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Surface defects in as-grown $\text{Ti}_3\text{Al} + \text{V}$

I. Ehrhart ⁽¹⁾, M. Thomas ⁽¹⁾, A. Vassel ⁽¹⁾ and P. Veyssire ⁽²⁾
⁽¹⁾ ONERA, Direction des Matriaux, BP 72, 92322 Chtillon Cedex, France

⁽²⁾ LEM, CNRS-ONERA, BP 72, 92322 Chtillon Cedex, France

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Rsum. — Les dfauts bidimensionnels prsents dans un alliage de $\text{Ti}_3\text{Al} + \text{V}$ brut de croissance (structure ordonne DO_{19}) sont tudis par microscopie en transmission (MET). Ils sont de deux types, parois d'antiphase (APB) et fautes d'empilement sans dfaut d'ordre (SISF). Les APB sont essentiellement des dfauts thermiques gauches, apparus au cours de la mise en ordre et souvent bords par une superpartielle de vecteur de Burgers $1/6 \langle 11\bar{2}0 \rangle$. Les SISF forment des groupes de quelques units, elles ne rsultent pas de la dissociation de superdislocations mais sont prsentes l'intrieur de boucles fermes de vecteur de Burgers $1/3 \langle 1\bar{1}00 \rangle$. Des interactions entre ces deux familles de dfauts donnent lieu des configurations complexes qui ont t analyses par MET. L'intersection d'une SISF et d'une APB peut se faire de diverses manres traduisant une attraction faible entre la SISF et la superpartielle de vecteur de Burgers $1/6 \langle 11\bar{2}0 \rangle$.

Abstract. — A transmission electron microscope (TEM) investigation of surface defects contained in an as-grown $\text{Ti}_3\text{Al} + \text{V}$ ordered alloy (DO_{19}) was carried out and evidence was obtained for two categories of defects, namely antiphase boundaries (APB) and superlattice intrinsic stacking faults (SISF). APBs are non-planar, they are thermal defects that were formed during alloy ordering; they are often terminated by a superpartial with a $1/6 \langle 11\bar{2}0 \rangle$ Burgers vector. SISFs appear as groups of several unities, they do not originate from superdislocation dissociation but are part of closed superpartial loops with $1/3 \langle 1\bar{1}00 \rangle$ Burgers vector. SISFs and APBs may interact in order to give complex configurations that have been analyzed by TEM. Several different types of intersections between a SISF and an APB may occur which all indicate a rather weak interaction between a SISF and a $1/6 \langle 11\bar{2}0 \rangle$ superpartial.

1. Introduction.

The intermetallic compound Ti_3Al has an hexagonal packing that orders under the DO_{19} structure below $T_{\text{OD}} = 1\,150\,^\circ\text{C}$. It exhibits good mechanical properties at elevated temperature but a very limited ductility up to $600\,^\circ\text{C}$ that can be however improved by addition of a β stabilizer [1]. The present study is a preliminary work, part of an extensive study devoted to the mechanical properties of Ti_3Al -based alloys [2-3]; it is aimed at analyzing various types of defects on a fine scale, their modes of formation and their mutual interactions, in an as-cast $\text{Ti}_3\text{Al} + \text{V}$ alloy.

Depending upon their displacement vector $\mathbf{R}$, several surface defects are liable to occur in the basal plane [4]: antiphase boundaries (APBs;

$\mathbf{R} = 1/6 \langle 11\bar{2}0 \rangle$), superlattice intrinsic/extrinsic stacking faults (SISF/SESF; $\mathbf{R} = 1/3 \langle 10\bar{1}0 \rangle$) and complex stacking faults (CSFs; $\mathbf{R} = 1/6 \langle 10\bar{1}0 \rangle$). The atomic stacking parallel to the basal plane in the DO_{19} structure is such that a SISF differs from a CSF essentially because it does not introduce any wrong first nearest-neighbour at the interface, this is a consequence of atomic ordering. Hence, the surface energy of the SISF is expected to be substantially smaller than that of a CSF. A very similar situation is met in the L_{12} structure [5].

