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ON GRAIN BOUNDARY DISLOCATIONS IN
PLANE MATCHING GRAIN BOUNDARIES

MASTER

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ABSTRACT

Plane matching (PM) boundaries are defined as boundaries in which a single stack of planes of indices (hkl) in each crystal adjoining the boundary is either parallel, or nearly parallel, and where no other significant lattice matching exists. A search was made (by transmission electron microscopy) for possible intrinsic secondary grain boundary dislocation (GBD) arrays which might be present in such boundaries possessing a variety of deviations from the exact PM condition. (002) , (220) and (420) PM boundaries of controlled geometry were prepared in gold thin film bicrystal specimens. Wide ranges of twist and tilt deviations from the exact PM orientation were introduced, and the orientation of the boundary plane was also varied for cases of fixed crystal misorientation. Arrays consisting of parallel GBDs were found in the (002) and (220) boundaries but not in the (420) boundaries. The Burgers vector of the GBDs was parallel to $[hkl]$ with a magnitude given by the (hkl) interplanar spacing. Arrays were found in boundaries with twist deviations as large as 4° and tilt deviations as large as 14° and with a wide range of grain boundary plane orientations. The results suggest that discrete GBDs should be present in a variety of (002) , (111) and (220) PM boundaries over a considerable range of misorientation which in certain cases may be as large as 20° . Such boundaries should therefore appear rather frequently in general polycrystalline materials in agreement with the estimates of Warrington and Boon. It is pointed out that the physical basis for the stability of such GBD structures is not understood at present.

1. INTRODUCTION

In the present paper we define a plane matching (PM) boundary as a boundary in which a single stack of planes of indices (hkl) in each crystal adjoining the boundary is either parallel, or nearly parallel, and where no other significant lattice matching of the two crystals exists. When the (hkl) planes are nearly parallel, and the indices are fairly low (i.e., the planes are fairly dense) there is considerable evidence [1-7] that the boundary energy can often be reduced by introducing secondary relaxations in the boundary structure which improve the degree of alignment⁽³⁾ of these planes across the boundary. These secondary relaxations appear in the form of secondary grain boundary dislocations (GBDs) which have frequently been observed as line defects in such boundaries by electron microscopy [1-7].

A number of purely geometrical descriptions of such relaxations has been given by various workers. Pumphrey [2] focused attention on the traces in the boundary plane made by the nearly matched (hkl) planes in many unrelaxed PM boundaries and showed that the pattern of the subsequent secondary relaxation should often resemble the Moiré pattern formed by these traces. However, Balluffi and Schober [8] pointed out that this approach cannot be applied universally and that there are cases where the traces do not form Moiré patterns, e.g., in symmetric tilt boundaries where the (hkl) planes are almost parallel to the boundary plane. Later, Ralph, Howell and Page [4] gave a description of PM boundaries in terms of the disregistry of the (hkl) planes across the boundary and discussed a variety

3) The term "alignment" is meant to be very general here, and, for example, does not necessarily imply actual planar continuity across the boundary in cases where the edges of the matching planes impinge upon the boundary. (See Discussion in Section 4.)

of types of disregistry and the types of GBDs which would be produced by secondary relaxations. Finally, it has been emphasized in several places (e.g., Balluffi and Schober [8] and Warrington and Boon [5]) that PM boundaries are actually special cases of the general Coincidence Site Lattice (CSL) grain boundary model of Bollmann [9]. In this model the CSL is generated by rotating Crystal 2 with respect to Crystal 1 around a common axis, and a three-dimensional lattice is produced when the crystal lattices match in three dimensions. The accompanying DSC-Lattice [9], which defines the Burgers vectors of all possible perfect GBDs, $\vec{b}_1$, is then also a three-dimensional lattice. Examples of these lattices are given in Figs. 1 (a,b,c) for the case of a 36.9° rotation around [001]. The periodicity of the grain boundary, which is determined by its intersection with the CSL [9,10] is therefore two-dimensional. In the special case of plane matching where the (hkl) planes are exactly parallel, the crystal misorientation is again described by a rotation around [hkl], and good crystal matching is obtained along the rotation axis. However, the unit cell of the CSL is then exceedingly large in directions normal to the rotation axis due to the lack of significant lattice matching in those directions. On the other hand, the unit cell of the DSC-Lattice becomes correspondingly small in those directions since the cell dimensions in those directions tend to be reciprocally related to those of the CSL. In the limit of no matching in directions normal to the rotation axis the CSL unit cell becomes infinite in those directions, and the DSC-Lattice unit cell degenerates into a single finite $\vec{b}_3$ vector which is normal to (hkl) and is of magnitude d_{hkl} [d_{hkl} = interplanar spacing of (hkl) planes] as illustrated in Fig. 1(d) for the case of (002) plane matching. The

