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AN OPTICAL MOIRÉ TECHNIQUE FOR THE ANALYSIS OF DISPLACEMENTS IN LATTICE IMAGES

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Abstract

High resolution electron microscopy is a means for imaging not only the local structure at a defect or interface but also the displacement field in the surrounding lattice. However, in general it is difficult or tedious to analyse this field which can extend across the entire micrograph. The optical moiré technique, which is based on interference effects between the experimental lattice image and an artificial reference lattice, allows a rapid and accurate measurement of the displacements. Small violations of translation, rotation or mirror symmetries give rise to large changes in the periodicity or orientation of the moiré pattern.

The spacing and orientation of the reference lattice should be chosen in order to produce the appropriate optical moiré pattern. The different types of patterns: simple rotation, simple parallel and "mixed", are then best interpreted by reference to reciprocal space vectors of the component lattices. Displacements in the experimental image revealed by the moiré pattern represent displacements in the actual specimen under certain conditions. The technique therefore provides a means for detecting lattice defects and for measuring lattice rotations and rigid body shifts.

Keywords: Moiré pattern, high resolution electron microscopy, strain fields, distortions, rigid body shifts, displacements.

Introduction

As high resolution electron microscopy (HREM) matures into a quantitative technique for the analysis of atomic structure and structural defects, it also becomes important to be able to measure the long range lattice distortions around defects. However, in HREM micrographs, the long range strains can be relatively difficult to observe. A direct measurement of the small deviations of individual lattice fringes or dots is generally impractical over the 500 to 1000 interatomic spacings found across a typical high resolution negative. By digitizing a small portion of the whole image, an automated measurement of the displacements in a local region can be made using suitable software (e.g. SEMPER written by Saxton 1979) but the technique is unsuitable for the problem of long range displacements across the entire micrograph. Indirect techniques such as viewing or displaying a micrograph at an oblique angle (see Bitzek et al. 1988) have been used to emphasize the distortions around dislocations, but only in a semi-quantitative sense, i.e. to locate the core of a dislocation or the extent of a displacement field. The optical moiré technique described here is a novel means for extracting and displaying the information about long range in-plane displacement fields from high resolution micrographs; compared with other techniques, it is relatively simple and fast and can be adapted to many problems.

The moiré effect between two overlapping crystals has been used in X-Ray topography (e.g. Lang 1968) and in electron microscopy (see Menter 1958 and Hirsch et al. 1977a for reviews). Green and Weigle (1948) first raised the idea that moiré patterns from superposed atomic lattices could have a sufficiently large spacing to be resolved by a transmission electron microscope (TEM) and such patterns were first observed by Mitsuishi et al. (1951). Applications included the detection of dislocations (Hashimoto and Uyeda 1957) and, more recently, the measurement of diamond lattice displacements by platelet defects (Bursill et al. 1981). The interpretation of moiré fringes from overlapping crystals is not straightforward due to the elastic interaction between the crystals at an interface and the dynamical nature of electron diffraction (see Gevers, 1962 for the full dynamical treatment of geometry and intensity of moiré fringes). In addition, application of the method is severely limited by the difficulties of specimen preparation (Ecob and Stobbs, 1983).

Current high resolution microscopes routinely resolve lattice planes directly, so that the possibility arises to use the interference between two images rather than between two crystals. Lord Rayleigh in 1874 formed moiré fringes (a "system of parallel bars") by superimposing two photographic copies of diffraction gratings of like periodicity. He commented that "when parallelism is very closely approached,
the bars become irregular, in consequence of the imperfection of the ruling. This phenomenon might perhaps be made useful as a test. Similarly, if two lattice images are superimposed, we can expect to be able to observe distortions in the lattice as irregularities in the moiré pattern. Perhaps the first example of such a test applied to electron micrographs can be found in figure 6b of Takeda and Hashimoto (1984) in which two lattice images generate a moiré pattern that displays the antiphase relation between two ordered domains. Optical moiré patterns of micrographs have also been produced, albeit unintentionally, in figures in published articles where the array of dots used to create the half-tone image has interfered with the lattice image (e.g. figure 1a in Ponce and Hetherington, 1989).

