Low temperature plasticity of an AlPdMn quasicrystal

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ABSTRACT

TEM observations have been performed in AlPdMn single-grain quasicrystal deformed at low temperature. They show that dislocation motion has occurred by climb associated with vacancy diffusion. At room temperature, deformation also occurs by crack followed by re-healing.

INTRODUCTION

Since quasicrystals have been discovered, several studies have been devoted to explain their unusual mechanical properties, such as high brittleness at low and medium temperature. It is now well established that plastic deformation at high temperature takes place by nucleation and motion of dislocations at least for icosahedral AlPdMn [1]. From the first and further experiments, substantial progress has been made in the interpretation of these defects in transmission electron microscopy. The idea that dislocations essentially move by glide has then raised, although no experimental determinations of both Burgers vectors and displacement planes have been obtained. The first evidence of climb came out recently from careful studies of dislocations in as-grown samples [2-4]. However, since these observations have been performed on dislocations induced by the constraints generated during the elaboration and cooling of the samples, further ones had to be performed on plastically deformed materials to confirm the importance of climb.

In that context, we have performed TEM observations on samples deformed at low temperature (20°C and 300°C) under a high confining pressure. At such low temperatures, the planes of motion could be determined as the habit planes of the so-called “phason faults”, which have been produced during the motion of dislocations [5]. Details on the rules of contrast of “imperfect” dislocations and phason faults can be found in [6].

EXPERIMENT

Single grains of icosahedral $Al_{70.1}Pd_{20.4}Mn_{9.5}$ were grown by Y. Calvayrac in CECM (Vitry) along a 5-fold direction [1/0, 0/1, 0/0] (notation from [7]) by the Czochralski method. Two cylindrical samples were then deformed in a multi-anvil apparatus designed to generate a high differential compressive stress. A pressure of 5 and 7 GPa has been reached respectively at 20°C and 300°C. After a few percents of deformation, the samples were cut in, 20°, and 45° away from the 5-fold compression axis. They were polished mechanically and thinned down by ion milling. All the observations have been performed in a JEOL 2010 HC electron microscope operating at 200 kV.

RESULTS

Samples deformed at 300°C

Several dislocation families have been found with large corresponding densities. All the dislocations are imperfect and exhibit phason faults in their wake.

Dislocations of the first family are shown in figure 1. They form typical arrangements consisting of one leading pair of dislocations (1, 2) followed by one or several isolated ones (3). From its trace direction and its variation of apparent width as a function of tilt axis, the plane of motion was determined as the 5-fold plane perpendicular to the compression axis, noted $P_{\perp C}$. In bright field, phason faults appear as a symmetrical pattern of bright and dark fringes.