DSC-Lattice in such a case consists of a stack of planar sheets identical to the (hkl) planes. As we shall show below, all of the secondary relaxations observed in PM boundaries can be interpreted in terms of GBDs with $\vec{b}_3$ Burgers vectors. Also, it is evident that PM boundaries therefore possess one-dimensional periodicity at most and may exhibit no periodicity at all if the boundary plane is parallel to (hkl) . (Boundaries of the latter type have been observed experimentally and are discussed in detail in Sections 3 and 4.)

PM boundaries are of considerable interest since they should occur more commonly in random polycrystals than boundaries of the three-dimensional CSL type due to the higher probability of achieving one-dimensional lattice matching than three-dimensional matching [5]. Despite this situation very little systematic information about PM boundaries has been reported in the literature. In the present work we have carried out a systematic study of such boundaries in gold employing thin film bicrystal specimens containing grain boundaries of controlled geometry. Of special interest were:

- (i) the ranges of (hkl) over which physically distinguishable GBDs occurred,
- (ii) the types and magnitudes of the angular deviations from exact plane matching which could be accommodated by arrays of distinguishable GBDs, and
- (iii) effects caused by varying the orientation of the grain boundary plane relative to $[hkl]$.

2. EXPERIMENTAL

Thin film gold bicrystals containing several types of PM boundaries possessing a variety of deviations from exact planar matching were prepared using a thin film welding technique which has been described elsewhere [11]. Briefly, thin gold single crystal films of controlled orientation were first grown by epitaxial vapor deposition on suitable single crystal NaCl substrates. There were then welded together face-to-face at 200°C while still on their substrates to produce bicrystals which contained the desired PM boundaries. After removing the NaCl by dissolution in H₂O, the specimens were annealed at 200°C, and the grain boundaries were then examined at approximately normal incidence by transmission electron microscopy. In order to control the imaging conditions the crystals in each bicrystal film were usually of different thicknesses, i.e., 15 nm and 45 nm respectively.

A description of the types of boundaries which were investigated is given below. Each boundary can be visualized as the result of a construction process carried out in two steps. In the first step the boundary in the exact planar matching condition is constructed. In the second step deviations from the exact planar matching condition are introduced. The following parameters were therefore used to describe the boundaries:

θ = rotation around [hkl] to produce PM boundary with exact planar matching

γ = angle between grain boundary plane and the (hkl) plane in the exact planar matching condition

$\Delta\alpha$ = angular rotation of Crystal 2 with respect to Crystal 1 away from exact planar matching around axis normal to grain boundary plane

$\Delta\beta$ = angular rotation of Crystal 2 with respect to Crystal 1 away from exact planar matching around axis lying in grain boundary plane parallel to the trace of (hkl). In the present work this axis was always $[100]_1$.

(002) PM boundaries: basic PM conditions were first achieved by rotating Crystal 2 relative to Crystal 1 by $\theta = 42^\circ$ around $[002]$ (see Fig. 2.) This misorientation is close to the $\Sigma = 97$ misorientation and is therefore well away from any misorientation corresponding to physically significant matching in three dimensions (Σ = reciprocal of the fraction of atoms in three-dimensional coincidence). In a first series (Series 1) of deviated boundaries Crystal 2 was then rotated around $[010]_1$ by various angles, $\Delta\alpha$, with the grain boundary plane maintained parallel to $(010)_1$. In this case, therefore, $\Delta\beta = 0$, $\gamma = 90^\circ$. In a second series of deviated boundaries (Series 2) Crystal 2 was rotated around $[100]_1$ by the angle $\Delta\beta$ and then rotated by the angle $\Delta\alpha$ around $[010]_1$ with the boundary plane maintained parallel to $(010)_1$. In this case, therefore, $\gamma = 90^\circ$. In a third series (Series 3) the grain boundary was set at an angle, γ , to $(002)_1$ (while held parallel to $[100]_1$) and Crystal 2 was rotated around an axis normal to the grain boundary plane by $\Delta\alpha$ as shown in Fig. 2. In addition, we list two further series (Series 4 and 5) of (002) PM boundaries which were not studied in the present work but were investigated in previous work [12] by essentially identical experimental techniques. In these series basic PM boundaries were established by either 37° or 45° rotations around $[002]$, i.e., $\theta = 37^\circ$ or 45° , and the grain boundary was established parallel to $(001)_1$, i.e., $\gamma = 0$. Crystal 2 was then rotated around $[100]_1$ by the angle $\Delta\beta$.

