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Statistically motivated model of mechanisms controlling evolution of deformation band substructure

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ABSTRACT

Deformation bands are interpreted as a spontaneously formed microstructure caused by anisotropy induced by the slip nature of plastic deformation. The gradient terms in the proposed constitutive equations have been derived by averaging the assembly of discrete dislocations. The rigid-plastic model points to the main constituents which control the fragmentation mechanism: anisotropy of the hardening matrix, anisotropic resistance of the boundaries to slip, and the bowing (Orowan) stress. For symmetric double slip compression, the model provides an explanation of the observed band orientation and band width, and of the significant change in structural morphology seen as the band reorientation occurs at large strains. The predictions are in favorable agreement with available observations.

1. Introduction

In metal single crystals and polycrystals, a deformation microstructure evolves within a common framework. At all strain levels, the structural subdivision occurs in a form of elongated, alternately misoriented domains of a specific orientation. The domains, commonly called the *deformation bands*, are separated by roughly parallel families of geometrically necessary boundaries (GNBs). The deformation bands have only relatively recently come to light as a valuable tool for understanding the mechanism of plastic deformation (reviews, e.g. Bay et al., 1992; Kuhlmann-Wilsdorf, 1999; Hughes, 2001; Hansen and Jensen, 2011).

The inner structure built in the deformation bands depends on the character of slip, being different in cell forming and non-cell forming materials. In medium to high stacking fault energy crystalline materials at moderate strain (easy cross-slip, cell forming materials, e.g. rolled Al and Ni at von Mises effective strain $\bar{\varepsilon} \sim 0.3 - 0.7$), the deformation substructure most often consists of one or two sets of extended planar GNBs with a specific alignment, between which fairly equiaxed cells are formed (Bay et al., 1992; Hansen and Jensen, 2011; Hong et al., 2012). On the other hand, as observed by Hughes (1993), in the rolled Al–Mg, the framework for a crystal domain subdivision in non-cell forming metals is analogous to that observed in cell forming metals. However, the inner substructure of the deformation bands in Al–Mg consists of dislocations organized into a Taylor lattice containing multiple Burgers vectors. The domains have an alternating misorientation along the [111] slip plane. Unlike the rather sharp GNBs in the cell forming metals, the GNBs observed in the Al–Mg are diffuse.

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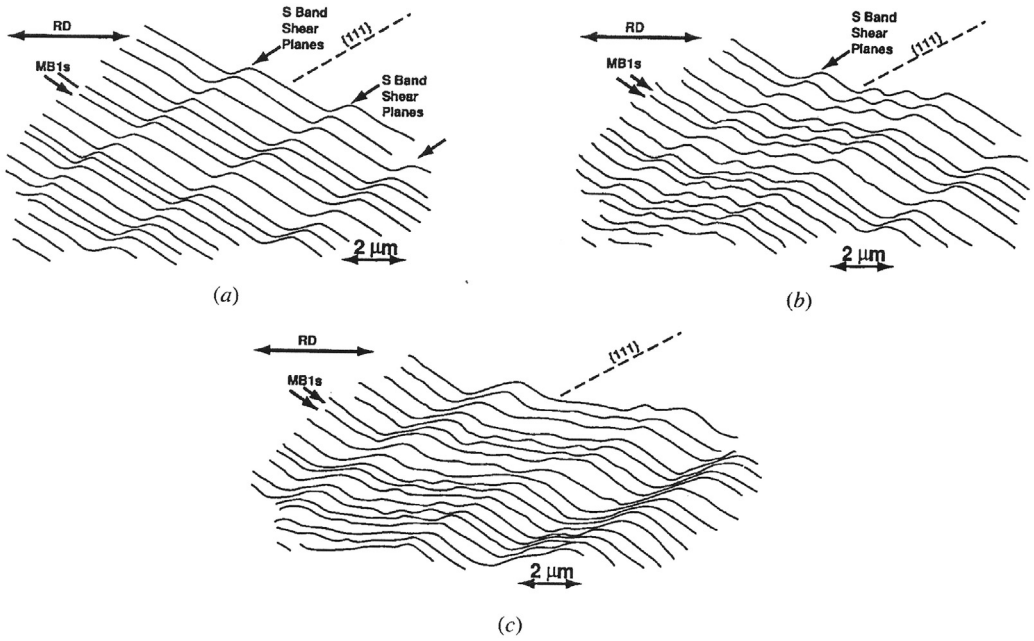