In this paper, we describe the use of an artificial reference grid, rather than a second high resolution micrograph, to form the moiré pattern with the experimental lattice image. The advantage of this optical moiré technique is that it is then possible to choose the magnification, type and spatial resolution of the pattern and thus optimise the effect for any given case.

**Theory**

Although algebraic expressions for moiré spacings and directions are given in the literature (e.g. Hirsch et al. 1977b), the simplest way to understand their behaviour is by reference to reciprocal space, as shown in figure 1. (In many applications of the optical moiré technique, only one set of fringes in each image are made to interfere and in this section we treat only this simple case, representing lattices as one-dimensional grids.) Figure 1a shows a moiré pattern generated by superposition of two undistorted linear grids which have different spacings and which are also rotated relative to each other: we call this a "mixed" moiré pattern. The corresponding reciprocal lattice representation is shown in Figure 1d. The two linear grids are represented by two vectors of appropriate length and direction and the moiré pattern is represented by their difference vector \( \mathbf{m} \). The real space moiré fringes are perpendicular to the vector \( \mathbf{m} \) and their spacing is inversely proportional to the length \( |\mathbf{m}| \).

There are two special cases. Firstly, the linear grids can have the same spacing and the "rotational" moiré pattern is brought about solely by the relative rotation \( \Theta \) between the grids (figure 1b). It can be easily seen in the reciprocal lattice representation, figure 1e, that the spacing of the moiré fringes will be inversely proportional to the rotation \( \Theta \), and that for very small rotations, the moiré fringes will be nearly perpendicular to the component grids. Secondly, and as shown in figures 1c and 1f, the linear grids can be parallel but of different spacings \( d_1 \) and \( d_2 \), which results in a "parallel" moiré pattern; the spacing of the moiré fringes will be inversely proportional to the difference between the spacings of the linear grids.

In figure 1, undistorted grids were considered. In the problems addressed by the optical moiré technique, one of the grids, the "reference lattice", remains undistorted. The other grid, the "experimental lattice", has the local distortion that we treat only this simple case, representing lattices as one-dimensional grids. Figure 1e shows a moiré pattern with the experimental lattice leads to an expansion of the moiré pattern; the spacing of the moiré fringes will be inversely proportional to the rotation \( \Theta \), and that for very small rotations, the moiré fringes will be nearly perpendicular to the component grids. Secondly, and as shown in figures 1c and 1f, the linear grids can be parallel but of different spacings \( d_1 \) and \( d_2 \), which results in a "parallel" moiré pattern; the spacing of the moiré fringes will be inversely proportional to the difference between the spacings of the linear grids.

In this paper, we describe the use of an artificial reference grid, rather than a second high resolution micrograph, to form the moiré pattern with the experimental lattice image. The advantage of this optical moiré technique is that it is then possible to choose the magnification, type and spatial resolution of the pattern and thus optimise the effect for any given case.

Figure 1. Illustration of a) mixed, b) rotational and c) parallel moiré patterns from superposition of lattice arrays with corresponding reciprocal lattice representations shown in d), e) and f) respectively.
Moiré Technique for Displacements

Figure 2. Reciprocal space description of effect of local distortions in experimental lattice on a parallel moiré pattern. a) reference lattice ($g_{\text{ref}}$), undistorted experimental lattice ($g_{\text{exp}}$) and positive parallel moiré ($m$) b) a local lengthening of $g_{\text{exp}}$ to $g'_{\text{exp}}$ leads to an lengthening of $m$ to $m'$ c) a local rotation of $g_{\text{exp}}$ to $g'_{\text{exp}}$ leads to a rotation of $m$ to $m'$ in the same sense but of increased magnitude d) the general case where $g_{\text{exp}}$ moves to $g'_{\text{exp}}$. The circle of radius s, centred on the endpoint of $g_{\text{exp}}$, represents a maximum local strain. e) A negative moiré: a clockwise rotation of $g_{\text{exp}}$ to $g'_{\text{exp}}$ leads to an anti-clockwise rotation of $m$ to $m'$.