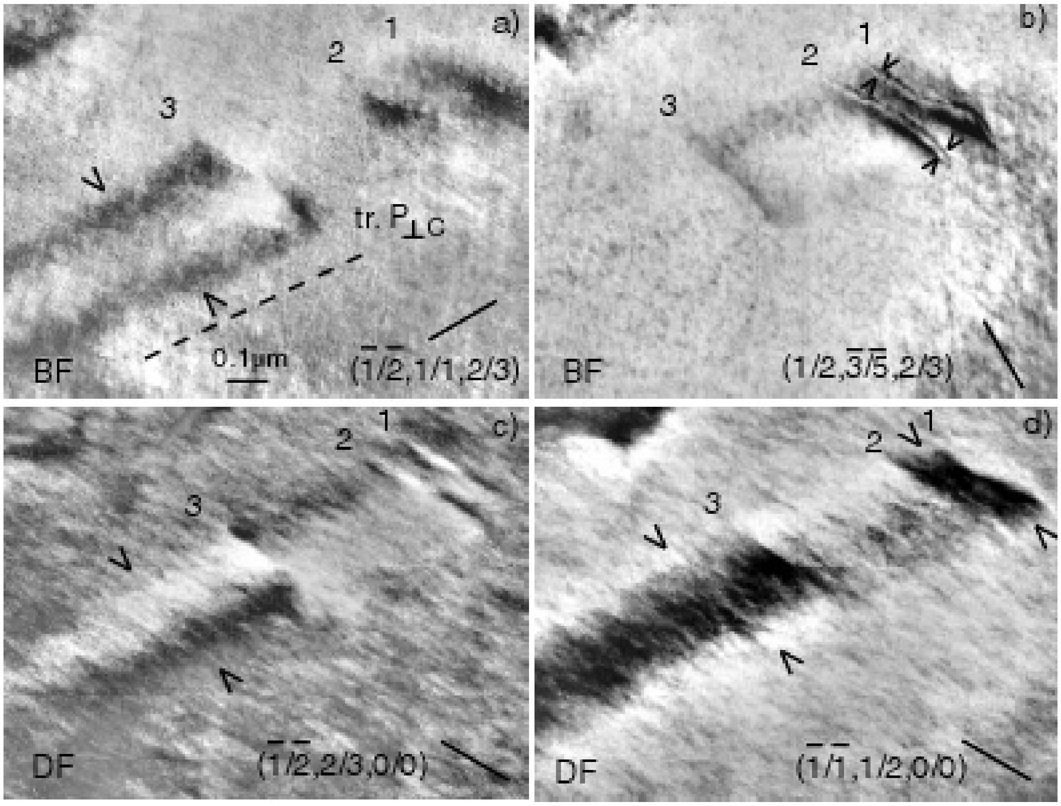

Figure 1. Typical arrangement of three dislocations (1, 2 and 3) in the 5-fold plane perpendicular to the compression axis ($P_{\perp C}$). Phason faults appear as a pattern of dark and bright fringes in the wake of dislocations (see arrowheads in (a)). Extinction and double contrast conditions of the leading dislocations (1, 2) are shown respectively in (a) and (b). An antiphase boundary ribbon is revealed between dislocations 1 and 2 and in the wake of dislocation 3, on the basis of a symmetrical fringe pattern in dark field with a superstructure spot (see arrowheads in d) at variance from the usual asymmetrical one (arrowheads in c).

Figure 1a shows, in the wake of dislocation 3, a typical phason fault with two external dark fringes and one internal bright one (arrowheads). In dark field, the fringe pattern appears asymmetrical (fig. 1c). Out-of-contrast conditions are satisfied for imperfect dislocations and phason faults when the scalar product in the physical space $\mathbf{g}_{//}.\mathbf{b}_{//}$ is set to 0. This is achieved for dislocations 1 and 2 in the conditions of figure 1a. The remaining contrast of the dislocations is due to the so-called residual contrast of edge dislocations when $\mathbf{g}_{//}.(\mathbf{b}_{//}\times\mathbf{u})\neq 0$ ($\mathbf{u}$ is the line direction).

Figure 1b shows both a single contrast for dislocation 3, and a double contrast for dislocations 1 and 2 (arrowheads). They are obtained respectively when $\mathbf{g}_{//}.\mathbf{b}_{//}\approx 1$ and $\mathbf{g}_{//}.\mathbf{b}_{//}\approx 2$, since the missing perpendicular components $\mathbf{g}_{\perp}.\mathbf{b}_{\perp}$ are small in that case. Figures 1c and 1d show the same dislocations imaged in dark field with two collinear diffraction vectors. In figure 1c, the phason fault behind dislocation 3, and between dislocations 1 and 2 exhibits a classical asymmetrical fringe pattern, whereas figure 1d shows a π-type symmetrical contrast. The latter situation is typical of an antiphase boundary (APB) ribbon imaged with a superstructure diffraction vector [6]. A complete contrast analysis leads to the following conclusions. Dislocations 1 and 2 have a 5-fold Burgers vector oriented along the compression axis. These dislocations have accordingly moved by pure climb. The Burgers vector length is 0.456 nm, which corresponds to the projection of half a translation of the perfect 6D structure in the physical space. Dislocation 3 has a 3-fold Burgers vector of length 0.247 nm oriented out of the plane of motion, with a rather large glide component. This type of motion, called mixed climb, is very similar to pure climb and controlled by the diffusion of matter. This Burgers vector is also the projection of half a translation of the 6D lattice.

Figure 2 shows several other dislocation families. The main ones are moving in the 2-fold planes parallel to the compression axis. In figure 2a, they are seen nearly edge-on (e. g. dislocation 7) and trail slightly wavy phason faults with traces noted tr. $P_{1//C}$ and tr. $P_{2//C}$. This situation is very typical of the motion observed in these planes during *in-situ* experiments [8].