(220) PM boundaries: basic (220) PM conditions were first achieved by rotating Crystal 2 by $\theta = 90^\circ$ around $[220]_1$ as illustrated in Fig. 3.

This misorientation was again well away from any misorientation corresponding to physically significant matching in three dimensions. A series of deviated boundaries (Series 6) was then produced by rotating Crystal 2 around $[001]_1$ by the angle $\Delta\alpha$ while holding the grain boundary plane parallel to $(001)_1$.

(420) PM boundaries: basic (420) PM conditions were first achieved by rotating Crystal 2 by $\theta = 90^\circ$ around $[210]_1$ as illustrated in Fig. 4.

A series of deviated boundaries (Series 7) was then produced by rotating Crystal 2 around $[001]_1$ by the angle $\Delta\alpha$ while holding the grain boundary plane parallel to $(001)_1$.

A summary of the boundaries which were investigated is given in the Table.

3. RESULTS

In many of the boundaries single sets of parallel lines were observed which were consistent with the presence of GBDs with $\vec{b}_3$ Burgers vectors. As Bollmann has shown [9], there is a close relationship between the primary dislocation structure of a low angle ($\Sigma = 1$) boundary and the O-Lattice which is produced by the adjoining crystal lattices. Using similar methods it is readily shown that there is a similar relationship between the secondary GBD structure of a general CSL boundary (possessing a deviational misorientation from the exact CSL orientation) and the O-Lattice which is generated by taking the DSC-Lattice corresponding to the exact CSL orientation and "beating" it against a second interpenetrating DSC-Lattice set at the same deviational misorientation⁽⁴⁾. In the present case of PM boundaries the anticipated structure of the $\vec{b}_3$ GBD array in the boundary is therefore determined by the intersection of the grain boundary plane with the O-Lattice produced by the interpenetrating [hkl] planes of the two adjoining crystals.

Series 1: for these (002) PM boundaries (see the Table), arrays of parallel GBDs were observed for values of $\Delta\alpha$ in the range $0^\circ \leq \Delta\alpha \leq 4^\circ$. An example of such an array is shown in Fig. 5. The GBD spacing, d , was consistent in every case with that expected on the basis of the previous discussion. For these boundaries the intersection of the O-Lattice, produced by the (hkl) planes as described above, with the grain boundary plane is identical to the Moiré pattern produced by the traces of the (hkl) planes in the boundary. In general, the Moiré pattern produced by any two sets of traces appears as illustrated in

4) This same result can be reached intuitively by realizing that the Burgers vectors of the secondary GBDs are the vectors of the DSC-Lattice just as the Burgers vectors of the primary GBDs are the vectors of the crystal lattice, and that a secondary GBD can be fully revealed by a construction in the DSC-Lattice [13] just as a lattice dislocation can be revealed by a similar construction in the crystal lattice.

Fig. 6 with the spacing, d_M , given by

$$d_M = \frac{s_1 s_2}{[s_1^2 + s_2^2 - 2s_1 s_2 \cos \psi]^{1/2}} \quad (1)$$

and the angle, ρ , given by

$$\rho = \sin^{-1} \left(\frac{d_M \sin \psi}{s_1} \right) \quad (2)$$

Here, s_1 and s_2 are the trace spacings, and ψ is the angle between the sets of traces. For the Series 1 boundaries, $s_1 = s_2 = d_{hkl}$, $\psi = \Delta\alpha$, and, therefore, the GBD spacing, d , should be given by

$$\frac{d}{d_{hkl}} = \frac{1}{2 \sin \left(\frac{\Delta\alpha}{2} \right)} \quad (3)$$

Measured values of d are seen to follow this relationship in Fig. 7. In addition, the GBDs ran along the average $[hkl]$ direction and accounted for a twist deviation, and were therefore screw GBDs.