Figure 3. Positive and negative moiré patterns on a sample experimental grid shown in real space: a) reference grid b) experimental grid having local clockwise rotations at the top and bottom ends c) positive superposition of grids (see text for details), note clockwise rotation of moiré fringes d) negative superposition of grids, note anti-clockwise rotation. e) and f) The effect of a clockwise rotation of the whole experimental grid relative to the reference grid: in e) (positive) the moiré fringes also rotate clockwise whereas in f) (negative) the moiré fringes rotate in the opposite sense.

Figure 4. a) A schematic incoherent interface at which an extra half plane terminates. The left side of the interface has n planes and the right side has n+1 planes, b) the same interface with an overlaid reference grid of approximately n-3 lines showing an extra half plane in the moiré pattern also. c) A coherent interface with a misfit dislocation which is also visible in the resulting moiré pattern d). and a local rotation in the experimental lattice leads to a rotation in the moiré pattern in the same sense. Hence we call it a “positive” parallel moiré. The corresponding “negative” parallel moiré, having $g_{\text{exp}}$ shorter than $g_{\text{ref}}$ is illustrated in figure 2e in the case of a local rotation; it can be seen that a clockwise rotation of $g_{\text{exp}}$ to $g'_{\text{exp}}$ leads to an anti-clockwise rotation of $m$ to $m'$.

As noted above, the local distortions in the experimental lattice are magnified in the parallel moiré pattern. The smaller the difference $m$ between $g_{\text{exp}}$ and $g_{\text{ref}}$, the larger the magnification M of the moiré. However, spatial resolution and strain resolution are inverse to each other: any local strain will be magnified by a factor $|g_{\text{exp}}|/|m|$ but can be spatially...
resolved only with a spacingMd between lattice fringes. For example, a moiré magnification of M=20 maps a 1% strain of the lattice as a 20% strain of the moiré pattern, but the "strain contours" have a spacing of 20 times the lattice spacing d. The moiré magnification enables the detection of very small distortions and enhances the accuracy of strain measurements. Furthermore, the spatial demagnification allows the display of strains across a whole high resolution micrograph.

Figure 3 illustrates in real space the effects of lattice distortions on positive and negative moiré patterns. Figure 3a shows a reference grid and figure 3b shows a similar grid having a slight clockwise rotation at the top and bottom ends; this second grid represents the experimental lattice. In figure 3c, the grids are superposed so that the reference grid is parallel to the central undistorted portion of the experimental grid and has the larger spacing (i.e. positive moiré). Parallel moiré fringes are seen in the central portion and there is an amplified clockwise rotation in the moiré fringes at the ends. On the other hand, in figure 3d, the reference grid has a smaller spacing and the resulting negative moiré fringes undergo an anti-clockwise rotation at the ends. Figure 3e and 3f illustrate the effect of a clockwise rotation of the whole experimental grid relative to the reference grid: in the positive moiré pattern (figure 3e), the moiré fringes also rotate clockwise whereas in the negative moiré pattern (figure 3f), the moiré fringes rotate in the opposite sense.

The effect on moiré patterns of discontinuities in the experimental lattice such as extra half planes at misfit dislocations in an interface, or such as a rigid shift across a stacking fault, is examined in figure 4. The reference grid has a smaller number of lines within the interface length, i.e. it has a larger spacing, and the moiré pattern is therefore positive. Again, if a positive parallel moiré is used, an extra moiré half plane indicates an extra half plane in the experimental image, and rigid body shifts will be in the same direction in the moiré pattern as in the experimental lattice.