The existence of surface defects in Ti_3Al -based alloys has been reported by several groups. After deformation at $900\,^\circ\text{C}$, Lipsitt *et al.* [6] observed faults extended on the basal plane whose nature was not elucidated; in addition, these authors provided

examples of paired dislocations, with a highly variable separation distance of the order of several tens of nm, that were analyzed in terms of a superdislocations ($\mathbf{b} = 1/3 \langle 11\bar{2}0 \rangle$) dissociated into two superpartials with collinear Burgers vectors and separated by an antiphase boundary (APB). It is however likely that these features were in fact dipoles since it was recently confirmed under weak-beam dark-field conditions by Thomas *et al.* [2] and Court *et al.* [7] that a superdislocations are indeed dissociated, but their actual separation is one order of magnitude lesser than those reported by Lipsitt *et al.* [6], i.e. such that it could not be resolved but by use of the weak-beam imaging technique. In Ti_3Al [8] and $\text{Ti}_3\text{Al} + \text{Nb}$ [9] deformed at 700 °C under constant strain-rate and in creep, respectively, Yang observed stacking faults limited by dislocations ; in the former alloy, the bordering dislocations were identified as $1/6 \langle 10\bar{1}3 \rangle$ partials and the faults were found to belong to the (0001) basal plane and to be intrinsic in nature. In a review paper, Williams [10] referred to Blackburn's unpublished observations of an anomalous contrast which arises at stacking faults, that may originate from the condensation of an extra-layer either of Ti or of disordered material.

2. Experimental procedure.

The alloy under investigation was Ti_3Al containing 3 wt. % of vanadium which, when used in larger concentration, is employed in order to stabilize the β phase. Buttons of this alloy were prepared by vacuum arc melting. They were aged for 1 h at 1 000 °C. Discs, 3 mm in diameter, were subsequently cut from one button and mechanically thinned down to 100 μm . They were then jet elec-

tropolished in a solution containing 60 % methanol, 34 % butylcellosolve and 6 % perchloric acid solution, maintained at a temperature of - 40 °C, under a voltage of 20 V.

A JEOL 200 CX electron microscope equipped with a double tilt goniometer stage was used to examine the foil at an accelerating voltage of 200 kV.

3. Observations.

Whereas the annealing temperature has the appropriate order of magnitude so as to promote β formation, if any, the resulting material was under the form of single phase (α_2) alloy containing a variety of surface defects that exhibit fringe systems typical of either one of the two principal categories introduced above, viz. APB or SISF. These are associated with specific shape and contrast properties (Figs. 1, 2) :

— since they are formed on the basal plane exclusively, SISFs and CSFs are always planar. Their fringes are thus *rectilinear*, SISFs exhibit symmetrical bright-field and asymmetrical dark-field images, typical of a phase shift $\alpha = 2 \pi \mathbf{g} \cdot \mathbf{R} = 2 n \pi / 3$, where n is an integer [11] and $\mathbf{g}$ is the operating diffraction vector. In as grown $\text{Ti}_3\text{Al} + \text{V}$, stacking faults never appear as isolated defects but under groups of several unities ; the average distance between individual faults is about 0.3 μm and they often expand over several μm in the foil ;

— APBs are in general associated to *curved* fringes, the fringe systems are symmetrical under both bright- and dark-field conditions ($\alpha = n \pi$). They are not distributed homogeneously in the material, their density is in general lesser than that of stacking faults.

Fig. 1. — Dark-field view of a set of SISFs with a fundamental reflection operating. The mark M features a detail which is common to figures 2 and 3.

Fig. 2. — Bright-field micrograph of the same area as in figure 1 showing the curved aspect of APBs which are now in contrast.

Burgers vectors and displacement vectors were determined with the appropriate invisibility criteria for lattice defects, i.e. $\mathbf{g} \cdot \mathbf{b} = 0$ and $\mathbf{g} \cdot \mathbf{R} = 2n\pi$, using either fundamental reflections ($22\bar{4}X$ or $02\bar{2}X$; $X \leq 2$) or superlattice reflections ($01\bar{1}X$ or $11\bar{2}X$), respectively (Tab. I). Since all dislocations

Table I. — List of reflections $\mathbf{g}$ used in order to determine displacement vectors $\mathbf{R}$ of the defects under analysis in figures 1 to 4, and corresponding values of the $\mathbf{g} \cdot \mathbf{R}$ for all possible displacement vectors of the DO_{19} structure (the Burgers vectors of the partial dislocations were determined under fundamental reflections, the corresponding $\mathbf{g} \cdot \mathbf{b}$ values are then twice as large as those listed in this table).