When $\Delta\alpha$ exceeded about 4° secondary GBDs were no longer observed and instead only Moiré fringes were observed in the electron microscope images. We note that considerable difficulty was often encountered in the present work due to the frequent presence of Moiré fringes resulting from interference between diffracted, or doubly diffracted, beams from the nearly matched (hkl) planes in Lattices 1 and 2. Since these fringes possessed the same spacing and direction as the GBDs, there was always a potential problem of distinguishing GBDs from Moiré fringes. This was overcome by: (1) observing the possible interactions of the observed lines with small bubbles in the grain boundaries which were produced in the original welding

process. The GBDs interacted strongly with these bubbles and disappeared within them as seen in Fig. 8(a), whereas Moiré fringes were generally less affected by them [Fig. 8(b)]; (2) observing the nature of the variation of the diffraction contrast in a direction transverse to the lines. The GBDs exhibited non-symmetric "black-white" contrast [Fig. 8(a)] while the Moiré fringe contrast was more sinusoidal [Fig. 8(b)]; (3) using a variety of imaging conditions and hunting for a fixed image; and (4) selecting one of the reflections from the matching (hkl) planes for dark field imaging. This latter procedure eliminated the possibility of producing Moiré fringes but it could only be used for relatively large $\Delta\alpha$ angles where the $(hkl)_1$ and $(hkl)_2$ reflections were well separated.

Series 2: arrays of GBDs were found in a relatively wide range of these (002) PM boundaries. The intersection of the O-Lattice produced by the [hkl] planes is again identical to the Moiré pattern produced by the traces of the (hkl) planes in the boundary. In this case in Eqs. (1) and (2) $s_1 = d_{hkl}$, $s_2 = d_{hkl}/\cos\beta$ and $\psi = \Delta\alpha$. Therefore, we anticipate

$$\frac{d}{d_{hkl}} = \frac{1}{[1 + \cos^2\Delta\beta - 2 \cos \Delta\beta \cdot \cos \Delta\alpha]^{1/2}}, \quad (4)$$

and,

$$\rho = \sin^{-1} \left[\frac{\sin \Delta\alpha}{[1 + \cos^2\Delta\beta - 2 \cos \Delta\beta \cdot \cos \Delta\alpha]^{1/2}} \right] \quad (5)$$

Calculated values of d/d_{hkl} and ρ as functions of $\Delta\alpha$ and $\Delta\beta$ are plotted in Figs. 9 and 10 along with experimentally measured values. Reasonably good agreement between the calculated and measured values was obtained.

The GBDs in this case were generally of mixed screw and edge type in order to account for both the twist and tilt deviations which were present.

Series 3: for these boundaries the intersection of the O-Lattice with the boundary is given by the Moiré pattern produced by the traces of the (hkl) planes in the boundary. Therefore, $s_1 = s_2 = d_{hkl}/\sin\gamma$, and from Eq. (4) we anticipate GBDs of spacing

$$\frac{d}{d_{hkl}} = \frac{1}{\sin\gamma \cdot 2 \sin(\frac{\Delta\alpha}{2})} \quad (6)$$

GBD arrays possessing spacings consistent with Eq. (6) were found, and the results for the observed spacings are given in Fig. 11.

Series 4 and 5: in these cases the O-Lattice spacing is $d = d_{hkl}[2\sin(\Delta\beta/2)]^{-1}$, and the anticipated spacing of the GBDs, as determined by the intersection of the O-Lattice with the grain boundary plane, is

$$\frac{d}{d_{hkl}} = \frac{1}{2 \sin \frac{\Delta\beta}{2} \cdot \cos \frac{\Delta\beta}{2}} \quad (7,a)$$

$$\approx \frac{1}{\Delta\beta} \quad (\text{for small } \beta) \quad (7,b)$$

GBDs of the anticipated type were observed in [12] for $0^\circ \leq \Delta\beta \leq 4^\circ$, and the measured spacings were found to be consistent with Eq. (7,b) as shown in Fig. 10 of [12].

Series 6: arrays of GBDs were observed in these (220) PM boundaries for values of $\Delta\alpha$ in the range $0^\circ \leq \Delta\alpha \leq 4^\circ$, and the results were consistent with Eq. (3) as shown in Fig. 7. We note that GBD spacings smaller than those reported in Fig. 7 were claimed in an earlier study [6] of similar (220) PM boundaries. It is now evident that those results were in error and can be attributed to confusion between GBDs and Moiré fringes.

Series 7: despite strenuous efforts involving numerous diffraction contrast experiments, no GBD arrays were detected in any of the (420) PM boundaries.

