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Burgers vector determination for quasi-crystalline dislocations by the diffraction contrast technique

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Abstract. The diffraction contrast method for studying dislocations in quasi-crystals is discussed and summarized. As a general principle, by finding five linearly independent extinction reflections g_i ($i = 1, 2, 3, 4, 5$), under which the dislocation contrast is invisible, the direction of the Burgers vector b of a dislocation in an icosahedral quasi-crystal is determined to be the vector product of these five reciprocal vectors. By applying this method we determined the Burgers vector b of a dislocation in an $Al_{70}Pd_{20}Mn_{10}$ icosahedral quasi-crystal to be parallel to the six-dimensional vector $[2\ -1\ 0\ -2\ 0\ -1]$ which possesses a rather large phason component.

1. Introduction

Unlike the case of conventional crystals, dislocations in quasi-crystals (QCs) may induce not only phonon strain but also phason strain and they must be characterized by a high-dimensional Burgers vector [1–3], e.g. a six-dimensional (6D) Burgers vector b for a dislocation in an icosahedral quasi-crystal (IQC). In order to determine the Burgers vector of a dislocation in an IQC experimentally, high-resolution electron microscopy (HREM), diffraction contrast and defocus convergent-beam electron diffraction (CBED) techniques have been employed and progress has been achieved [4–12]. Using the HREM technique and digital treatment, a useful analysis procedure for quasi-crystalline dislocations was suggested by Devaud-Rzepski *et al* [5]. The method based on the diffraction contrast technique has been discussed by Wollgarten *et al* [6]. They analysed the extinction properties of quasi-crystalline dislocations and proposed two basic extinction conditions, i.e. a strong-extinction condition (SEC) and a weak-extinction condition (WEC). On the basis of this analysis they proposed a principle for the determination of the Burgers vector direction. According to this principle, two SECs and one WEC should be found. Recently the theoretical and experimental details of the defocus CBED method for the Burgers vector determination of quasi-crystalline dislocations were described by Feng and Wang [13]. From this description we can determine the 6D Burgers vector of an isolated dislocation completely, including its direction and magnitude. However, for high-density dislocations or small dislocation loops, this method may not be suitable. In these cases, the diffraction contrast technique would be a useful choice. However, for the reason discussed in section 2.1, the principle proposed by Wollgarten *et al* is not generally practicable.

In the present paper, we firstly discuss basic principles for determining the direction of the 6D Burgers vector of a dislocation in an IQC and then give a typical example for a dislocation in $Al_{70}Pd_{20}Mn_{10}$ IQC using this method. From this example we can see that this method may be generally practicable.

2. General principles

2.1. The diffraction vectors used to form two-beam diffraction contrast of a defect in an icosahedral quasi-crystal

As we know, a strong diffraction spot separately situated is needed for two-beam imaging in a transmission electron microscope. According to our experience, in IQCs such as Al–Pd–Mn and Al–Cu–Fe alloys, generally only three types of diffraction spot are mostly appropriate for a good two-beam contrast experiment. Figure 1 shows a selected-area electron diffraction pattern taken along a twofold axis of the IQC. In figure 1, the three types of reflection are labelled F, T1 and T2. For convenience, we call them F-type, T1-type and T2-type reflections, respectively. For an F-type reflection, its indices are of the form $\{2422-2-2\}$, which is along a fivefold axis. The indices of T1- and T2-type reflections are of the form $\{02-2-404\}$ and $\{04-4-606\}$, respectively. They are in the same reflection row along a twofold axis. Clearly only the extinciton condition operated by a T1 or T2 reflection can be judged to belong to a SEC or a WEC. Furthermore, owing to the limitation of the specimen-tilting device in the experiment, only about two thirds of them can be obtained. Figure 2 shows a stereographic projection of the IQC along a twofold axis. If the foil normal is parallel to the projection axis, then only the reflections along the directions A, B, ..., N can be achieved practically. The indices of the reflections corresponding to directions A–N are listed in table 1. From figure 2 we can see that, if the physical component $b^{\parallel}$ of a Burgers vector is along a twofold axis such as direction I, then there are only six reflections T1(G), T2(G), T1(P), T2(P), F(C) and F($e_5^{\parallel}$) which are appropriate for good two-beam contrast experiment and orthogonal to $b^{\parallel}$ and hence may fulfil the SEC. However, owing to the limited tilting angle, T1(P) and T2(P) cannot be achieved experimentally. Moreover, since the reflections $\tau^{-1}g_F$ and τg_F are rather weak, it is very difficult to confirm whether reflection F(C) and F($e_5^{\parallel}$) belong to the SEC. Therefore, in this case, only one confirmative SEC can be obtained by using reflections T1(G) and T2(G).

