Short Communication

Guinier-Preston Platelets Interaction with Dislocations: Study at the Atomic Level

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Abstract. — Guinier-Preston zones, in Al-1.7 at % Cu, have been studied by means of high resolution electron microscopy. Most of the zones are atomic monolayers. Bilayers have been also observed. Observations have been carried out under ⟨100⟩ and ⟨110⟩ orientations. The shearing of a GP zone by an edge dislocation is reported. It is corresponding to one out of the three possible shearing geometries for a given glide plane. It is the one which is essentially at the origin of the chemical hardening of this kind of alloy. The other two variants for a given gliding plane seem to be soft obstacles. It is shown that the sheared GP zone which has been observed is very rich in Cu (close to 100%). We know from our other results that the content in Cu can be included in a range from less than 50% to 100%.

Résumé. — Les amas de Guinier-Preston ont été étudiés dans un alliage Al-Cu 1,7 % at. à l'aide de la microscopie électronique à haute résolution. La plupart de ces amas sont des monocouches atomiques. Les échantillons ont été observés selon deux orientations ⟨100⟩ et ⟨110⟩. Le cisaillement d'un amas par une dislocation coin a été observé. Il correspond à une des trois géométries possibles. Celle-ci est à l'origine du durcissement chimique de cet alliage. Les deux autres familles d'amas pour un même plan de glissement ne semblent pas, ou peu pour l'un d'entre eux, participer au durcissement. À partir de simulations du contraste de cette inter-section, on peut déterminer que l'amas cisaillé est très riche en cuivre (près de 100 %). De nos résultats précédents, on peut déduire que la concentration de cuivre dans les amas varie de moins de 50 à 100 % environ.

One of the most spectacular results of transmission electron microscopy has been the possibility of imaging atomic columns in thin crystals. In the beginning of the seventies, high resolution electron microscopy was restricted to the observation of blocks of atoms as in the oxide or crystals having a large unit cell as semiconductors or ceramics. A new generation

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of digitally controlled middle voltage microscopes and faster computing facilities enabled the expansion of this fascinating technique. In these days, a variety of metals, alloys and composite materials is being investigated at the atomic level. This approach enables to extract new information on materials, giving the possibility of a better interpretation of their physical, chemical or mechanical properties, confirming or disproving former theories and models. We report here a work which has been carried out with a 200 kV electron microscope (Philips CM20 UT) on Guinier-Preston zones in an Al-Cu alloy.

The strengthening of materials is due to obstacles for the movement of dislocations. A very common type of obstacles in alloys (except for other dislocations) are clusters or precipitates formed in the material by quenching and subsequent annealing. Usually a small volume fraction of these particles can cause an important hardening of the material. A variety of types of particles is going from very small coherent ones which can be cut by dislocations to large incoherent precipitates which can be impenetrable. Although many aspects about the dislocation-particle interaction have already been explained, it is nowadays possible to study these interactions at the atomic level, by means of high resolution transmission electron microscopy.

We have studied in detail an Al-1.7 at% Cu alloy, annealed at 100 °C for 10 hours. The strengthening of this alloy is due to the Guinier-Preston (GP1) zones which are small disc-shaped clusters rich in copper atoms, which form on the {100} atomic planes of aluminium matrix [1,2]. Our atomic resolution observations showed that the discs are from 4 to 10 nm in diameter and in majority of cases (> 80%) only one atomic layer thick (Fig. 1), in agreement with the work of Phillips [3], for instance. By means of computer simulations (EMS software due to Stadelmann [4]) it was confirmed that this kind of contrast, which consists in the alignment of spotty bright atomic columns amongst aluminium atomic columns of the matrix, corresponds to the structure image of a copper rich monolayer [5]. X-ray local chemical analysis and simulations of throughfocus series showed that the copper concentration in the zones is from less than 50 to 100%. From the point of view of the strengthening, the GP zones are coherent obstacles which can be sheared by dislocations as they move during deformation.

Under the ⟨110⟩ axis orientation of the crystal, we can observe the projection of one family of {100} atomic planes, the (001) - these of the GP zones, but also 2 over 4 {111} planes - which are slip planes in the f.c.c. structure. This geometry is then suitable for the study of the dislocation - GP zone interaction. A result is shown in Figure 2. An edge dislocation has sheared the monolayer GP zone, creating one atomic step on the cluster. In fact the direction of shearing (Burgers vector) is 30° out of the plane of the micrograph and we see its projection on the $(0\bar{1}1)$ plane due to the Burgers vector $1/2[1,1,0]$ or $1/2[1,0,1]$.

There are four points which are related to this observation.

