Acta Materialia 132 (2017) 517–524

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Persistent slip bands: The bowing and passing model revisited

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ARTICLE INFO

Article history:
Received 26 January 2017
Received in revised form
13 April 2017
Accepted 27 April 2017
Available online 29 April 2017

Keywords:
Persistent slip bands
Saturation stress
Similitude
Modeling
Screw annihilations

ABSTRACT

Brown's bowing and passing model for persistent slip bands (PSBs) was extended in Cu and Ni to the whole range of temperatures in which a saturation plateau is observed. Advantage was taken of the similitude relation to rewrite in dimensionless form the equations of the original model and of a more accurate revisited version. Input quantities for computing the solutions were taken from a previous study of experimental results; all unknown quantities could then be directly calculated without any assumption or approximation. The comparison between experimental results and the predictions of the revisited model confirms the basic assumptions of the bowing and passing model, according to which the thermally activated annihilation of screw dipoles is governing the channel widths, the Orowan stresses and the critical stresses in the channels. All other assumptions and numerical predictions are perfectly confirmed, save for the occurrence of small resistive stresses in the channels. In addition, a better understanding of the complex behavior of PSB walls under stress is necessary in order to accurately determine the plastic strain amplitude of PSBs. Mesoscale and atomistic simulations are needed for further modeling of the wall properties and the screw dipole annihilations.

1. Introduction

Persistent slip bands (PSBs) are formed in ductile materials cycled in single slip at imposed plastic strain amplitudes per cycle typically between 10^{-4} and 10^{-2}. Since their discovery in the 1950s these localized bands of plastic strain have drawn a lot of attention for practical reasons related to fatigue damage as well as for fundamental reasons. Indeed, they constitute a unique example of mechanical response exhibiting a constant saturation stress. Hence, there is a wealth of experimental and theoretical literature on the relation between their almost periodic wall-and-channel dislocation structure and their properties [1–4].

The PSB channels contain a constant density of screw dislocations, which shuttle forward and backward during cycling. These dislocations mutually annihilate by cross-slip after having travelled a certain mean free path and deposited edge segments along the PSB walls. A small fraction of these edge segments is able to cross the walls; it emerges and expands in the neighboring channels where it produces fresh screw dislocations of both signs. Hence, the saturation of the screw dislocation density results from an exact balance between creation and annihilation mechanisms. The PSB walls contain a large density of short edge segments, mostly in the primary plane but also in the cross-slip plane. The microstructure was found to be rather complex [5] and, as yet, former models for saturation in the walls were not revisited. The walls are partly permeable to edge dislocations, but screw dislocation motion in the channels is producing the largest part of the imposed plastic strain amplitude.

In its simplest form, the similitude relation expresses that the characteristic dimension of a dislocation microstructure, λ, is proportional to the average length of the dislocation segments, whereas the flow stress τ_c is inversely proportional to it. Thus, the flow stress is inversely proportional to the characteristic dimension and is written $\tau_c = K\mu b/\lambda$, where K is a similitude constant, μ is the shear modulus and b is the magnitude of the Burgers vector [7]. The saturation stress of PSBs is strongly temperature dependent, so that investigations on similitude require measurements performed on microstructures formed at different temperatures.

In the recent study [8], the similitude properties of PSB channels and their consequences were investigated in full detail from

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http://dx.doi.org/10.1016/j.actamat.2017.04.064
1359-6454/

experimental results in copper and nickel crystals cycled at saturation. The domains of temperature investigated encompassed the whole domain of occurrence of PSBs. It was found that both PSB channels and PSBs follow similitude relations. This may seem paradoxical in the case of PSBs since the wall-widths do not depend on temperature; it is so because of a compensating term arising from PSB channels, in which the critical stress for screw dipole annihilations is smaller than the saturation stress (see the discussion in Section 3 of [8]). The obtained results were confronted to the predictions of Brown's bowing and passing model [9], according to which the critical flow stress of PSB channels is governed by the annihilation of screw dipoles by cross-slip. This critical stress is defined as the stress corresponding to the maximum height of stable dipoles, that is, to their passing stress. As a whole, the predictions of the bowing and passing model were found to be in reasonable agreement with experimental results. However, as the model does not account for any other interaction than the ones between screw dislocations, the critical stresses in the channels were found smaller than the saturation stresses by a few MPa.

An alternative model, the composite model, was developed over the years by Mughrabi and co-workers, essentially at room temperature (see Ref. [4] for a full review). This model emphasizes the occurrence of significant internal stresses in the walls and channels and assumes that the annihilation of screw dipoles occurs spontaneously without the help of thermal activation.

Till now, debates about the modeling of the saturation stress essentially focused on the properties of screw dislocations in PSB channels at 300 K. The motivation of the present work is to provide an extension to a wide range of temperatures. The most basic equation of the bowing and passing model [9] is rather intricate and full predictions cannot be expressed in analytical form. Thus, the model was cast into a more transparent form with the help of a few simplifying assumptions, which were validated at room temperature. In the present work, the basic equation is solved numerically. This makes it possible to predict without any approximation the values of all the relevant quantities as a function of flow stress and temperature. For this purpose, use is made of the results drawn in Ref. [8] from experimental studies on copper and nickel.