In short, there are some practical difficulties in applying the principle (i.e. finding two SECs and one WEC) proposed by Wollgarten *et al* to determine the Burgers vector direction of a quasi-crystalline dislocation. In the following we shall demonstrate that we need not judge whether an extinction is a SEC or a WEC, and that finding two SECs and one WEC is not the only way to obtain the Burgers vector direction.

2.2. General method for the determination of the six-dimensional direction of the Burgers vector of a dislocation in the icosahedral quasi-crystal

It is well known that for conventional crystals the Burgers vector b of a dislocation is three dimensional; so, according to the extinction rule of a dislocation ($g \cdot b = 0$), only two independent extinction reflections g_1 and g_2 are needed to determine its direction. The direction of the Burgers vector can be obtained as the vector product of g_1 and g_2, which can be expressed as a determinant:

$$b \parallel g_1 \times g_2 = \begin{vmatrix} i & j & k \\ g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \end{vmatrix} \tag{1}$$

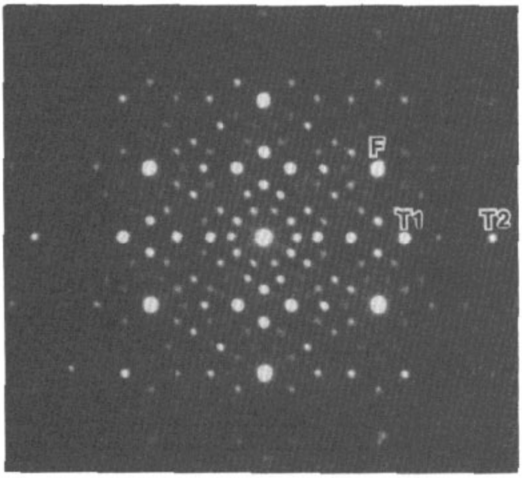

Figure 1. A selected-area electron diffraction pattern taken along a twofold axis of an Al–Pd–Mn IQC. Three types of reflection (F (along a fivefold axis), T1 and T2 (along a twofold axis but of different lengths)) which are suitable for forming a good two-beam contrast are labelled.