Fig. 1. Schema deduced from the micrographs of the transformation process of the large scale reorganization of the original MB and cell blocks microstructure to the lamellar structure oriented at a shallow angle to the RD (reproduced from Hughes and Hansen (1993)).

A typical microstructural evolution during rolling of fcc medium to high stacking fault energy metals has been analyzed in detail by Hughes and Hansen (1993, 2000). The deformation microstructures evolved in high purity nickel cold-rolled from 0.5 to 4.5 von Mises effective strain were observed and analyzed. Special focus was on factors which contribute to the transition from structures characteristic of small to medium strain microstructures to those characteristic of large strain microstructures (an analogous microstructure evolution was observed e.g. in Al and Al–Mg single crystals after room-temperature channel-die compression up to true strains 2.1 (Albou et al., 2010)). The observations reported in Hughes and Hansen (1993, 2000) can be summarized as follows.

To achieve energetically favorable strain accommodation, a subdivision occurs and created domains in which different slip systems operate. These domains have been defined as *cell blocks*. The cell blocks are bounded by GNBs which contain the lattice misorientation arising from as a consequence of strain accommodation. When increasing strain further exerted, the accommodation is met by refinement of the subdivision and by a change in substructural morphology.

At small strains, the GNBs bounding cell blocks are long single *dense dislocation walls* (DDWs) parallel to the transverse direction[1] and of a specific orientation with respect to the rolling direction (RD). With increasing strain, spacing between the DDWs decreases through the formation of new DDWs within the cell blocks, and misorientations across DDWs increase. The requirement of strain compatibility across the DDWs is met through further subdivision of the DDWs, which occurs by the formation of thin plate-like cell blocks in the DDWs. These new cell blocks have been defined as *microbands* (MBs). The DDWs and MBs have an orientation to the RD with no crystallographic preference.

At intermediate strain, most of the cell blocks are delineated by MBs which have formed from DDWs. These MBs have a characteristic morphology composed of parallel dislocation walls or small pancake-like cells, and the thickness of the MBs ranges from 0.1 to 0.4 μm. There are cells both within and between the MBs. Since MBs are formed from the DDWs, they maintain the same orientation with respect to the RD. Two families of the MBs have been observed: one being oriented $\pm 30^\circ$ to the RD and the other inclined $\pm 15^\circ$ to the RD. There is a difference for rolled nickel and aluminum: for aluminum, the peak in the distribution of orientations for the first family of MBs remains at 40° to the RD, whereas for nickel this peak shifts to 30° with increasing strain (Hughes and Hansen, 1993).

At intermediate strain, in addition to the MBs and DDWs, there have been observed dislocation configurations in which localized shear along {111} planes can develop. The most prominent are the bands of intense local crystallographic slip which intersects parallel groups of MBs, and thus creates a string of "S" shaped perturbations in the pre-existing MB structure. The *bands of the intense local slip* (called in Hughes and Hansen (1993) *S-bands*)[2] are narrow, from 0.05 to 0.3 μm in thickness, and long, with length ranging from 5 to 20 μm. Nearly all of the shear planes of these bands are parallel to a {111} slip plane within

[1] The transverse direction is in the rolling plane perpendicular to the rolling direction. The lateral (longitudinal) plane is parallel to the rolling direction and to the normal direction of the rolling plane.

[2] Note that the perturbed MBs become S-shaped, while the S-bands are straight.