain.

Fig. 4 shows the examples obtained on a slightly off-Σ25a† coincidence boundary ($\Delta\theta = 1.87°$) which has experienced a grain boundary sliding of 16 μm during creep deformation up to 12.6% elongation. The EGBDs are observed when (a) $\mathbf{g} = \bar{2}\,2\,0_A$ in the grain A and (c) $\mathbf{g} = \bar{2}\,0\,2_B$ in the grain B, but not observed when (b) $\mathbf{g} = \bar{2}\,0\,2_A$ in the grain A and (d) $\mathbf{g} = \bar{1}\,1\,1_B$ in the grain B (g is the diffraction vector). The result is tabulated in Table II. Strictly speaking, only a pure screw type dislocation is invisible when $\mathbf{g}\cdot\mathbf{b} = 0$. But images of other types of dislocations may also become remarkably weak. In this analysis the criterion, $\mathbf{g}\cdot\mathbf{b} = 0$ was used to determine six possible Burger's vectors of lattice dislocations of the $a/2\langle 1\,1\,0\rangle$-type in each grain, A and B (Fig. 4). In Table II (○) means the case with great possibility, while (×) means with no possibility. For example, the EGBDs were visible when $\mathbf{g} = \bar{2}\,2\,0_A$, as shown in Fig. 4a. The $\mathbf{g}\cdot\mathbf{b} = 0$ criterion suggests that $a/2[1\,1\,0]_A$ is an impossible Burger's vector among the six types of $a/2\langle 1\,1\,0\rangle_A$ and the others are not impossible. After the complete analysis the possible Burger's vector of the EGBDs in Fig. 4 is limited to $a/2[1\,0\,1]_A$. Table III lists the possible dislocation reactions and the energy reductions $-\Delta E/E$ for Σ25a fcc boundary, where all the vector index notations used in Fig. 4, Tables II and III are fixed to the rotation relationship in Table III. The Burger's vector, $a/2[101]_A$, corresponds to $\mathbf{b}_{L2}$ in Table III. Lattice dislocations with this Burger's vector are considered relatively difficult to absorb, because of the smaller energy change, $-\Delta E/E$, due to the reaction.

Fig. 5 shows a slightly off-Σ13a boundary ($\Delta\theta = 4.13°$) which produces a sliding of 15 μm during creep deformation up to 15.3% elongation. The boundary has two sets of EGBDs whose directions are indicated by lines 1 and 2. The result of Burger's vector analysis is shown in Table IV. The $\mathbf{g}\cdot\mathbf{b} = 0$ criterion limits the possible Burger's vectors of the EGBDs indicated by line 1 to $a/2[1\,\bar{1}\,0]_A$, $a/2[0\,1\,\bar{1}]_A$ and $a/2[1\,0\,\bar{1}]_B$. A trace

*Spreading of the lattice dislocations in slightly off-coincidence boundaries seems to be possible to smaller extent.
†For Σ25 coincidence orientation, there are two different coincidence lattices, 16.25°⟨1 0 0⟩/Σ25a and 156.93°⟨2 1 1⟩/Σ25b [30].