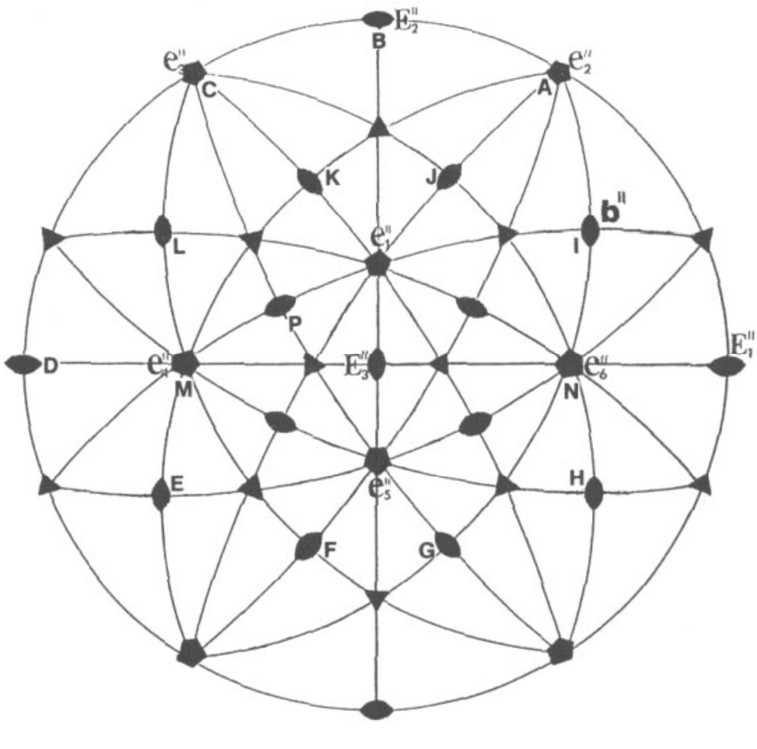

Figure 2. Stereographic projection of the icosahedral point group along a twofold direction. $E_1^{\parallel}$, $E_2^{\parallel}$ and $E_3^{\parallel}$ are basic vectors of the physical subspace and $e_1^{\parallel}$, $e_2^{\parallel}$, $e_3^{\parallel}$ $e_4^{\parallel}$, $e_5^{\parallel}$ and $e_6^{\parallel}$ are the projections of the basis vectors e_1, e_2, e_3, e_4, e_5 and e_6. A–N denote 14 directions used in the contrast experiment (see table 1). The Burgers vector component $b^{\parallel}$ is also indicated.

Table 1. 6D indices of the operating reflections and the corresponding behaviour in experiment (In indicates in contrast, and Out indicates out of contrast). The first column lists their directions indicated in figure 2 and the fourth column lists the relevant figure.

Direction in figure 2	6D indices of the reflection	Contrast	Figure
A	242 −2 −22	In	3(*a*)
B	2440 −20	Out	3(*g*)
	4660 −40	In	
C	2242 −2 −2	Out	3(*b*)
D	02 −2 −404	In	
	04 −4 −606	In	
E	0 −4042 −2	In	
	0 −6064 −4	In	
F	0 −4 −2240	Out	
	0 −6 −4460	In	
G	0 −2 −4042	Out	3(*d*)
	0 −4 −6064	Out	3(*c*)
H	00 −4 −224	Out	
	00 −6 −446	In	
I	240 −204	Out	3(*f*)
	460 −406	In	3(*e*)
J	442002	In	
	664004	In	
K	424200	In	
	646400	Out	3(*h*)
L	20440 −2	In	
	40660 −4	Unclear	
M	2 −2242 −2		
N	22 −2 −224		

where i, j and k are the orthogonal basis vectors, and g_{1i} and g_{2i} ($i = 1, 2, 3$) are the indices of g_1 and g_2, respectively.

For IQCs, the Burgers vector b is six dimensional; thus things may not be so easy. In this case, as a reasonable analogy of the rule for crystals, five independent extinction reflections g_j ($j = 1, 2, \ldots, 5$) have to be found. This should be the basic principle. Let $b = (b_1, b_2, b_3, b_4, b_5, b_6)$; then we have a set of homogeneous linear equations expressed in the following matrix form:

$$\begin{pmatrix} g_{11} & g_{12} & g_{13} & g_{14} & g_{15} & g_{16} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} & g_{26} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} & g_{36} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} & g_{46} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} & g_{56} \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

or, in short, $\mathbf{M}b = 0$, where $\mathbf{M}$ is the parameter matrix consisting of the indices g_{ji} of these five reflections.

Let us define determinants M_i as follows:

$$(-1)^{i+1} M_i = \begin{vmatrix} g_{11} \cdots g_{1,i-1} & g_{1,i+1} \cdots g_{16} \\ g_{21} \cdots g_{2,i-1} & g_{2,i+1} \cdots g_{26} \\ \vdots & \vdots \\ g_{51} \cdots g_{5,i-1} & g_{5,i+1} \cdots g_{56} \end{vmatrix} \tag{3}$$

whose elements are those of the matrix **M** after eliminating the ith column of **M**.

It is easy to show that the determinant

$$\begin{vmatrix} g_{j1} & g_{j2} & g_{j3} & g_{j4} & g_{j5} & g_{j6} \\ g_{11} & g_{12} & g_{13} & g_{14} & g_{15} & g_{16} \\ \vdots & & & & & \vdots \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} & g_{56} \end{vmatrix} = \sum_{i=1}^{6} g_{ji} M_i \tag{4}$$

is equal to zero, i.e.

$$\sum_{i=1}^{6} g_{ji} M_i = 0 \qquad (j = 1, 2, \ldots, 5) \tag{5}$$

because there are two repeated rows $(g_{j1} \ldots g_{j6})$ in this determinant.