$\mathbf{R}$	$\mathbf{g}$	$1\bar{2}1X$	$11\bar{2}X$	$2\bar{1}\bar{1}X$	$0\bar{1}1X$	$1\bar{1}0X$	$1\bar{0}1X$	
$1/6[\bar{1}010]$	0	$-1/2$	$-1/2$	$1/6$	$-1/6$	$1/3$		CSF
$1/6[0\bar{1}\bar{1}0]$	$-1/2$	$1/2$	0	$-1/3$	$-1/6$	$-1/6$		
$1/6[1\bar{1}00]$	$1/2$	0	$1/2$	$1/6$	$1/3$	$-1/6$		
$1/3[\bar{1}010]$	0	-1	-1	$1/3$	$-1/3$	$2/3$		SISF
$1/3[0\bar{1}\bar{1}0]$	-1	1	0	$-2/3$	$-1/3$	$-1/3$		
$1/3[1\bar{1}00]$	1	0	1	$1/3$	$2/3$	$-1/3$		
$1/6[11\bar{2}0]$	$-1/2$	1	$1/2$	$-1/2$	0	$-1/2$		APB
$1/6[\bar{1}2\bar{1}0]$	-1	$1/2$	$-1/2$	$-1/2$	$-1/2$	0		
$1/6[\bar{2}110]$	$-1/2$	$-1/2$	-1	0	$-1/2$	$1/2$		

which belong to the configurations under investigation are out of contrast when $\mathbf{g} = 0002$ is operating, the direction of their Burgers vectors is of either the $\langle 11\bar{2}0 \rangle$ or the $\langle 10\bar{1}0 \rangle$ type. It is worthy of mention that the present results differ substantially from Yang's determinations [8] in which the Burgers vectors, i.e. $1/6\langle 10\bar{1}3 \rangle$, of the partial dislocations that border stacking faults do not belong to the basal plane.

The same choice limitation as for partial dislocations, between the $\langle 11\bar{2}0 \rangle$ and the $\langle 10\bar{1}0 \rangle$ directions, of course applies for the displacement vector $\mathbf{R}$ of the planar defect that each of these partials generates. Since stacking faults are in general out of contrast when imaged with $\{11\bar{2}X\}$ reflecting planes (Fig. 3), $\mathbf{g} \cdot \mathbf{R}$ is always an integer for these reflec-

Fig. 3. — Dark-field micrograph within the same field as for figures 1 and 2 illustrating the fact that SISFs are out of contrast under a $\{11\bar{2}X\}$ -type reflection. A residual contrast is however observed at SISFs (arrows).

tions. In view of the values of the $\mathbf{g} \cdot \mathbf{R}$ product, which are listed in table I for any physically possible displacement vector parallel to either one of the two remaining $\langle 11\bar{2}0 \rangle$ and $\langle 10\bar{1}0 \rangle$ directions, (i) the potential CSF nature of these defects is then unambiguously excluded and (ii) the observed contrast is consistent with the fact that these stacking faults are superlattice stacking faults, i.e. $\mathbf{R} = 1/3\langle 10\bar{1}0 \rangle$. A contrast experiment showing their intrinsic nature is presented in figure 4. Unfortunately, the invisibility criterion does not allow for discrimination between the three types of SISF displacement vectors of the DO_{19} structure since, whatever $\mathbf{g}$, they are either visible or invisible simultaneously (Tab. I). This is

Fig. 4. — Dark-field contrast of a SISF to prove the intrinsic nature of stacking faults : the g vector points toward the (faint) dark outer fringe (DF) (see Ref. [11]) ; although it is less visible than the two other systems, the left hand side fault is also bordered on its right side by a dark fringe.

because distinct $1/3 \langle 10\bar{1}0 \rangle$ displacement vectors differ from each other by one unit translation of the Bravais lattice ($1/3 \langle 11\bar{2}0 \rangle$). As it will be exemplified in the following, this may render defect analysis more complex when a SISF has reacted with APBs

or dislocations, i.e. when the Burgers vector of the bordering partial and the SISF displacement vector are no longer the same.