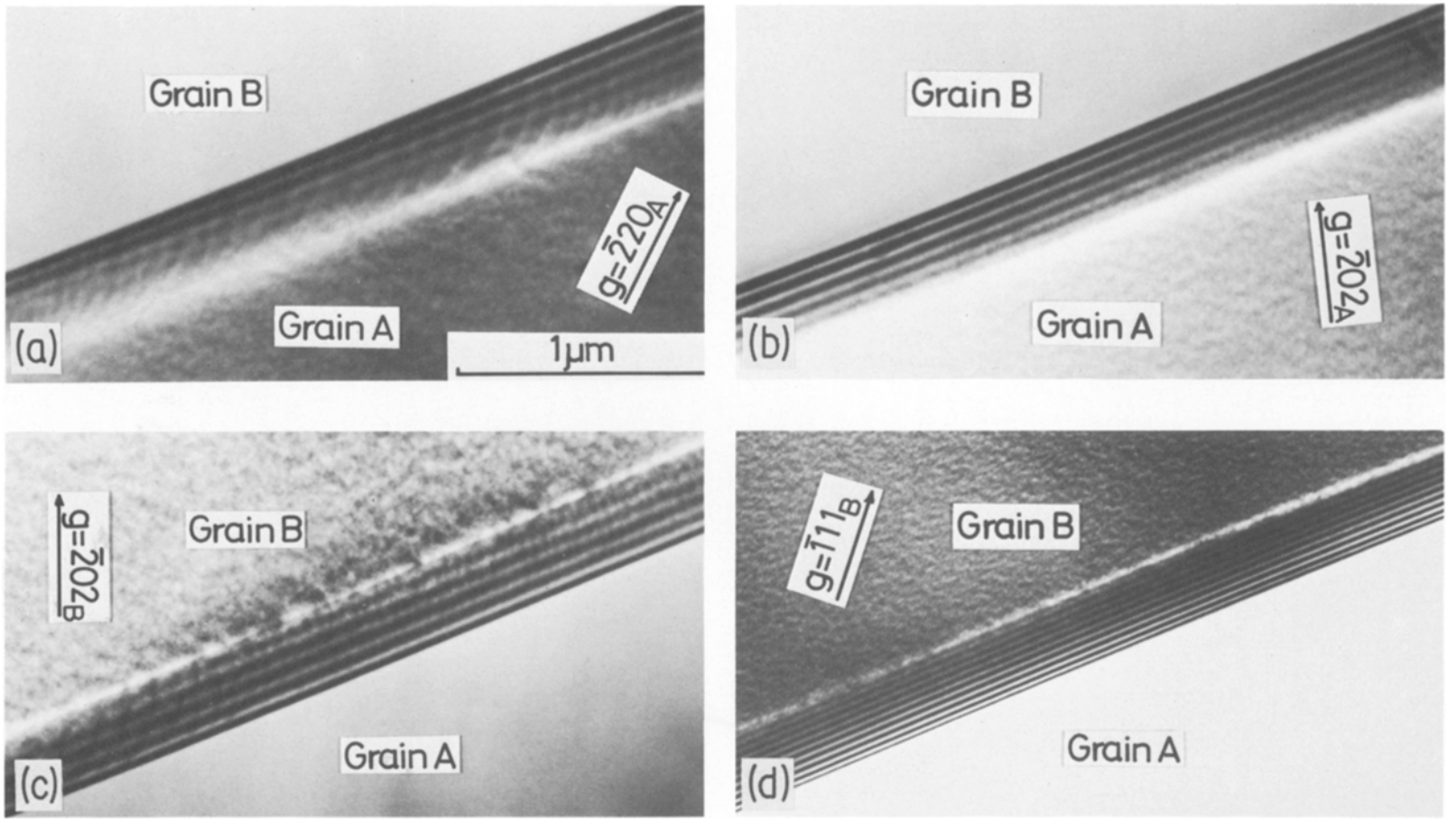


Figure 4 Micrographs taken from a slightly off-Σ25a coincidence boundary which produced sliding of 16 μm using different reflections; (a) $\mathbf{g} = \bar{2}20$ in grain A, (b) $\mathbf{g} = \bar{2}02$ in grain A, (c) $g = \bar{2}02$ in grain B, (d) $\mathbf{g} = \bar{1}11$ in grain B.

TABLE II The Burger's vector analysis of EGBDs in a slightly off-Σ25a coincidence boundary

g	$[1\,1\,0]_A$	$[1\,0\,1]_A$	$[0\,1\,1]_A$	$[1\,\bar{1}\,0]_A$	$[1\,0\,\bar{1}]_A$	$[0\,1\,\bar{1}]_A$	g	$[1\,1\,0]_B$	$[1\,0\,1]_B$	$[0\,1\,1]_B$	$[1\,\bar{1}\,0]_B$	$[1\,0\,\bar{1}]_B$	$[0\,1\,\bar{1}]_B$
$\bar{2}\,2\,0_A$	×	○	○	○	○	○	$\bar{2}\,0\,2_B$	○	×	○	○	○	○
$\bar{2}\,0\,2_A$	×	○	×	×	×	×	$\bar{1}\,1\,1_B$	○	○	×	×	×	○
$\bar{1}\,1\,1_A$	○	○	×	×	×	○	$1\,1\,1_B$	○	○	○	×	×	×
$1\,1\,1_A$	○	○	○	×	×	×	$1\,\bar{1}\,1_B$	×	○	×	○	×	○

TABLE III Possible dislocation reactions and the energy reduction, $-\Delta E/E$, for a Σ25a f c c boundary in the grain A. The Burger's vectors of lattice dislocations are the same as in Table I