Now we define a 6D vector $\boldsymbol{b}$:

$$\boldsymbol{b} = (b_1, b_2, b_3, b_4, b_5, b_6)(e_1 e_2 e_3 e_4 e_5 e_6)^{\mathrm{t}} \tag{6a}$$

(where the superscript t denotes the transpose of a matrix) with its indices

$$b_i = \beta M_i \tag{6b}$$

where β is an arbitrary coefficient and $e_1, e_2, \ldots, e_6$ are a set of orthogonal basis vectors.

By substituting equation (6) into equation (5) we obtain

$$\sum_{i=1}^{6} g_{ji} b_i = 0 \qquad (j = 1, 2, \ldots, 5) \tag{2a}$$

which is just the developed form of equation (2).

Therefore, the vector $\boldsymbol{b}$ as expressed in equation (6) fulfils equation (2). From the definition (3), $\boldsymbol{b}$ can be expressed as

$$\boldsymbol{b} = \beta \begin{vmatrix} e_1 & e_2 & e_3 & e_4 & e_5 & e_6 \\ g_{11} & g_{12} & g_{13} & g_{14} & g_{15} & g_{16} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} & g_{26} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} & g_{36} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} & g_{46} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} & g_{56} \end{vmatrix}. \tag{7}$$

Because of the independence of the five reflections $\boldsymbol{g}_i$ there must be at least one determinant M_i which is non-zero; hence we have $\boldsymbol{b} \neq \boldsymbol{0}$, and it is just the Burgers vector which fulfils equation (2).

The above discussion is related to the hypercubic coordinate system $(e_1, e_2, e_3, e_4, e_5, e_6)$. In principle, it is suitable for any orthogonal coordinate system, e.g. the coordinate system $(\boldsymbol{E}_1^{\parallel}, \boldsymbol{E}_2^{\parallel}, \boldsymbol{E}_3^{\parallel}, \boldsymbol{E}_1^{\perp}, \boldsymbol{E}_2^{\perp}, \boldsymbol{E}_3^{\perp})$, where $(\boldsymbol{E}_1^{\parallel}, \boldsymbol{E}_2^{\parallel}, \boldsymbol{E}_3^{\parallel})$ are basis vectors in the physical subspace and $(\boldsymbol{E}_1^{\perp}, \boldsymbol{E}_2^{\perp}, \boldsymbol{E}_3^{\perp})$ are those in the complementary subspace. In this case the indices of a reflection $\boldsymbol{g}_i$ may be written as

$$\boldsymbol{g}_i = (G_{i1}^{\parallel}, G_{i2}^{\parallel} G_{i3}^{\parallel} G_{i1}^{\perp} G_{i2}^{\perp} G_{i3}^{\perp})$$

with its components in the physical and perpendicular subspaces being $G_i^{\parallel} = (G_{i1}^{\parallel} G_{i2}^{\parallel} G_{i3}^{\parallel})$ and $G_i^{\perp} = (G_{i1}^{\perp} G_{i2}^{\perp} G_{i3}^{\perp})$, respectively. Then the Burgers vector b may be written as

$$b = \beta \begin{vmatrix} E_1^{\parallel} & E_2^{\parallel} & E_3^{\parallel} & E_1^{\perp} & E_2^{\perp} & E_3^{\perp} \\ G_{11}^{\parallel} & G_{12}^{\parallel} & G_{13}^{\parallel} & G_{11}^{\perp} & G_{12}^{\perp} & G_{13}^{\perp} \\ G_{21}^{\parallel} & G_{22}^{\parallel} & G_{23}^{\parallel} & G_{21}^{\perp} & G_{22}^{\perp} & G_{23}^{\perp} \\ G_{31}^{\parallel} & G_{32}^{\parallel} & G_{33}^{\parallel} & G_{31}^{\perp} & G_{32}^{\perp} & G_{33}^{\perp} \\ G_{41}^{\parallel} & G_{42}^{\parallel} & G_{43}^{\parallel} & G_{41}^{\perp} & G_{42}^{\perp} & G_{43}^{\perp} \\ G_{51}^{\parallel} & G_{52}^{\parallel} & G_{53}^{\parallel} & G_{51}^{\perp} & G_{52}^{\perp} & G_{53}^{\perp} \end{vmatrix}. \tag{8}$$

Equations (7) and (8) are equivalent, but (8) is more convenient for discussing the SEC (see the next section). Similar to equation (1), the 6×6 determinant in equations (7) or (8) can be defined as a vector product of five independent vectors in 6D space.

This method can be summarized as follows.