A related technique has been used to measure the rigid body shift across a symmetrical grain boundary (Dahmen et al. 1990a). A mirror image of the high resolution micrograph is made by rotating 180° about the boundary line and it is superimposed on the original so that the lattices on one side of the boundary are in registry. Then the overlay is translated parallel to the boundary until the lattices on the opposite side are in registry; the displacement of this translation is twice the rigid body shift.

**Lattice in Image vs. Lattice in Specimen**

The preceding section discussed moiré patterns formed by interference between high resolution images. The question arises as to whether there is a one-to-one correspondence between these and the actual distortions in the specimen (and a further question as to whether the lattice in the specimen has undergone significant relaxations during the preparation of the thin TEM foil.) Clearly there may be image contrast reversals, from white atom to black atom say, due to thickness changes or focus changes across the image of a lattice of the same material and projection. Contrast reversals may also arise across interfaces of dissimilar materials (e.g. metal silicide/silicon interfaces) due to different extinction distances or due to crystal tilt at strained interfaces. However, it is beyond the scope of this paper to discuss this issue in detail. This moiré technique serves only to display the strains present in the image and the usual precautions must be taken when interpreting the image and its strains in terms of the actual specimen.

One point to note, however, is that we are not dealing here with large deviations from perfect periodicity, i.e. strongly localised displacements, that could lead to local contrast reversal and which would require image simulations for their interpretation. We deal here, and in most of the proceeding examples, with two basic cases. Firstly, there is the long range part of a displacement field surrounding, e.g., a dislocation or a precipitate which generally varies slowly enough to maintain neighbouring atom columns close to their perfect periodic distance. Secondly, there is the long range rigid body shift or rotation between two like lattices across discontinuities such as grain boundaries, twins and stacking faults. (On the other hand, the short range structure at the discontinuity will have the large deviations from perfect periodicity mentioned above.)

High resolution images of these slowly varying displacement fields or discrete rigid shifts between like lattices are thus a direct representation of the atomic displacements (given the above caveats about contrast change due to variation in imaging conditions and specimen tilt or composition across the micrograph) and can be used to map displacement fields quantitatively to allow comparison with model calculations.

**Practical Considerations**

The first requirement is a reference lattice: a regular square set of black dots on a white background is suggested. Although it has been mentioned above that often only one set of lines is used in producing optical moiré patterns, it is actually easier to find and to use a two dimensional set of dots rather than a one dimensional set of lines. We have been using a set of dots found in a large area of plain grey printed by the "half-tone technique" in a high quality publication. An area of the half-tone that contains up to the same number of dots as a typical high resolution image should be photographed, preferably using a large format camera. We have found such sets of dots to be highly regular. A straightforward check of the level of distortions in a reference lattice can be performed by taking duplicate negatives of the latter, inverting one and superposing it on the second with a slight relative rotation. Small distortions in the reference lattice will show up as magnified distortions in the resulting rotational moiré. Another possible square array of dots is a print-out of suitable shading as found in various applications on the Apple Macintosh Computer. On the other hand, an experimental lattice image of a "perfect" TEM specimen (i.e. without obvious defects) which has a uniform brightness and high contrast across the whole micrograph could also be used as a reference lattice but would be rather more difficult to generate.

Moiré patterns are generated by superposing the reference lattice onto the experimental image and we use two methods in practice. For a quick inspection of the possible moiré patterns, we use a transparency of the reference lattice overlaying it onto the experimental image. A light box used as a base can improve the visibility of the moiré pattern. For more precise work (and for the subsequent printing of the moiré patterns), we use a negative of the reference lattice and a darkroom enlarger. The reference lattice is projected onto a print of the experimental lattice. The scale of the reference lattice is adjusted in the first case by using a photocopier that has a percentage reduction/enlargement facility, or, in the second case, by adjusting the height of the enlarger.

In order to produce a print of the moiré pattern, the following steps are followed:

1. Two sheets of photographic paper should be exposed with the image of the experimental lattice. Ensure that the sheets are located in precisely the same place on the enlarger table and add a mark to each sheet to identify the orientation of the paper. The exposure time should be approximately half the usual time.