Rotation angle/axis	Rotation matrix	Burger's vector of GBD	Dissociation reaction	$-\Delta E/E$ (%)
16.26°/[1 0 0]	$\frac{1}{25}\begin{pmatrix} 25 & 0 & 0 \\ 0 & 24 & -7 \\ 0 & 7 & 24 \end{pmatrix}$	$\mathbf{b}_1 = \frac{a}{50}[0\,7\,\bar{1}]_A = \frac{a}{50}[0\,7\,1]_B$	$\mathbf{b}_{L1} = 3\mathbf{b}_1 + \mathbf{b}_{31}$	36
		$\mathbf{b}_2 = \frac{a}{50}[0\,\bar{1}\,\bar{7}]_A = \frac{a}{50}[0\,1\,\bar{7}]_B$	$\mathbf{b}_{L2} = -3\mathbf{b}_2 + \mathbf{b}_{33}$	36
		$\mathbf{b}_{31} = \frac{a}{50}[2\,5\,4\,3]_A = \frac{a}{50}[2\,5\,3\,4]_B$	$\mathbf{b}_{L3} = 3\mathbf{b}_1 - 4\mathbf{b}_2$	72
		$\mathbf{b}_{32} = \frac{a}{50}[2\,5\,3\,\bar{4}]_A = \frac{a}{50}[2\,5\,4\,\bar{3}]_B = \mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L4} = -3\mathbf{b}_1 + \mathbf{b}_{34}$	36
		$\mathbf{b}_{33} = \frac{a}{50}[2\,5\,\bar{3}\,4]_A = \frac{a}{50}[2\,5\,\bar{4}\,3]_B = -\mathbf{b}_1 + \mathbf{b}_{31}$	$\mathbf{b}_{L5} = 3\mathbf{b}_2 + \mathbf{b}_{32}$	36
		$\mathbf{b}_{34} = \frac{a}{50}[2\,5\,\bar{4}\,\bar{3}]_A = \frac{a}{50}[2\,5\,\bar{3}\,\bar{4}]_B = -\mathbf{b}_1 + \mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L6} = 4\mathbf{b}_1 + 3\mathbf{b}_2$	72

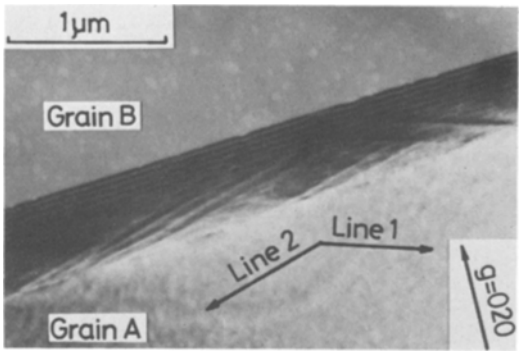


Figure 5 Two sets of EGBDs in a slightly off-Σ13a coincidence boundary which produced sliding of 15 μm.

analysis was also made to determine the active slip planes ($\{1\,1\,1\}$) which would have supplied the EGBDs to the boundary. The result obtained shows that the EGBDs may lie on $(1\,1\,\bar{1})_A$ and $(1\,1\,\bar{1})_B$. If the Burger's vector of the EGBDs lies on the crystal slip plane, only $a/2[1\,\bar{1}\,0]_A$ satisfies all the above condition. After all, the Burger's vector of the EGBDs indicated by line 1 is concluded to be $a/2[1\,\bar{1}\,0]_A$, which corresponds to $\mathbf{b}_{L4}$ in Table I. The Burger's vector $\mathbf{b}_{L4}$ gives the smaller $-\Delta E/E$, so that the EGBDs are considered the more difficult to be absorbed. On the other hand, the possible Burger's vectors of the EGBDs indicated by line 2 are limited to $\mathbf{b}_{L1}$ and $\mathbf{b}_{L3}$ in Table I as shown in Table IV (the trace analysis shows that the EGBDs may lie on $(1\,\bar{1}\,1)_A$). For $\mathbf{b}_{L1}$ dislocations the absorption may be relatively difficult because of the smaller $-\Delta E/E$ in Σ13a, while $\mathbf{b}_{L3}$ dislocations of the larger $-\Delta E/E$ are considered to be easily absorbed. Therefore, the energetics discussion in Section 2 suggests that the EGBDs indicated by line 2 probably have a Burger's vector of $\mathbf{b}_{L1}$.

From the analysis of EGBDs in a slightly off-Σ9 boundary ($\Delta\theta = 4.76°$) which produced a small amount of sliding of 4 μm during 11.0% creep strain, it is suggested that the possible Burger's vector is $a/2[1\,1\,0]_A$, which is $\mathbf{b}_{L1}$ giving the smaller $-\Delta E/E$ for Σ9 boundary as shown in Table V.

The above results obtained in the three coincidence boundaries show that the examined EGBDs have the Burger's vectors which produce only a small energy change, $-\Delta E/E$, upon absorption so that they are difficult to dissociate. This is in good agreement with the result which was obtained from the energetics discussion in Section 2.