(1) Find experimentally five extinction reflections g_1, g_2, g_3, g_4 and g_5 (or G_1, G_2, G_3, G_4 and G_5) which are linearly independent in the 6D space.

(2) Calculate the value of the determinant in equation (7) (or (8)) which is a parallel vector of b.

In short, the Burgers vector b is just parallel to the vector product of five linearly independent extinction reflections in 6D space.

It should be noted that the above discussion does not involve the SEC *and* WEC *in the* concepts. It is not always necessary to use them to determine the Burgers vector of a quasi-crystalline dislocation.

2.3. A special case

As mentioned above, Wollgarten *et al* [6] proposed a method to determine the 6D direction of b based on the SEC and WEC concepts. It is a special case but very useful to illustrate the relation and difference between a quasi-crystalline dislocation and an ordinary crystalline dislocation. In the following we shall discuss this according to equation (8).

Because of the incommensurability of IQC, there are two and only two incommensurate reflections in a systematic row which correspond to two independent reflections in 6D space [13]. If two linearly independent extinctions G_3 and G_1 are from a systematic row (G_3 is the inflated vector of G_1 [14]), this is called a SEC [6]:

$$G_3^{\parallel} = (G_{31}^{\parallel} G_{32}^{\parallel} G_{33}^{\parallel}) = \tau G_1^{\parallel} \qquad G_3^{\perp} = (G_{31}^{\perp} G_{32}^{\perp} G_{33}^{\perp}) = -\tau^{-1} G_1^{\perp}.$$

Suppose that G_4 and G_2 are from another row (i.e. another SEC); then

$$G_4^{\parallel} = (G_{41}^{\parallel} G_{42}^{\parallel} G_{43}^{\parallel}) = \tau G_2^{\parallel} \qquad G_4^{\perp} = (G_{41}^{\perp} G_{42}^{\perp} G_{43}^{\perp}) = -\tau^{-1} G_2^{\perp}.$$

By substituting them into equation (8) and subtracting a multiple of one row from another, we can easily obtain

$$b = \beta(\tau + \tau^{-1})^2 \begin{vmatrix} E_1^{\parallel} & E_2^{\parallel} & E_3^{\parallel} & E_1^{\perp} & E_2^{\perp} & E_3^{\perp} \\ G_{11}^{\parallel} & G_{12}^{\parallel} & G_{13}^{\parallel} & 0 & 0 & 0 \\ G_{21}^{\parallel} & G_{22}^{\parallel} & G_{23}^{\parallel} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{11}^{\perp} & G_{12}^{\perp} & G_{13}^{\perp} \\ 0 & 0 & 0 & G_{21}^{\perp} & G_{22}^{\perp} & G_{23}^{\perp} \\ G_{51}^{\parallel} & G_{52}^{\parallel} & G_{53}^{\parallel} & G_{51}^{\perp} & G_{52}^{\perp} & G_{53}^{\perp} \end{vmatrix} = b^{\parallel} + b^{\perp} = \alpha^{\parallel} B^{\parallel} + \alpha^{\perp} B^{\perp} \tag{9}$$

where

$$B^{\parallel} = \begin{vmatrix} E_1^{\parallel} & E_2^{\parallel} & E_3^{\parallel} \\ G_{11}^{\parallel} & G_{12}^{\parallel} & G_{13}^{\parallel} \\ G_{21}^{\parallel} & G_{22}^{\parallel} & G_{23}^{\parallel} \end{vmatrix} \tag{10}$$

$$B^{\perp} = \begin{vmatrix} E_1^{\perp} & E_2^{\perp} & E_3^{\perp} \\ G_{11}^{\perp} & G_{12}^{\perp} & G_{13}^{\perp} \\ G_{21}^{\perp} & G_{22}^{\perp} & G_{23}^{\perp} \end{vmatrix} \tag{11}$$

$$\alpha^{\parallel} = \beta(2\tau - 1)^2 \begin{vmatrix} G_{11}^{\perp} & G_{12}^{\perp} & G_{13}^{\perp} \\ G_{21}^{\perp} & G_{22}^{\perp} & G_{23}^{\perp} \\ G_{51}^{\perp} & G_{52}^{\perp} & G_{53}^{\perp} \end{vmatrix}$$

$$\alpha^{\perp} = \beta(2\tau - 1)^2 \begin{vmatrix} G_{11}^{\parallel} & G_{12}^{\parallel} & G_{13}^{\parallel} \\ G_{21}^{\parallel} & G_{22}^{\parallel} & G_{23}^{\parallel} \\ G_{51}^{\parallel} & G_{52}^{\parallel} & G_{53}^{\parallel} \end{vmatrix}.$$