2. Only one sheet is immediately developed to form a print of the experimental lattice. The second sheet is placed in a light-tight drawer.
Figure 5. a) Experimental image of intersecting twin bands T1 and T2 in silicon, b) with overlaid reference lattice. The moiré pattern is formed using horizontal (111) fringes (parallel at "A"), note rotation of moiré fringes at "B".
3. In the enlarger, replace the negative of the experimental lattice with the negative of the reference lattice and project the reference lattice onto the print of the experimental lattice. Adjustments are made to the height of the enlarger and the orientation and position of the print to obtain the desired moiré pattern.

4. The print is replaced by the second sheet from the light-tight drawer; the sheet has to be placed in exactly the same position and with exactly the same orientation as the print. The sheet is exposed (double exposed) for approximately half the normal time and then developed.

The following tips concerning the printing process may be helpful:

- A positive moiré is obtained when the reference lattice spacings are larger than the experimental lattice spacings. That the moiré is positive can be checked by rotating the experimental image; if the moiré fringes rotate in the same sense, then they are positive (see figure 3e).
- If parallel moiré fringes in the undistorted regions of the experimental lattice are desired, then without adjusting the height of the enlarger, rotate the experimental image until the moiré fringes have the maximum spacing.
- It is recommended that more than 2 sheets are exposed in step 1 so that several undeveloped sheets are stored in the light-tight drawer. Then further attempts at steps 3 and 4 can be made (perhaps with different exposure times or different moiré magnifications) without having to repeat steps 1 and 2.
- During each exposure, a small mask can be placed on two areas of little interest so that the final print has 2 "windows" which reveal each component lattice separately and which can be used to measure the relative size and orientation of the lattices. (Alternatively, simply make single-exposure prints of each lattice with the paper aligned as for the double-exposure print.)
- Of course, in the method described above, it is equally valid to expose onto the photographic paper the reference lattice followed by the experimental lattice.

Applications

Long range strain fields are expected to be found in specimens of hot-indented silicon that undergo deformation by twinning (Pirouz et al. 1988). Barriers to twin band propagation, such as a second, non co-planar twin band, leave significant stresses and strains, sufficient even to force the material within a twin band intersection into hexagonal stacking (Dahmen et al. 1989, Hetherington 1990). Figure 5a is a high resolution micrograph of a horizontal twin band (T2) that has terminated within the inclined twin-band (T1); the image was taken down the [110] zone at 800kV on the Atomic Resolution Microscope at Berkeley and the (111) planes are resolved. The silicon above T2 has been sheared relative to the silicon below as indicated by the arrows. This shear is accommodated by elastic strain in the lattice surrounding the termination - although this strain is not immediately visible in the image. However in figure 5b, the superposition of a reference lattice in order to produce a parallel moiré pattern with the horizontal (111) fringes clearly reveals severe distortions within the lattice image.

The reference lattice has a larger spacing than the (111) fringes so the moiré pattern is positive. At areas marked "A" in figure 5b, the moiré fringes are exactly parallel to the (111) fringes and the ratio of the spacing of the moiré fringes to those of the reference lattice calibrates the moiré magnification as about 35 times. The moiré fringes at "B" are rotated 38° from the horizontal and a geometric construction of the reciprocal vectors has shown that the rotation of the (111) fringes is 1°, (see also figure 8 of Hetherington, 1990).

It is likely that there has been buckling of the TEM specimen around the region of the intersection, especially since the specimen thickness approaches zero at the right hand end of the figure. This buckling, relieving some of the stress in the specimen, will have altered the strain field and broken the plane-strain conditions. Deductions about the actual strain field must take this into account.