- As it is clearly seen, one part of the cluster has been shifted with a part of the matrix on one side of the gliding plane, but the whole geometry of the crystal appears as unchanged. The absence of apparent disorder at the level of the dislocation passage is related to the fact that the elastic energy of the interaction is small, giving more importance to the "chemical" energy due to the cutting of the atomic bonds in the GP zone and adjacent atomic planes.

- Two columns of the GP zone adjacent to the shearing appear somewhat brighter than the other columns of the zone.

- As we know that the elastic part of the energy to shear the zone is not the essential part, this experimental result pushes to calculate the chemical energy involved in the crossing of the dislocation.

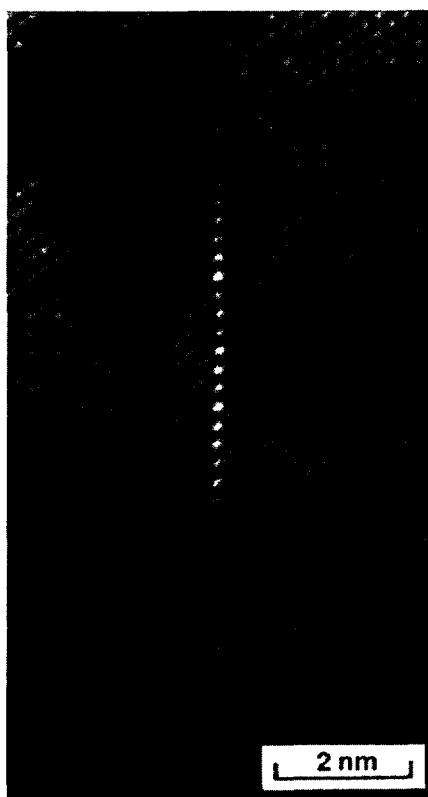- There is a black contrast on one side of the zone.

Fig. 1. — A typical monolayer Guinier-Preston zone showing a decreasing contrast on both sides due to the decreasing number of copper atoms in the projection.

The first remark needs to look in detail on the geometry of the interaction of dislocations with three sets of GP zones lying parallel to {100} matrix planes. For a given slip system the Burgers vector is parallel to one set of the GP zones while it is inclined with respect to the other two sets of particles. In the former case the dislocation shears a GP zone in its plane, creating only two atomic steps on its edge. The other two families of the GP zones are sheared into two parts. One example is shown in Figure 2. These two crossing mechanisms have to be considered in the strengthening model. Moreover, for a given glide plane, a dislocation originating from one side with a Burgers vector b, does not give the same configuration as a dislocation with the same Burgers vector b coming from the other side.

The black contrast on the right side of the GP1 zone is due to a Bragg reflection of the electron beam on the curved atomic planes adjacent to the particle (copper atoms are smaller than aluminum ones and so the first neighbouring planes to the GP1 zone are bowed). Electrons which are reflected on these curved atomic planes, on one side out of the GP1 zone are eliminated by the aperture placed in the diffraction plane of the objective lens.