Now we can see that the directions of the components of the 6D Burgers vector $\boldsymbol{b}^{\parallel}$ and $\boldsymbol{b}^{\perp}$ in the physical and complementary subspaces, respectively, are only dependent on the corresponding components of the SEC diffractions vectors $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$ calculated according to equations (10) and (11) which are the same form as (1) for crystals. Only the ratio $|\alpha^{\perp}\boldsymbol{B}^{\perp}|/|\alpha^{\parallel}\boldsymbol{B}^{\parallel}|$ of their magnitudes is related to $\boldsymbol{G}_5$.

3. A typical application of the method to a dislocation in an Al–Pd–Mn icosahedral quasi-crystal

The alloy of composition $Al_{70}Pd_{20}Mn_{10}$ was prepared by melting the high-purity elements in an induction furnace under an Ar atmosphere. The slowly cooled ingot was cut into slices and specimens for transmission electron microscopy were prepared by mechanical thinning and ion milling. The diffraction contrast analyses were carried out in a Philips-CM12 electron microscope at an accelerating voltage of 100 kV. The foil normal of the specimen is very close to a twofold axis of the IQC, which can be taken as $\boldsymbol{E}_3^{\parallel}$ in figure 2.

Figure 3(a) shows a bright-field (BF) image (in contrast) of a dislocation in the specimen; the operating reflection is $\boldsymbol{g}_{F(A)}$, which is along a fivefold axis (see table 1). When we use another reflection $\boldsymbol{g}_{F(C)}$, the dislocation is invisible; this indicates that $\boldsymbol{g}_{F(C)} \cdot \boldsymbol{b} = 0$. We have taken 22 such two-beam BF images for this dislocation, of which the contrast behaviours are listed in table 1; of them, eight are invisible (out of contrast), 13 in contrast and one unclear (with a weak contrast). In figure 3, eight of them are displayed (indicated in table 1). Figures 3(b)–(d) and 3(f)–(h) show six extinctions and five of them, e.g. $\boldsymbol{g}_{F(C)}$, $\boldsymbol{g}_{T2(G)}$, $\boldsymbol{g}_{T1(G)}$, $\boldsymbol{g}_{T1(I)}$ and $\boldsymbol{g}_{T1(B)}$ are linearly independent (the indices of these reflections are taken from table 1); so, according to equation (7), we can obtain the 6D direction of the Burgers vector $\boldsymbol{b}$:

$$\boldsymbol{b} = \beta \begin{vmatrix} e_1 & e_2 & e_3 & e_4 & e_5 & e_6 \\ 2 & 2 & 4 & 2 & -2 & -2 \\ 0 & -4 & -6 & 0 & 6 & 4 \\ 0 & -2 & -4 & 0 & 4 & 2 \\ 2 & 4 & 0 & -2 & 0 & 4 \\ 2 & 4 & 4 & 0 & -2 & 0 \end{vmatrix} = 32\beta(2\ -1\ 0\ -2\ 0\ -1)(e_1 e_2 e_3 e_4 e_5 e_6)^{\mathrm{T}}.$$