If the (111) fringes (those parallel to the inclined twin band T1) are examined by the optical moiré technique, the extra planes above twin band T2 that were introduced by the deformation are revealed (figure 6). The moiré fringes can also be seen to shift when crossing stacking faults at points such as those marked by the arrows. The (111) fringes have a weaker contrast than the (111) fringes due to a slight misorientation of the crystal from the precise [110] pole, and therefore the moiré fringes are less clear than in figure 5b.

The inclusion of a coherent precipitate into the surrounding matrix also provides the circumstances in which strain can be expected. Figure 7a shows a high resolution micrograph of the end of a 9° precipitate in Al-Cu in which strain fields or dislocations are not immediately apparent. The overlaying of a reference lattice in figure 7b forms a positive moiré pattern and reveals the distortion field around the end of the precipitate. Also made visible is an interfacial dislocation formed by an extra horizontal plane in the surrounding matrix.

Figure 6. Moiré pattern formed from (111) fringes in image of intersecting twin bands. Extra half planes are revealed above twin band T2 due to shear, and a rigid shift of lattice across stacking fault is marked by arrows.

Figure 7a. High resolution micrograph of a 9° precipitate in Al-Cu showing characteristic strain field and dislocations.

Figure 7b. Reference lattice formed from (111) fringes showing the distortion field.
In order to illustrate the wide extent of a displacement field that can be examined using the optical moiré technique, figure 8 shows a section of an entire grain of aluminium of 100nm diameter contained by a second aluminium grain. The moiré pattern is formed using (111) fringes of spacing 0.23nm of which there are almost 800 across the length of the micrograph. The lattice of the inner grain is rotated 90° with respect to the outer grain and the moiré fringes in the inner and outer grains are formed from orthogonal lattice fringes. In places, particularly the thicker regions at right, the moiré fringes are not clear due to defects in the aluminium caused by electron beam radiation damage.

Another region of the same aluminium bicrystal specimen, in which all neighbouring crystals are rotated by about 90°, contained a length of symmetric boundary which has recently been the subject of considerable investigation (Dahmen et al. 1990b) and which is located in the box in figure 9a. The exact tilt across the boundary was of interest and investigated using the moiré technique. The reference lattice had fringes that were exactly orthogonal and of the same spacing as the aluminium (111) fringes. It was overlaid onto the experimental image with a small rotation with respect to near-orthogonal (111) fringes on either side of the boundary. The result, for the identical area of image shown in 9a, is shown in figure 9b. The rotational moiré fringes so produced have spacings that were used to measure the deviation from orthogonality of the (111) fringes across the boundary. The spacing of the moiré fringes is larger above the boundary than below which means that the relative rotation of the experimental lattice with respect to the reference lattice is smaller above the boundary. Full analysis gives a value of 89.3° for the tilt across the boundary which compares favourably to the value of 89.4° required for the Σ99 grain boundary. The accuracy of the measurement relies on the high moiré magnification due to the small relative rotation of the reference lattice with respect to the experimental lattice. However, the high moiré magnification results in a low spatial resolution that makes it difficult to obtain a measurement from the small area around the 10nm long boundary located in the box in figure 9a.

Conclusion

The optical moiré technique of overlaying a reference lattice onto an experimental image is a simple and useful method for analysing long range displacement fields in high resolution micrographs. Lattice expansions and rotations in the experimental image are amplified in the moiré pattern. The interpretation is best made by considering the reciprocal lattice vectors. Information about rigid shifts, dislocations and strains is transferred into the moiré pattern in the same sense as in the experimental lattice if a "positive" parallel moiré is used.
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Figure 8. Strain fields within and without a grain of aluminium revealed by the moiré pattern.