In figure 5 is presented a low magnification view of extremities of SISF strips, which belong to a

Fig. 5. — Low magnification of SISFs extremities showing that they are bordered by partial dislocations.

group, a few μm long, that is entirely located within a transparent area of the foil. It was determined that, unless the SISF has reacted with other defects, each SISF that belongs to this group is terminated on both sides by superpartials with same $1/3 \langle 10\bar{1}0 \rangle$ Burgers vector but with opposite signs. Hence, the stacking faults under analysis do not result from the dissociation of a perfect dislocation, according to the generic reaction: $1/3 \langle 11\bar{2}0 \rangle = 1/3 \langle 10\bar{1}0 \rangle + 1/3 \langle 01\bar{1}0 \rangle$, they are in fact inclined sections of parallel extended SISF loops. Since each superpartial is normally submitted to a back force that originates from surface tension (γ/b , where γ is the SISF energy), that these loops remain in metastable equilibrium in the foil points to a significant lattice resistance to superpartial motion (the order of magnitude of the friction stress would be 100 MPa for a SISF energy of 5 to 10 mJ/m²).

In order to obtain additional quantitative structural information on these defects and on their interactions, three different areas that contained a number of surface defects of both categories (APBs and SISFs) have been the object of a detailed transmission electron contrast analysis, the results of which are reported below.

3.1 EXAMPLE A. — The first area is represented in figure 6 with the notations for the different elements under analysis indicated; all defects simultaneously in contrast.

Since R_4 and R_5 are out of contrast with the superlattice reflections $g = 1\bar{1}01$ and $g = \bar{1}010$, respectively, then $R_5 = \pm 1/6 [1\bar{2}10]$ and $R_4 = \pm 1/6 [11\bar{2}0]$.

Fig. 6. — Dark-field view of configuration A with the notations employed in the text indicated. The numbers in white refer to the alternative reactions of an APB and a SISF, viz. 1, 2 and 3, discussed in section 4.

The line of dislocation b_4 remains in contrast with both $g = 2\bar{2}02$ and $g = \bar{2}020$, it becomes out of contrast with $g = 0\bar{2}22$ (Figs. 7a, 7b, 7c, respectively), whereas b_3'' is visible with $g = 0\bar{2}22$ and $g = 2\bar{2}02$ and invisible with $g = \bar{2}020$; therefore, $b_4 = \pm 1/6 [2\bar{1}\bar{1}0]$ and $b_3'' = \pm 1/6 [1\bar{2}10]$.

a)

b)

c)

Fig. 7. — Contrast analysis of dislocation Burgers vectors. The operating reflections are chosen in order to show that dislocations b_1 and b_3'' , which remain in contrast, cannot be collinear with a $\langle 11\bar{2}0 \rangle$ direction. a) $g = 2\bar{2}02$, dislocations b_2 , b_3'' and b_4 are in contrast, b) $g = \bar{2}020$, b_2 and b_3'' are out of contrast, c) $g = 0\bar{2}22$, b_4 is invisible.

Since dislocation b_2 , which bounds on one side the APB R_5 :

(i) does not induce any shift between the fringe systems of R_2 and R_3 , this dislocation must be a partial translation of the ordered lattice (it should be noted that, in terms of nature and position of their fringe systems, there is no difference between R_2 and R_3 which differ only from their intensities; hence $R_2 = -R_3$);

(ii) is invisible with $g = \bar{2}020$, then $b_2 = R_5 = \pm 1/6 [1\bar{2}10]$.