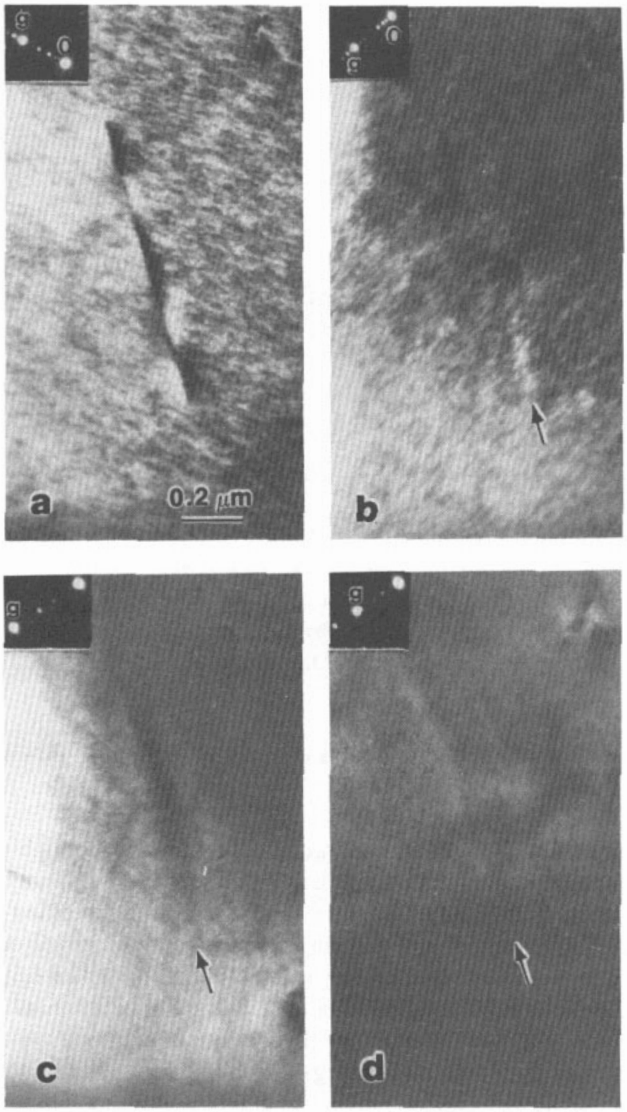

Figure 3. Eight two-beam BF images of a dislocation in an $Al_{70}Pd_{20}Mn_{10}$ IQC operating under different reflections: (*a*) $g_{F(A)}$; (*b*) $g_{F(C)}$; (*c*) $g_{T2(G)}$; (*d*) $g_{T1(G)}$; (*e*) $g_{T2(I)}$; (*f*) $g_{T1(I)}$; (*g*) $g_{T1(B)}$; (*h*) $g_{T2(K)}$. The reflection indices are given in table 1.

So $\boldsymbol{b}$ is parallel to the 6D vector $[2\ -10\ -20\ -1]$. Other experimental data listed in table 1 are all consistent with this result, which is also in agreement with our previous defocus CBED result [9]. In addition, we can conclude that the image from the reflection $g_{T2(L)}$ must be residual contrast because $g_{T2(L)} \cdot \boldsymbol{b} = 0$. By projection, the components of $\boldsymbol{b}$ in the physical and complementary subspaces are $[\tau - 1, 2 - \tau, 2\tau - 3]$ and $[\tau + 1, 2 + 3\tau, -1 - 2\tau]$, respectively. Clearly, the direction of $\boldsymbol{b}^{\parallel}$ is along a twofold axis. The ratio of $|\boldsymbol{b}^{\perp}|/|\boldsymbol{b}^{\parallel}|$ is about 11.