Acknowledgments

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References


R Gevers (1962) Dynamical theory of moiré fringe patterns, Phil. Mag. 2 1681-1720
H Hashimoto and R Uyeda (1957) Detection of dislocation by the moiré pattern in electron micrographs, Acta Cryst. 10 143
Figure 9. a) An aluminium tilt boundary with length of symmetric boundary shown by box. b) Pure rotational moiré patterns are formed on each side of the boundary from orthogonal fringes in the reference lattice and near-orthogonal \{111\} fringes in the experimental lattice image. The reference and experimental fringes and their relative rotations are highlighted by the pairs of white lines drawn onto the figure and the different moiré fringe spacings, \(\lambda_1\) and \(\lambda_2\) are indicated.
on the enlarger table, then the enlarger is raised so that the
reference lattice is in the enlarger and the experimental lattice is
component images.) To proceed to a pure rotational pattern is
print can then be noted in order to obtain an alternative
obtain any mixed moire pattern, then rotate the reference lattice
convenient route to the final moire pattern is via the exact
construction of the reciprocal space vectors. In other words,
moire magnification or spatial resolution required. A
shifted and rotated relative to the experimental image depends
accurate measurements can be made after producing the pattern
as the moire fringes themselves give the relative rotation,
spaceing and displacements of the two images.
The amount by which the reference image should be
shifted and rotated relative to the experimental image depends
on the type of moiré pattern (rotational vs. parallel) and the
moiré magnification or spatial resolution required. A
convenient route to the final moiré pattern is via the exact
alignment of the two lattices. To reach this alignment, first
obtain any mixed moiré pattern, then rotate the reference lattice
until the moiré fringe spacing is a maximum (the pattern is
pure parallel) and finally adjust the enlargement until the
moire fringe spacing is a maximum (the pattern is
positive if a rotation of the

The final recommendation is to try out the moiré
technique in practice, as many of the procedures and
explanations offered in this paper should then immediately
become rather clear.

R Hull: Could you comment on possible distortions of the
experimental image of an otherwise perfect structure, e.g.
from the negative not being perfectly flat during exposure
(many groups cut out the backs of their plate holders), or from
possible lens distortions? These effects would clearly
influence the moiré contrast.

Authors: It is true that, if there are distortions in the imaging
system, then they will be much more apparent across the entire
micrograph – an area often examined in the moiré technique –
than within the very small areas typically selected in standard
HREM studies. Moreover, the moiré technique should, in
principle, be particularly efficient at detecting them. Hence,
the possible presence of distortions should be remembered
when interpreting the moiré patterns.

Authors' late addition: Distortions in experimental lattice
images due to imperfections in the projector lenses have
recently been observed and measured (via optical moires) in
the JEOL 4000EX at the Department of Materials Science and
Metallurgy, University of Cambridge. The TEM specimen
used was α-Al2O3 viewed down [0001] since it contained
areas that were flat, unstrained and uniformly thick. The
following measurements were made on a micrograph taken at
800,000X, comparing the image at the centre of the negative
with the image at the edge, i.e. 40mm from the centre, equivalent
to 50nm at the specimen plane. Two distortions were found to
arise: i) a spiral distortion causing the fringes at the edge to be
rotated up to 1.5° with respect to the fringes at the centre and
ii) a pin cushion distortion causing an increase in
magnification of 1.7% at the edge. For the nominal
magnification of 800,000X in the centre, a magnification of
814,000X would be seen at the edge.

Discussion with Reviewers

R Hull: Do you have recommendations as to how to
measure rotation and displacement of reference and
experimental images accurately? By how much should the
reference image be shifted and rotated relative to the
experimental image in the enlarger?

Authors: The orientation and spacing of the reference lattice
can be measured from inside the “window” described in the
text. (N.B. an area of the experimental image having a weak
contrast can also serve as a window within which the
reference lattice would be clearly visible e.g., see the top right-
hand corner of fig 9b.) Then, with a measurement of the
orientation and spacing of the moiré fringes, there is sufficient
information to obtain the orientation and spacing of the
experimental lattice fringes by a simple geometrical
construction of the reciprocal space vectors. In other words,
accurate measurements can be made after producing the pattern
as the moiré fringes themselves give the relative rotation,
spaceing and displacements of the two images.

The final recommendation is to try out the moiré
patterns.