Conversely, since a change is observed between the fringe contrast of defects R_1 and R_2 , the Burgers vector of dislocation b_1 cannot be that of a APB-generating superpartial, but should rather be of the $\langle 10\bar{1}0 \rangle$ type (Figs. 7b, 7c). In addition, since dislocation b_1 remains in contrast with both $g = 4\bar{2}\bar{2}2$ and $g = 22\bar{4}0$, its Burgers vector b_1 is a multiple of $\pm 1/6[10\bar{1}0]$ (i.e. either $\pm 1/6[10\bar{1}0]$ or $\pm 1/3[10\bar{1}0]$). Similarly, b'_3 remains in contrast with both $g = 22\bar{4}2$ and $g = 2\bar{4}24$ and becomes invisible with $g = 4\bar{2}\bar{2}2$, hence b'_3 is a multiple of $\pm 1/6[01\bar{1}0]$; although the experimental evidence for this is unambiguous, no micrographs are presented in order to illustrate the imaging conditions in question since the structure factors of superlattice reflections and their resulting contrast are poor.

The uncertainties that one usually gets from the application of the invisibility criteria, upon the sign of the displacement and of the Burgers vectors and occasionally upon the amplitude of these, could be eliminated by making use of the set of conservation

equations that appears in bold letters in relations (1a-1e). Considering that any solution that involves a dislocation Burgers vector whose amplitude is larger than that of a SISF-generating superpartial ($1/3\langle \bar{1}100 \rangle$) is not physically acceptable, it was found that the observed contrast happens to be consistent with one unique set of displacement and Burgers vectors that constitutes the right member of equations (1a) to (1e) :

$$\begin{aligned} \mathbf{R}_5 + \mathbf{b}_4 &= \mathbf{R}_4 \rightarrow 1/6[\bar{1}2\bar{1}0] + 1/6[2\bar{1}\bar{1}0] \\ &= 1/6[11\bar{2}0] \end{aligned} \quad (1a)$$

$$\begin{aligned} \mathbf{R}_4 + \mathbf{b}_3'' &= \mathbf{R}_6 \rightarrow 1/6[11\bar{2}0] + 1/6[1\bar{2}10] \\ &= 1/6[2\bar{1}\bar{1}0] \end{aligned} \quad (1b)$$

$$\begin{aligned} \mathbf{R}_6 + \mathbf{b}_3' &= \mathbf{R}_3 \rightarrow 1/6[2\bar{1}\bar{1}0] + 1/6[0\bar{1}10] \\ &= 1/3[1\bar{1}00] \end{aligned} \quad (1c)$$

$$\mathbf{R}_2 = -\mathbf{R}_3 \quad (1d)$$

$$\begin{aligned} \mathbf{R}_2 + \mathbf{b}_1 &= \mathbf{R}_1 \rightarrow 1/3[\bar{1}100] + 1/3[10\bar{1}0] \\ &= 1/3[01\bar{1}0] \end{aligned} \quad (1e)$$

Fig. 8. — Configuration B with the notations of selected defects are indicated (bright-field).

3.2 EXAMPLE B. — The second area which will be examined here, was located in the thin foil close to the previous example (Fig. 2) ; it includes a number of APBs which, together with notations, are shown in figure 8. Since the sets of defects $\{R_1, R_6 \text{ and } R_8\}$, $\{R_2, R_4 \text{ and } R_9\}$ and $\{R_3, R_5 \text{ and } R_7\}$ are invisible with $\mathbf{g} = 0\bar{1}11$, $\bar{1}010$ and $1\bar{1}01$, respectively, one gets :

$$\mathbf{R}_1 = \mathbf{R}_6 = \mathbf{R}_8 = \pm 1/6 [\bar{2}110] \quad (2a)$$

$$\mathbf{R}_2 = \mathbf{R}_4 = \mathbf{R}_9 = \pm 1/6 [\bar{1}2\bar{1}0] \quad (2b)$$

$$\mathbf{R}_3 = \mathbf{R}_5 = \mathbf{R}_7 = \pm 1/6 [\bar{1}\bar{1}20]. \quad (2c)$$