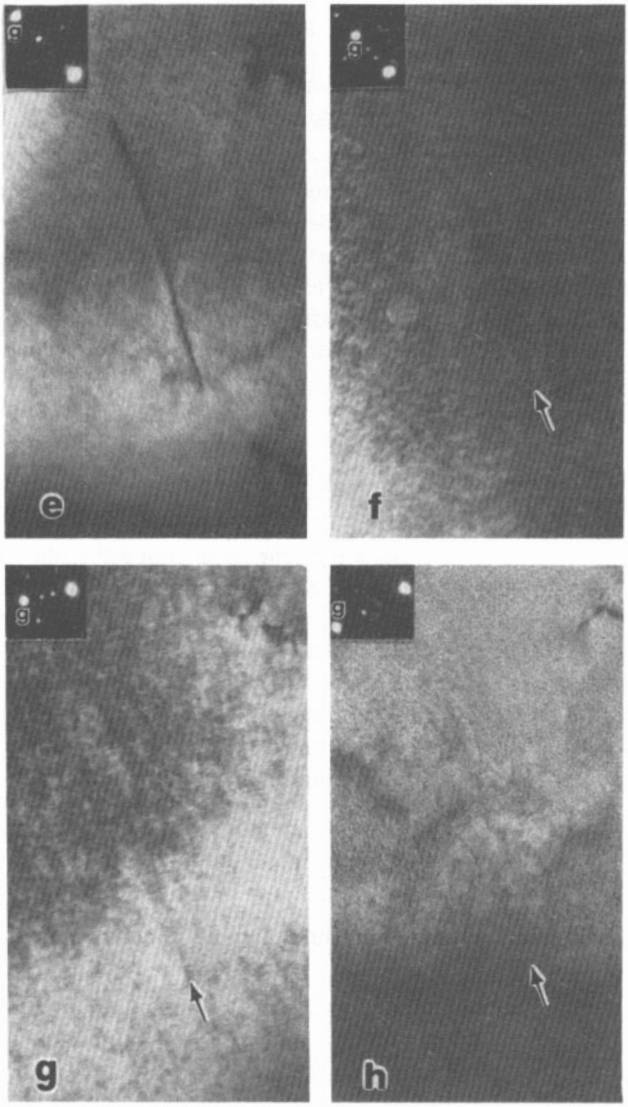

Figure 3. (Continued)

4. Discussion

The Burgers vector $\boldsymbol{b} \parallel [2\ -1\ 0\ -2\ 0\ -1]$ as determined in the present work is in agreement with that determined by the defocus CBED technique [9] and assumed by Wollgarten *et al* [15], but different from that supposed by Devaud-Rzepski *et al* [5] and determined by Wang and Dai [7] and Dai [8]. This is not surprising if we remember that the dislocations in most crystals possess several Burgers vectors. The parallel components of these two Burgers vectors are both along the twofold axes of the IQC but with different length ratios $|\boldsymbol{b}^{\perp}|/|\boldsymbol{b}^{\parallel}|$ which are $\tau^3 = 4.236$ for $\boldsymbol{b} \parallel \langle 1\ -1\ 0\ -1\ 0\ -1 \rangle$ and $\tau^5 = 11.09$ for $\boldsymbol{b} \parallel \langle 2\ -1\ 0\ -2\ 0\ -1 \rangle$. This indicates that the phason components of these Burgers vectors are much larger than the phonon components, especially for $b \parallel \langle 2-1\,0\,-2\,0\,-1\rangle$.

From the above determination we can see three important features.

(1) The above result shows that $b^{\parallel} \parallel g^{\parallel}_{\mathrm{T1(I)}}$ (see figure 2), but the dislocation is still invisible under $g^{\parallel}_{\mathrm{T1(I)}}$ excitation. If we simply apply the invisibility rule for crystals and write $g^{\parallel}_{\mathrm{T1(I)}} \cdot b^{\parallel} = 0$, then $b^{\parallel}$ would be orthogonal to $g^{\parallel}_{\mathrm{T1(I)}}$, which is completely wrong.

(2) The angle between $b^{\parallel}$ and the foil normal is larger than 50°. According to the rules suggested by Wollgarten *et al* [6], in order to determine the 6D Burgers vector of this dislocation, we must obtain two SEC sequences: P and G sequences (see figure 2). Owing to the limitation of the specimen-tilting device, only the G sequences can be achieved for two-beam imaging. Moreover, $g_{\mathrm{F(C)}}$ is along a fivefold axis; the intensity of other reflections in this systematic row is not high enough to perform a good two-beam contrast experiment. Hence it is very difficult to confirm whether $g_{\mathrm{F(C)}} \cdot b = 0$ belongs to a SEC or a WEC; so we would not be able to determine the Burgers vector of this dislocation.

(3) From table 1 we can see that the WEC is popular, e.g. $g_{\mathrm{T1(I)}}$ and $g_{\mathrm{T2(I)}}$ are from a systematic row but the dislocation is invisible for $g_{\mathrm{T1(I)}}$ (figure 3(*f*)) and visible for $g_{\mathrm{T2(I)}}$ (see figure 3(*e*)). Systematic rows along B, F, H and K show similar behaviour.

In summary the present work extended the diffraction contrast method for determining the direction of a Burgers vector b used by Wollgarten *et al* [6, 15]. It is not necessary to find two SECs and one WEC [6]. In general, finding five linearly independent extinction reflections is sufficient to determine the direction of the Burgers vector of a dislocation in an IQC. If completed by computer simulation fitting of the contrast images it may be possible to determine both the direction and the magnitude of the 6D Burgers vector of a quasi-crystalline dislocation. For high-density dislocations and small dislocation loops, this method is superior to the defocus CBED technique.

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