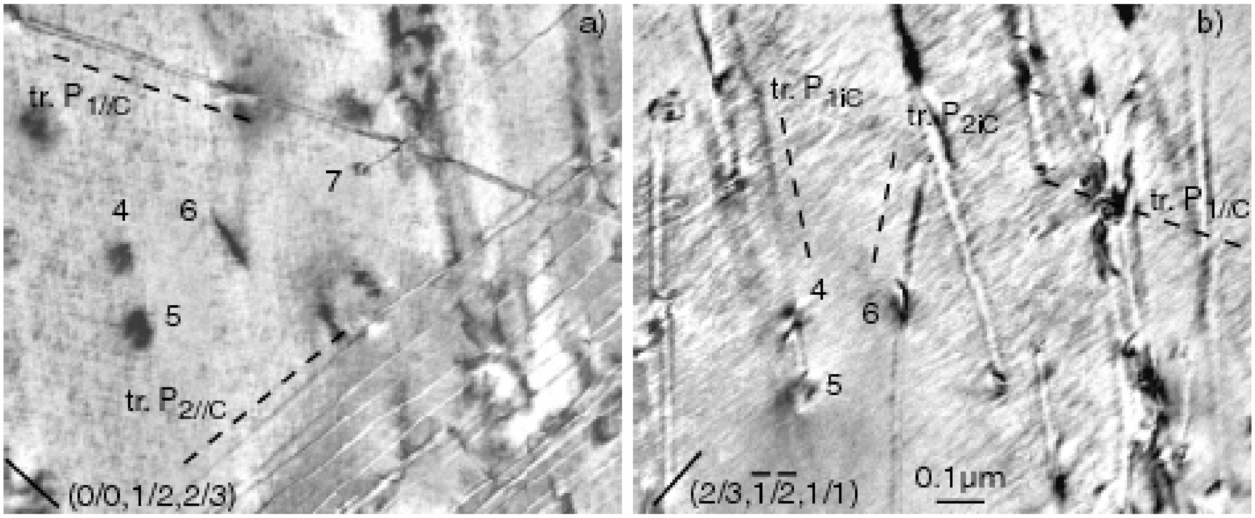

Figure 2. Overview of dislocations moving in planes $P_{//C}$ parallel to the compression axis (dislocation 7) and in inclined planes P_{iC} (dislocations 4, 5, 6). The former, seen edge-on in (a), trail wavy phason faults. The later are clearly all in contrast in (b).

Complete contrast analysis has yielded 2-fold Burgers vectors all perpendicular to the corresponding planes of motion. Thus all these dislocations have moved by pure climb. Other dislocations can be observed, and noted 4, 5 and 6. Dislocations 4 and 5 are out of contrast in figure 2a. They can be easily seen in figure 2b whereas dislocations in $P_{2//C}$ are extinct and those in plane $P_{1//C}$ are edge-on. A detailed analysis shows that dislocations 4, 5 and 6 have moved by pure climb in 2-fold plane at 31.71° from the compression axis (P_{1iC} and P_{2iC}). The more complete analysis of phason faults allows us to determine the sign of their displacement vector. It was found that dislocations in $P_{//C}$ trail "interstitial" faults whereas dislocations in $P_{\perp C}$ trail "vacancies" faults [6].

All these results can be interpreted in the following way. The deformation is accommodated by the cooperative motion of dislocations of the main systems. Dislocations climb in the plane $P_{\perp C}$ perpendicular to the compression axis by absorption of vacancies whereas dislocations climb in planes $P_{//C}$ parallel to the compression axis by emission of vacancies. Accordingly, the latter act as vacancy sources for the former.

Samples deformed at 20°C

Figure 3 shows the general features of samples deformed at room temperature. Many walls can be observed containing a large density of defects. Figure 3a shows that walls build a 3-dimensional network. They are usually non planar as their wavy traces at the surfaces indicate, but close to 2-fold planes. For example, the wall noted W, seen edge-on, deviates from a 2-fold plane trace (dashed line). From these walls, several dislocations have been emitted. Figure 3c shows dislocations (d_e) emitted by W, trailing phason faults (PF). Contrast analyses have shown that they move by pure climb in 2-fold planes. The same situation has been observed in samples deformed at 300°C although less walls have been found.

Dislocations can be clearly seen at wall extremities. Figure 3d shows several overlapping walls (W) ending by two pile-ups of curved dislocations (d). Contrast analysis has yielded a unique Burgers vector for all the dislocations, almost contained in the wall plane. However, the wavy aspect of walls indicates that their formation cannot be attributed to the glide and cross-slip motion of these dislocations, in contrast with the conclusions of [10].

All the results can be coherently interpreted by a non-planar crack mechanism in mode III, followed by a re-healing assisted by the confining pressure. This interpretation is in agreement with an accommodation at the crack tip by screw dislocations, and corroborated by LACBED experiments [9]. Similar behaviour has been observed in bounded silicon wafers [11] and in indented silicon [12]. However, considering that the two surfaces of the crack are non-planar, the high strain incompatibilities generate high internal stress that must be relaxed by climbing dislocations.