Then, in the same vein as for configuration A, consistency between the determinations of Burgers vectors and displacement vectors that take part in configuration B is ensured by making use of the following set of consistent conservation equations :

$$\mathbf{b}_1 = \mathbf{R}_1 \quad (3a)$$

$$\mathbf{R}_2 + \mathbf{b}_2 = \mathbf{R}_3 \rightarrow \mathbf{R}_1 + \mathbf{R}_3 = \mathbf{R}_4 \quad (3b)$$

$$\rightarrow \mathbf{R}_4 + \mathbf{R}_5 = \mathbf{R}_6 \rightarrow \mathbf{b}_3 = \mathbf{R}_5 \rightarrow \quad (3c)$$

$$\mathbf{R}_6 + \mathbf{b}_4 = \mathbf{R}_7 \rightarrow \mathbf{R}_7 + \mathbf{b}_5 = \mathbf{R}_8 \rightarrow \mathbf{R}_8 + \mathbf{b}_6 = \mathbf{R}_{10} \quad (3d)$$

$$\rightarrow \mathbf{R}_{10} + \mathbf{b}_7 = \mathbf{R}_9 \rightarrow \mathbf{b}_8 = \mathbf{R}_9. \quad (3e)$$

Since b_1 is found not to introduce any fringe shift at the SISF on which it appears to be located, it is pinned onto it without having reacted ; then, $\mathbf{b}_1$ and $\mathbf{R}_1$ can be determined independently (Eq. (3a)).

Considering that dislocations b_1 and b_2 happen to be simultaneously invisible under $\mathbf{g} = 0\bar{1}11$ (Fig. 9), one gets $\mathbf{b}_1 (= \pm \mathbf{R}_1) = \pm \mathbf{b}_2 = \pm 1/6 [2\bar{1}\bar{1}0]$.

Dislocations b_3 and b_4 are out contrast with $\mathbf{g} = 2\bar{2}02$ and $\mathbf{g} = \bar{1}010$, respectively ; hence, $\mathbf{b}_3 = \pm 1/6 [11\bar{2}0]$ and $\mathbf{b}_4 = \pm 1/6 [\bar{1}2\bar{1}0]$. For dislocation b_5 is visible with all three $\langle 22\bar{4} X \rangle$ reflection vectors, b_5 is an APB-generating superpartial (Tab. I) and, similar to dislocation b_1 , interaction between dislocation b_5 and SISFs is not manifested by any contrast peculiarity that is discernible under a fundamental reflection. From equation $\mathbf{R}_7 + \mathbf{b}_5 = \mathbf{R}_8$ in relation (3d), it can therefore be deduced that $\mathbf{b}_5 = \pm 1/6 [1\bar{2}10]$.

Eventually, since dislocations b_6 and b_7 are invisible with $\mathbf{g} = 4\bar{2}\bar{2}2$ and $\mathbf{g} = 2\bar{4}24$, their Burgers vector must be a multiple of $\pm 1/6 [01\bar{1}0]$ and $\pm 1/6 [10\bar{1}0]$, respectively (i.e. $1/6 \langle 1\bar{1}00 \rangle$ or $1/3 \langle 1\bar{1}00 \rangle$).

Taking into account equations (2) and the above independent determinations of Burgers vectors, one gets the unique solution listed in table II.

a)

b)

c)

Fig. 9. — Configuration B. Contrast experiment that shows that dislocations b_1 and b_2 possess the same Burgers vector.

A SISF, noted R_{10} , with a $1/3 [\bar{1}100]$ displacement vector is located between b_6 and b_7 . Under a fundamental reflection, its contrast is distinct from the contrast of the SISFs that are located on the same plane but on the other side of superpartials b_6 and b_7 (Fig. 10). The origin of R_{10} will be discussed in section 4.

Table II. — *List of displacement and Burgers vectors of the defects that belong to example B (Fig. 8) ; the appropriate relations in equations (2) and (3), from which these vectors are deduced, are indicated.*