4. Conclusions

Assuming that the elementary process of the absorption of the lattice dislocations into the grain boundaries is a dissociation into GBDs, the absorp-

TABLE IVA Line 1. Burger's vector analysis of EGBDs in a slightly off-Σ13a coincidence boundary

g	$[1\,1\,0]_A$	$[1\,0\,1]_A$	$[0\,1\,1]_A$	$[1\,\bar{1}\,0]_A$	$[1\,0\,\bar{1}]_A$	$[0\,1\,\bar{1}]_A$
$0\,2\,0_A$	○	×	○	○	×	○
$1\,1\,1_A$	×	×	×	○	○	○
$1\,\bar{1}\,1_A$	×	○	×	○	×	○
g	$[1\,1\,0]_B$	$[1\,0\,1]_B$	$[0\,1\,1]_B$	$[1\,\bar{1}\,0]_B$	$[1\,0\,\bar{1}]_B$	$[0\,1\,\bar{1}]_B$
$0\,0\,2_B$	×	○	○	×	○	○
$1\,\bar{1}\,1_B$	○	×	○	×	○	×
$0\,\bar{2}\,0_B$	×	○	×	×	○	×

TABLE IVB Line 2. Burger's vector analysis of EGBDs in a slightly off-Σ13a coincidence boundary

g	$[1\,1\,0]_A$	$[1\,0\,1]_A$	$[0\,1\,1]_A$	$[1\,\bar{1}\,0]_A$	$[1\,0\,\bar{1}]_A$	$[0\,1\,\bar{1}]_A$
$0\,2\,0_A$	○	×	○	○	×	○
$1\,1\,1_A$	○	○	○	×	×	×
$1\,\bar{1}\,1_A$	○	×	○	×	○	×
g	$[1\,1\,0]_B$	$[1\,0\,1]_B$	$[0\,1\,1]_B$	$[1\,\bar{1}\,0]_B$	$[1\,0\,\bar{1}]_B$	$[0\,1\,\bar{1}]_B$
$0\,0\,2_B$	×	○	○	×	○	○
$1\,\bar{1}\,1_B$	○	×	○	×	○	×
$0\,\bar{2}\,0_B$	×	○	×	×	○	×

TABLE V Possible dislocation reactions and the energy reduction, $-\Delta E/E$, for a $\Sigma 9$ fcc boundary in the grain A. The Burger's vectors of lattice dislocations are the same as in Table I

Rotation angle/axis	Rotation matrix	Burger's vector of GBD	Dissociation reaction	$-\Delta E/E$ (%)
38.94°/[1 1 0]	$\frac{1}{9}\begin{pmatrix} 8 & 1 & 4 \\ 1 & 8 & -4 \\ -4 & 4 & 7 \end{pmatrix}$	$\mathbf{b}_1 = \frac{a}{18}[1\,\bar{1}\,4]_A = \frac{a}{18}[\bar{1}\,1\,\bar{4}]_B$	$\mathbf{b}_{L1} = \mathbf{b}_{31} + \mathbf{b}_{34}$	33
		$\mathbf{b}_2 = \frac{a}{9}[2\,\bar{2}\,1]_A = \frac{a}{9}[2\,\bar{2}\,\bar{1}]_B$	$\mathbf{b}_{L2} = -\mathbf{b}_1 + \mathbf{b}_2 + \mathbf{b}_{31}$	33
		$\mathbf{b}_{31} = \frac{a}{6}[2\,1\,1]_A = \frac{a}{18}[7\,2\,1]_B$	$\mathbf{b}_{L3} = -2\mathbf{b}_1 + \mathbf{b}_{32}$	44
		$\mathbf{b}_{32} = \frac{a}{18}[2\,7\,1]_A = \frac{a}{6}[1\,2\,1]_B = -\mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L4} = \mathbf{b}_1 + 2\mathbf{b}_2$	44
		$\mathbf{b}_{33} = \frac{a}{18}[7\,2\,\bar{1}]_A = \frac{a}{6}[2\,1\,\bar{1}]_B = \mathbf{b}_1 + \mathbf{b}_{31}$	$\mathbf{b}_{L5} = 2\mathbf{b}_1 + \mathbf{b}_{33}$	44
		$\mathbf{b}_{34} = \frac{a}{6}[1\,2\,\bar{1}]_A = \frac{a}{18}[2\,7\,\bar{1}]_B = \mathbf{b}_1 - \mathbf{b}_2 + \mathbf{b}_{31}$	$\mathbf{b}_{L6} = \mathbf{b}_1 - \mathbf{b}_2 + \mathbf{b}_{34}$	33

tion process was discussed. The elastic energy reduction during the dissociation reaction was considered to be the driving force for the process. The results were compared with the transmission electron microscope observations of lattice dislocations in crept aluminium grain boundaries of different structures. The conclusions are as follows:

1. A lattice dislocation is suggested to be more easily absorbed into coincidence boundaries with larger Σ-values. Transmission electron microscopy showed a large difference in the absorption rate between coincidence and random boundaries.

2. The absorption of the lattice dislocations depends strongly on its Burger's vector even in the same grain boundary. The experimental results have shown that most of the EGBDs observed in the coincidence boundaries in crept specimens are of the Burger's vectors which give rise to a smaller energy change, $-\Delta E/E$, due to the dissociation reaction and this may make the absorption of the lattice dislocation more difficult.

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