The atomic columns close to the impact of the dislocation appear brighter due to the geometry of the new sheared interface. This fact is proved by the calculation of the observed contrast. The simulation of the rectangular monolayer GP zone containing 100% of copper gives an observable brighter contrast for the edge columns of the GP zone. The reason for this contrast is related to the fact that the interferences due to the scattering of the incident
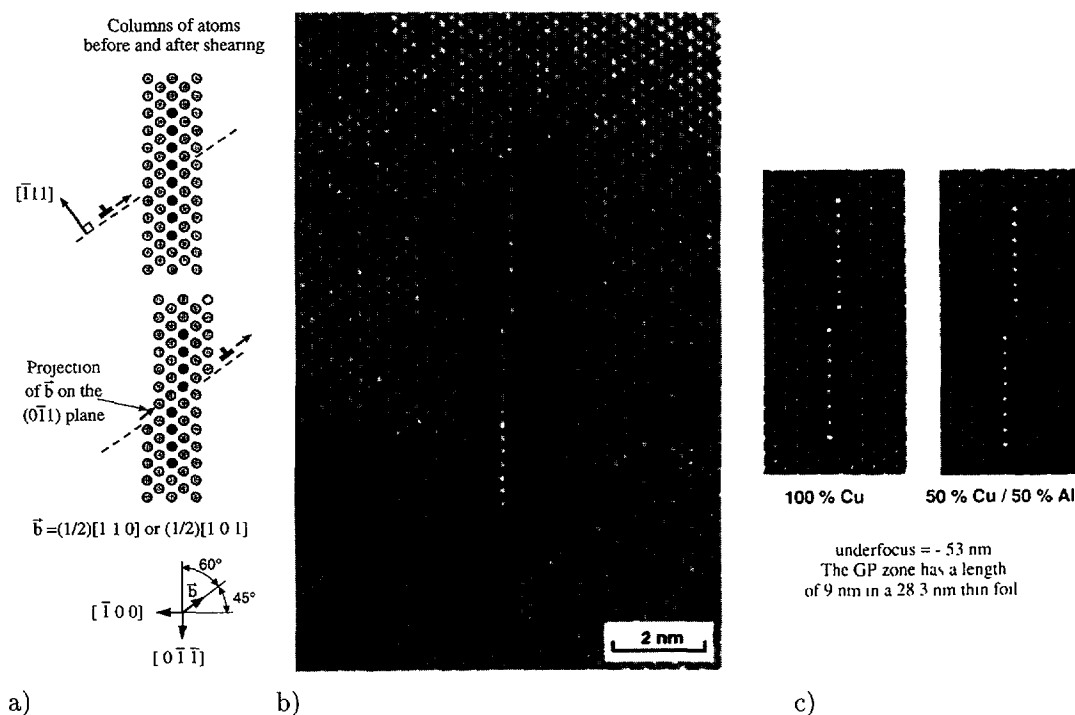
Fig. 2. — A Guinier - Preston zone sheared by an edge dislocation. a) Geometry of the crossing, b is not in the plane of the figure. b) Micrograph showing one type of crossing of a GP1 zone by an edge dislocation. c) Contrast simulations corresponding to two models - 100% Cu and 50% Cu / 50% Al in the GP zone. The simulations have been calculated for a rectangular GP zone 9 nm in depth embedded in the middle of the foil 28.3 nm thick. The simulations show that this zone has a Cu concentration close to 100%.

electron wave by the atoms of the neighbouring columns is not the same for this two interface columns which have not the same neighbours as the other bright columns of the zone. As the real GP zones are disc shaped (and not rectangular) the contrast fades out with the decreasing number of the copper atoms in the projection (Fig. 1). The only geometry to observe an abrupt interface (and then reinforcement of the contrast) is the case of shearing of the GP zone by a dislocation. The contrast observed in this special geometry can be used to estimate the copper content in the GP zone on the micrograph. We did the simulations for the sheared rectangular GP zones containing 100% Cu and 50% Cu / 50% Al. As it can be seen in Figure 2c, the 100% concentration gives the edge columns brighter than the others, which is not the case of the model with 50% Cu /50% Al. Therefore, the copper concentration in this GP zone is about 100%.

As we know that this zone is 100% rich in copper, it is possible to develop a model for calculating the chemical energy involved in this shearing geometry. There are two possibilities, depending on the Burgers vector orientation. It can be shown that the elastic interaction between a dislocation and a GP zone treated as a small dislocation loop of a Burgers vector equal to εb_{GP} ($|b_{GP}| = a/2$, where a is the lattice parameter of aluminum) and ε related to the change of lattice parameter ($\varepsilon \approx 0.11$) between Cu and Al (Cu atom is smaller than aluminium atom) gives a critical resolved shear stress of about 11 MPa (by including the Taylor factor,

yield stress in polycristal is of the order of 34 MPa). This value is not sufficient to explain the strengthening by the GP zones since the experimental yield stress corresponding to the alloy which is studied here is about 280 MPa.

In order to explain the yield stress, it is necessary to introduce a chemical energy change related to the redistribution of bonds due to the crossing of dislocations [6]. We looked in detail to the geometry. The neighbouring bondings Cu-Cu and Al-Al close to the edge of the shearing are replaced by two Al-Cu bondings when a dislocation crosses a GP zone in the configuration which is shown in Figure 2. The change of energy by atom length b of dislocation is given by:

$$\Delta U = 2E_{\text{Al-Cu}} - (E_{\text{Al-Cu}} + E_{\text{Cu-Cu}}) \tag{1}$$

which is the energy to create the two atomic interfaces of the zone which is sheared in two parts.

From the literature [7], giving the values of the energy pairs Al-Al, Al-Cu and Cu-Cu, ΔU can be estimated as 1.72 eV. The calculated value of the corresponding critical resolved shear stress is found to be between 102 and 144 MPa. After multiplication by the Taylor factor (being 3.1 for the f.c.c. structure) the yield stress for a polycristal is obtained as being between 316 and 446 MPa, which is a good order of magnitude as the experimental value is found to be 280 MPa. The difference can be originated from another interaction, mentioned above, which seems to give two sets of GP zones as possible easy obstacles (to be published), and changes the actual mean free path of dislocations in the alloy.

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