$\mathbf{b}_1$ (3a) $1/6[\bar{2}110]$	$\mathbf{R}_1$ (2a) (3a) $1/6[\bar{2}110]$	$\mathbf{b}_2$ (3b) $1/6[\bar{2}\bar{1}\bar{1}0]$	$\mathbf{R}_2$ (2b) (3c) $1/6[\bar{1}2\bar{1}0]$	$\mathbf{b}_3$ (3c) $1/6[\bar{1}\bar{1}20]$	$\mathbf{R}_3$ (2c) $1/6[11\bar{2}0]$	$\mathbf{b}_4$ (3d) $1/6[\bar{1}210]$	$\mathbf{R}_4$ (2b) $1/6[\bar{1}2\bar{1}0]$	$\mathbf{b}_5$ (3d) $1/6[\bar{1}2\bar{1}0]$
$\mathbf{R}_5$ (2c) $1/6[\bar{1}\bar{1}20]$	$\mathbf{b}_6$ (3c) $1/6[01\bar{1}0]$	$\mathbf{R}_6$ (2a) $1/6[\bar{2}110]$	$\mathbf{b}_7$ (3e) $1/6[10\bar{1}0]$	$\mathbf{R}_7$ (2c) $1/6[\bar{1}\bar{1}20]$	$\mathbf{R}_8$ (2d) $1/6[\bar{2}110]$	$\mathbf{R}_9$ (2b) $1/6[\bar{1}2\bar{1}0]$	$\mathbf{R}_{10}$ (3d) $1/3[\bar{1}100]$	$\mathbf{b}_{10}$ (3e) $1/6[\bar{1}2\bar{1}0]$

Fig. 10. — Configuration B. Set of micrographs to show the contrast peculiarities of planar defect R_{10} . All the micrographs located on the left-hand side of this figure were taken with $\{10\bar{1}1\}$ -type reflections in order to show that the APBs (R_8 and R_9) which border R_{10} are different. Each right-hand side micrograph corresponds to a diffraction vector twice as large as that of the micrograph on its left, they are aimed at pointing out that R_{10} differs from the bordering SISFs.

Fig. 11. — Configuration C. a) Overall view in bright field and notations, b) dark-field, R_1 and R_2 are in contrast and out of contrast, respectively, c) dark-field where R_1 and R_2 are now out and in contrast, respectively, d) detailed dark-field view of the dislocation that borders R_1 .

3.3 EXAMPLE C. — This configuration reproduces many of the features exhibited by the two previous ones (Fig. 11). It contains two distinct APBs (displacement vectors $\mathbf{R}_1 = 1/6[11\bar{2}0]$ and $\mathbf{R}_2 = 1/6[\bar{2}110]$) which, rather than terminating at SISFs, are always bordered by individual superpartials. Also is exemplified the fact that intersections between a given APB and a group of identical parallel SISFs may either be such that the defects look transparent to one another (1) or be manifested by a reaction that involves a dislocation (2).

4. Discussion.

Dislocations with a $1/6\langle 11\bar{2}0 \rangle$ Burgers vector, which are perfect dislocations in the disordered state, become partial dislocations of the DO_{19} structure and ordering governs the arrangement of surface defects relative to dislocations. Upon cooling, these $1/6\langle 11\bar{2}0 \rangle$ dislocations which are interspersed in the crystal as perfect dislocations at temperatures above T_{OD} , must terminate APBs in the ordered state. It is thus expected that APBs are created between pairs

of these partials at ordering and that interconnection occurs statistically within pairs of grow-in dislocations. Since thermal APBs result from the impingement of neighbouring ordered domains, the distance between superpartials connected by a thermal APB is not determined in the same way as it would be in a regular dissociation process, as the balance between elastic and surface tension forces. The APB distribution in the crystal is the consequence of a complex dynamical interaction between as-grown dislocations and the APBs that may still diffuse once formed at elevated temperature in order to relax their surface energy. Of course, APB connection may also occur between one partial and a grain boundary, a free surface, another APB, or between any combination of two of these. That APBs adopt non-planar shapes in the crystal indicates that non-conservative processes have been extensively involved during their formation and this is supported by the fact that the potential glide plane of the APB-bonding superpartials was often determined to be of the basal type, i.e. parallel to the SISFs that they intersect.

In so far as APB energy is concerned, the absence of favoured orientations at these interfaces indicates a rather isotropic energy at high temperature.

We have evidenced several kinds of interactions between a SISF and an APB. These interactions are in general not very strong since superpartials with a $1/6\langle 11\bar{2}0 \rangle$ Burgers vector, which border an APB, are not necessarily pinned onto these SISFs with which they have been subjected to an intersection (dislocations b_2 and b_1 in examples A and B, respectively).