4. DISCUSSION

The results, summarized in the last column of the Table, prove that secondary relaxations consisting of $\vec{b}_3$ GBDs occur in (002) and (220) PM boundaries over a wide range of deviations from the exact plane matching orientation. The failure to detect GBDs in (420) PM boundaries indicates that relaxations into GBDs do not occur when (hkl) becomes too large, and the atomic density of the planes to be matched becomes too low. This result is consistent with that of Levy [1] who found what were evidently GBDs of the Series 1 type in PM boundaries in aluminum for (hkl) equal to (002), (111) and (220). GBDs were not found [1] for planes with higher indices. The results in Fig. 7 for the (002) and (220) PM boundaries demonstrate that twist deviations up to $\Delta\alpha \approx 4^\circ$ lead to arrays of discrete GBDs possessing spacings as small as $d \approx 15 d_{hkl}$. Physically detectable GBDs were not observed at larger values of $\Delta\alpha$ (i.e., smaller GBD spacings).

The above results, taken all together, indicate that the cores of GBDs in PM boundaries must be relatively wide, and that the width increases as (hkl) becomes larger, i.e., the planar atomic density decreases. This behavior would explain the difficulty in observing any discrete GBD structure when the cores become too close or (hkl) becomes too large. It seems likely that the cores are relatively wide because the ordering energy of the boundary due to the one-dimensional matching is relatively low.

The results in Fig. 9 demonstrate that tilt deviations, as large as $\Delta\beta \approx 14^\circ$, lead to arrays of discrete GBDs possessing spacings as small as $d \approx 30 d_{hkl}$. Such deviations are larger than those which have often been associated with CSL special boundaries. On the basis of the present results we may speculate that arrays of discrete GBDs may form at deviations even larger than those documented here. For example, if $d \approx 15 d_{hkl}$ is a lower limit for the GBD spacing, as suggested by the results in Fig. 7, then discrete GBDs might be present at tilt deviations larger than $\Delta\beta = 20^\circ$.

Of considerable interest are the results for the specimens in Series 3, 4 and 5 where the grain boundary plane was not perpendicular to the

(hkl) planes. These results show that secondary GBD structures are stable over a wide range of orientations of the grain boundary plane when the crystal misorientation is fixed. Particularly noteworthy is the observation of secondary GBDs in Series 4 and 5 where the grain boundary was parallel to the matching (hkl) planes. In this case the (hkl) planes were not attempting edge/edge alignment across the boundary but instead were attempting face/face alignment as indicated schematically in Fig. 12.

A comparison of the results for Series 2 with those for Series 4 and 5 shows that GBDs were observed for a fixed crystal misorientation at both extremes of the possible range of grain boundary orientations, i.e., at orientations parallel to and perpendicular to the matching (hkl) planes.

The present results, that secondary GBD structures were observed in PM boundaries over a relatively wide range of crystal misorientations and grain boundary orientations, suggest that many boundaries occurring in polycrystalline materials which have been assumed to be "general" boundaries in previous studies may actually have been "special" boundaries of the PM type. Also, it appears that such boundaries should be found in general polycrystalline material with a relatively high probability in general agreement with the predictions of Warrington and Boon [5]. If we assume that physically distinguishable GBDs can form in PM boundaries with (hkl) as high as (220) and with deviational misorientations as large as $\Delta\beta = 14^\circ$ we may construct the angular misorientation space over which GBDs may form shown in Fig. 13 where a cone of angles including all misorientations less than 14° has been constructed around each [hkl]. It is seen that the probability that any $\langle 200 \rangle$, $\langle 111 \rangle$ or $\langle 220 \rangle$ direction of a randomly oriented crystal will fall into an appropriate cone is relatively large. Of course, if allowed values of $\Delta\beta$ exceed 14° according to the possibility

discussed previously, or if the polycrystalline material possesses a favorable texture, the probability would be correspondingly increased.

Finally, it should be pointed out that we have no adequate understanding of the physical basis for secondary PM relaxations at the present time. Pond et al. [14] have suggested that the energy of the exactly matched condition is low in certain symmetric tilt boundaries since mirror symmetry can thus be achieved perpendicular to the tilt axis. However, it is clear that this explanation does not apply in the general case. No atomistic calculations or computer simulation of PM boundaries have yet been carried out, and the details of the atomistic structure are therefore undetermined. It is interesting to note that recent lattice imaging observations by Gronsky and Thomas [15] suggest that the (hkl) planes may actually tend to be aligned edge-to-edge when $\gamma \neq 0$. However, more work will have to be done before this point is settled. In cases where $\gamma = 0$ (Series 4 and 5) the (hkl) planes facing the boundary (i.e., planes A and B in Fig. 12) evidently tend to preserve their planar integrity even though there is no matching across the boundary (i.e., across the dashed boundary in Fig. 12). Note also that this boundary possesses no periodicity.