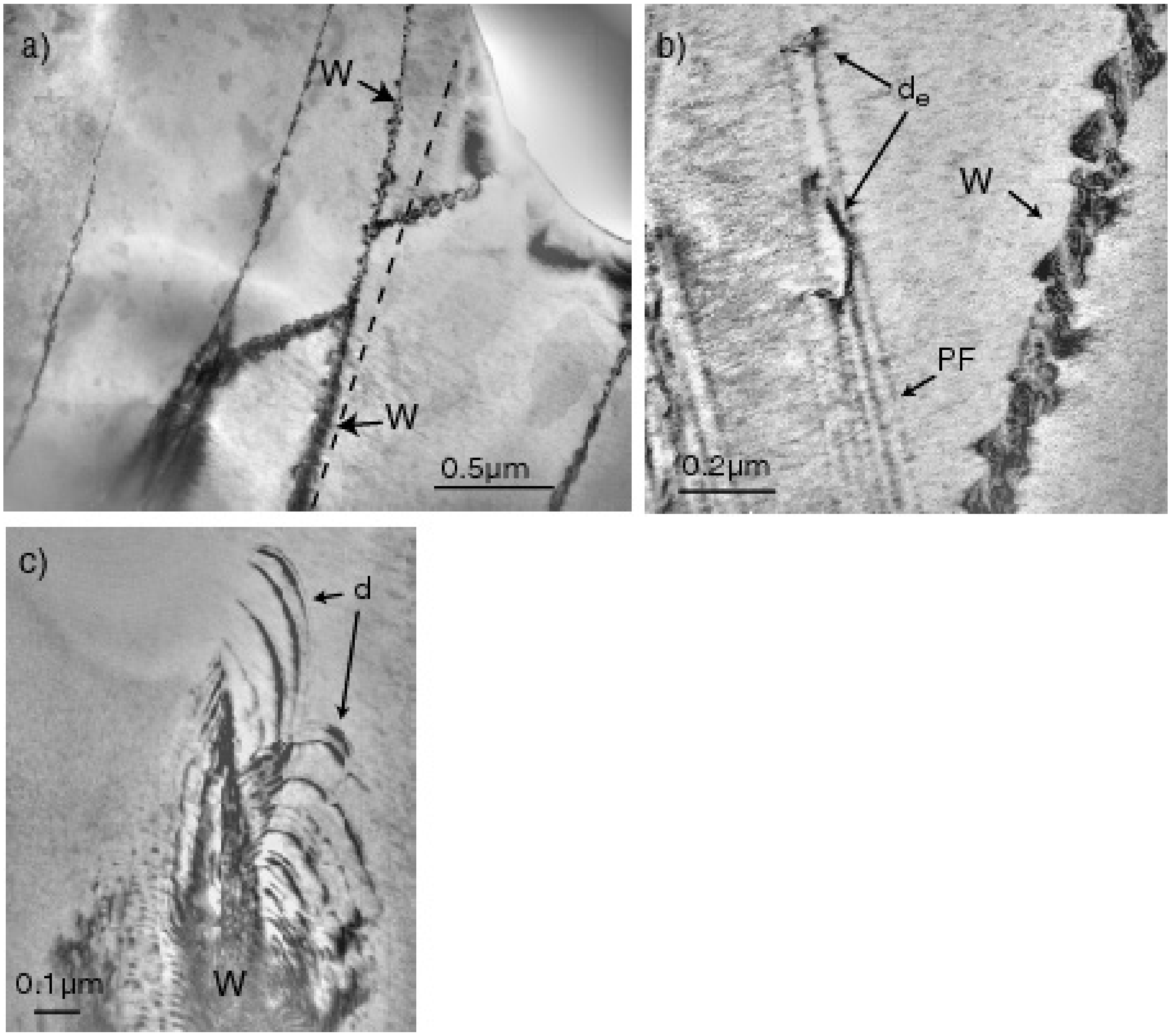

Figure 3. TEM observations of samples deformed at room temperature. (a) 3-dimensionnal network of walls (W). (b) Emission of climbing dislocations (d_e) from the wall W. (c) Dislocations pile-ups at wall extremities.

CONCLUSIONS

TEM observations of sample deformed at low temperature have yielded the following results:

- evidence of extensive climb have been found in samples deformed at 300°C. Dislocation movements take place mostly by pure climb in planes parallel and perpendicular to the compression axis, the first system providing vacancies to the second one.
- deformation at 20°C is mediated by the propagation of non-planar cracks followed by their re-healing. This leads to the formation of a 3-dimensional network of wavy walls. High strain incompatibilities are accommodated by emissions of climbing dislocations from the walls.

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