In fact three types of intersections between a SISF and an APB have been identified according to the nature of the defect that lies at their intersection; these modes are all present in the first example (Fig. 6) :

— type 1 : no interaction occurs (in example A, R_4 and R_5 when intersecting the group of unlabelled SISFs located in between dislocations b_2 and b_4 , and any intersection between surface defects in example C) ;

Fig. 12. — Schematic sequence of the postulated mechanism that yields to the formation of R_{10} : a) initial curved APBs separated by a superpartial, b) the APBs are sheared by SISFs and the superpartial moves toward the trace of the SISF on the APB while the outer APB c) tends to collapse towards the SISF, d) the superpartial dissociates in order to erase the CSF that results from the superimposition of the APB onto the SISF, e) in between the two superpartials lies a SISF whose displacement vector differs from that of the bordering SISFs.

— type 2: the APB surface has two distinct displacement vectors $\mathbf{R}'$ and $\mathbf{R}''$ on each side of the SISF: the APB is pinned onto the SISF by a dislocation with a $1/6\langle 11\bar{2}0 \rangle$ Burgers vector that corresponds to the difference between $\mathbf{R}'$ and $\mathbf{R}''$ (for instance dislocation b_4 in configuration A, with $\mathbf{R}' = \mathbf{R}_5$ and $\mathbf{R}'' = \mathbf{R}_4$);

— type 3: a partial dislocation with a $1/6\langle 1\bar{1}00 \rangle$ Burgers vector lies at the intersection between the APB and the SISF (b'_3 , example A, see also b_6 and b_7 in configuration B).

The situation where the APB terminates onto the SISF (b_1 and b_2 in configurations B and A, respectively) is a particular case of either type 1 or type 2 interaction. The fact that the partial which borders an APB may be pinned onto a SISF but that, at the intersection between a SISF and an APB, a « stair-rod » dislocation is not necessarily left, indicates that SISFs are not transparent to $1/6\langle 11\bar{2}0 \rangle$ partials but that interaction between these is weak. The variety of interactions between an APB and a SISF is well illustrated in configuration A where all three above modes of interaction are found within one curved defected surface (see Fig. 6).

In so far as type 2 interaction is concerned, it is not insured that the « stair-rod » dislocation that is cozonal with an APB and a SISF, is a direct by-product of the intersection event. In fact, it may be the result of a high temperature reorganization of the APB microstructure in the vicinity of a SISF, according to the scheme of figure 12. In this particular instance, we suggest that a curved APB, containing a $1/6\langle 11\bar{2}0 \rangle$ superpartial was first formed in the crystal (Fig. 12a). This APB was then intersected by a group of SISFs and the whole system transformed

into the configuration schematized in figure 12b, by climb of the APB superpartial toward the SISF. As already mentioned above, the occurrence of such a process would mean that a $1/6\langle 11\bar{2}0 \rangle$ superpartial has a slightly favoured position at the intersection between an APB and a SISF. In order for the superpartials to be attracted, it is in fact sufficient that the dislocation is locally intersected by the SISF, a situation which provides a nucleation site from where further rearrangement of the superpartial line may then zip along this favoured position.

Again a reorganization of SISF at high temperature can serve as a basis to explain type 3 interaction, which we regard as a continuation of the preceding process. In fact, if temperature is still high enough, the curved APB tends to adopt planar forms in order to reduce its surface energy. In the particular instance of figure 12c, this would promote diffusion of the APB toward the SISF and eventually their mutual combination (Fig. 12d). The net result of this is a CSF which, despite being the defect with the highest energy per unit surface (Sect. 1), provides the lowest net energy for this very configuration. Further energy reduction can however be obtained from the stair-rod $1/6\langle 11\bar{2}0 \rangle$ superpartial that may dissociate into two different $1/6\langle 1\bar{1}00 \rangle$ partials. The driving force for this dissociation originates from the gain in energy provided by the subsequent transformation of the CSF into a SISF (Fig. 12e). This is actually the eventual combination that was found for R_{10} and dislocations b_6 and b_7 in figures 2 and 10. It can be added that the fact that dislocation b'_3 , which borders APB R_4 , is exactly aligned with the trace of SISF R_3 , suggests that the complex arrangement of R_4 , b'_3 , R_6 , b'_3 and R_3 corresponds to a further step in the reorganization of scheme 12e, which will not be discussed here.

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