In Section 2, the basic equations of the model are set in dimensionless forms, which incorporate the similitude constants of PSB channels determined in [8]. The results presented in Section 3 are concerned with the temperature and critical stress dependencies of the critical screw dipole heights and of the coefficient determining the respective contributions of the bowing and passing stresses to the critical stress. Except for the small differences between critical and saturation stresses mentioned above, a striking agreement is found between the model predictions and experimental results on copper and nickel. A few other predictions, in particular on the intrinsic plastic shear amplitudes of PSBs, are discussed in Section 4 and concluding remarks highlighting the major results are presented in Section 5.

2. The bowing and passing model revisited

This part recalls first the original bowing and passing model and next the way it is expanded to a wide range of temperatures. Further, a revisited version is established in order to verify whether or not an approximation made at room temperature is valid at all temperatures.

2.1. The original bowing and passing model

In its original form, Brown's bowing and passing model [9] has brought an improved analytical answer to comments by Mughrabi and Pschenitzka [10] on a previous attempt [11] to estimate the saturation stress in PSB channels.

The discussion of the model is based on Eq. (10*).[1] This equation yields the critical stress of the channels τ_c as a linear combination of the Orowan stress τ_{Or}, which sets screw dislocations in motion, and the passing stress, τ_{pass}, which corresponds to the maximum critical height, h_c, for the annihilation of screw dipoles

$$\tau_c = \alpha_{\mathrm{B}}\tau_{\mathrm{Or}} + \tau_{\mathrm{pass}} = \alpha_{\mathrm{B}}\frac{2E_{\mathrm{edge}}}{bd_{ch}} + \frac{\mu b}{4\pi h_c} \quad (1)$$

In the assumed absence of any other stress contribution, the flow stress τ_c is assumed to be the stress at saturation. The constant coefficient α_{B} accounts for the contribution of the Orowan stress to the flow stress. In this Orowan stress, E_{edge} is the line energy of edge segments (see Supplementary Section S1 for line tensions and line energies) trailed by the bowing screws in channels of width d_{ch}.[2] The contribution of the passing stress is expressed in terms of the critical dipole height, h_c. In the present context, it is convenient to introduce similitude in Eq. (1) by rewriting it in the form

$$K_{ch} = \frac{\tau_c d_{ch}}{\mu b} = \frac{2\alpha_{\mathrm{B}}E_{\mathrm{edge}}}{\mu b^2} + \frac{1}{4\pi}\left(\frac{d_{ch}}{h_c}\right), \quad (2)$$

where the first equality expresses the similitude relation in the channels and K_{ch} is the related similitude slope. In Eqs. (1) and (2) the channel widths and wall thicknesses are known from experiment. The value usually quoted in the literature for the critical annihilation distance of copper at room temperature is $h_c \approx 50$ nm [1,12]. The value of the coefficient α_{B} is critical too because it contributes to the magnitude of resistive stresses in the channels, $\delta\tau_{ch} = \tau_{\mathrm{PSB}} - \tau_c$, where τ_{PSB} is the saturation stress. Such resistive stresses were found in the previous study [8] but, as they are not included in the bowing and passing model, they do not appear in its equations.

In the model, the coefficient α_{B} is drawn from a rather complex master equation describing the critical configuration of a dipole of flexible screw dislocations at the passing stress. For this purpose, a small transition zone is defined close to the PSB walls. It connects the straight edge lines deposited on the walls by the motion of the screws to the two interacting screw lines with large critical radii in the central part of the channels. In the transition zone, the characters of the interacting lines go from nearly edge to nearly screw and the curvature radii are quite small. The equilibrium condition for this critical configuration is estimated using an effective value of the line tension, T_{eff}, which is taken for line orientations of 45° (see Sections S1 and S2.2). As a result, one obtains the master equation given by Eq. (9*):

$$\tau_c = \frac{2E_{\mathrm{edge}}}{bd_{ch}} + \frac{\mu b}{4\pi h_c}\left(1 - \frac{b^2 d_{ch}^4\left(\tau_c - \frac{\mu b}{4\pi h_c}\right)^2}{640 h_c^2 T_{\mathrm{screw}}^2}\right)k, \quad (3)$$

where $k = (1{-}2\ T_{\mathrm{eff}}/\tau_c d_{ch} b)$ and T_{screw} is the line tension of screw dislocations (Eqs. (S1-2) and (S2-3)). At room temperature k does not differ much from unity, so that it is assumed that $k = 1$ at all temperatures. Eq. (3) is then rewritten in terms of the coefficient α_{B} as given by Eq. (1) or (2). This leads to Eq. (11*)

[1] In what follows, starred equations are those of the original bowing and passing model [9].

[2] In Brown's model [9], the channel widths (or wall spacings) are denoted by d. In what follows, d denotes the periodicity of a PSB, $d = d_{ch} + d_w$, where d_w is the wall thickness.