We may conclude that further work will be required to reveal the full range of stability of $\vec{b}_3$ GBDs in PM boundaries and to reveal the physical basis for their stability.

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Table. Summary of PM boundaries investigated and results which were obtained.

Series	[hkl]	θ (deg.)	$\Delta\alpha$ (deg.)	$\Delta\beta$ (deg.)	γ (deg.)	Results
1	[002]	42	$0 < \Delta\alpha \leq 8$	0	90	GBDs observed for $0^\circ < \Delta\alpha \leq 4^\circ$
2	[002]	42	$0 < \Delta\alpha \leq 2$	$0 < \Delta\beta \leq 14$	90	GBDs observed over full range
3	[002]	42	$0 < \Delta\alpha \leq 3$	0	$30 \leq \gamma \leq 60$	GBDs observed over full range
4 *	[002]	37	0	$0 < \Delta\beta \leq 4$	0	GBDs observed over full range
5 *	[002]	45	0	$0 < \Delta\beta \leq 4$	0	GBDs observed over full range
6	[220]	90	$0 < \Delta\alpha \leq 10$	0	90	GBDs observed for $0^\circ < \Delta\alpha \leq 4^\circ$
7	[420]	90	$0 < \Delta\alpha \leq 8$	0	90	no GBDs observed in any boundaries

* Not investigated in present work but studied previously in [12].

FIGURE CAPTIONS

- Fig. 1. (a) Unit cell of FCC crystal lattice. (b) Unit cell of CSL formed by 36.9° rotation of FCC crystal in (a) around $[001]$. Cell is body centered tetragonal. (c) Unit cell of DSC-Lattice corresponding to CSL in (b). Cell is body centered tetragonal. (d) Unit cell of DSC-Lattice for (002) plane matching situation.
- Fig. 2. Schematic diagram illustrating construction of various (002) PM boundaries investigated. (a) Oblique view. (b) Side view as seen along $[100]_1$. Grain boundary plane is ABCD or DCEF.
- Fig. 3. Schematic diagram illustrating construction of various (220) PM boundaries. Grain boundary plane is ABCD.
- Fig. 4. Schematic diagram illustrating construction of various (420) PM boundaries. Grain boundary plane is ABCD.
- Fig. 5. Array of $\vec{b}_3$ secondary GBDs in a Series 1 (002) PM boundary. $\theta = 42^\circ$, $\Delta\alpha = 1.5$, $\Delta\beta = 0$, $\gamma = 90^\circ$. Mag. = $1 \times 10^6 \times$.
- Fig. 6. Moiré pattern produced by two sets of planar traces in grain boundary.
- Fig. 7. Measurements of d/d_{hkl} versus $\Delta\alpha$ for GBDs in Series 1 (002) and Series 6 (220) PM boundaries. $\Delta\beta = 0$, $\gamma = 90^\circ$. Curve calculated from Eq. (3).

Fig. 8. (a) Interaction of GBDs with bubbles in (002) PM boundary.

Mag. = $1 \times 10^6 \times$.

(b) Appearance of Moiré fringes in (220) PM boundary. Note

two sets of superimposed fringes. Spacing of coarser

fringes $\approx 60 \text{ \AA}$. Spacing of finer fringes $\approx 10 \text{ \AA}$.

Fig. 9. Measurements of d/d_{hkl} as a function of $\Delta\alpha$ and $\Delta\beta$ for Series 2 (002) PM boundaries. $\theta = 42^\circ$, $\gamma = 90^\circ$. Curves calculated from Eq. (4).

Fig. 10. Measurements of ρ as a function of $\Delta\alpha$ and $\Delta\beta$ for Series 2 (002) PM boundaries. $\theta = 42^\circ$, $\gamma = 90^\circ$. Curves calculated from Eq. (5).

Fig. 11. Measurements of d/d_{hkl} as a function of $\Delta\alpha$ and γ for Series 3 (002) PM boundaries. $\theta = 42^\circ$, $\Delta\beta = 0$. Curves calculated from Eq. (6).

Fig. 12. Schematic side view of plane matching in Series 4 and 5 (002) PM boundaries. Center of grain boundary core indicated by dashed line.

Fig. 13. Standard stereographic projection of angular misorientation space (within small circles) over which discrete $\vec{b}_3$ GBDs may be stable in PM boundaries. See text for details.

(a)

(b)

(c)

(d)

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

(a)

(b)

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13