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Directionality of yield point in strain-aged steels: The role of polar dislocations

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Abstract

The directionality of the sharp yield point in strain-aged steels has been investigated by modeling tension/compression and forward/reverse torsion tests separated by accelerated aging. The occurrence of a Bauschinger effect and the absence of a yield point after a forward straining–aging–reverse straining sequence are interpreted within the framework of a field dislocation theory coupling the evolution of statistical and polar dislocation densities with that of point defects due to strain aging. The polar dislocation density reflects lattice incompatibility and long-range internal stresses. By assisting yielding in reverse straining, the associated back-stress is seen as the origin of the Bauschinger effect. By also promoting dislocation unlocking, the back-stress is found to be responsible for the absence of a yield point in reverse straining. Polarized dislocation structures formed in forward straining in association with back-stress build up may annihilate and inverse polarization occur in reverse straining. This microstructure evolution translates into an inflexion of strain hardening after strain path reversal.

Keywords: Yield point; Static aging; Bauschinger effect; Dislocation structures; Strain gradient plasticity

1. Introduction

The sharp yield point phenomenon has been known since 1842, when it was discovered by Piobert in mild steel sheets hit by bullets [1]. However, it is still not fully understood. Described by Lüders in 1860 [2], it occurs in body-centered cubic (bcc) polycrystals at room temperature, and has also been observed in Al–Mg alloys [3]. In a tensile sample loaded at constant cross-head velocity, it is associated with a band of localized dislocation activity travelling along the sample. The band nucleation, usually at one grip, corresponds to a drop in stress, from the upper yield point (UYP) to the lower yield point (LYP). The plastically strained area then spreads along the sample. A clear cut front separates this area from the undeformed one, into which it propagates, until the sample is uniformly stretched at the so-called Lüders strain level. From this point onwards, the deformation proceeds uniformly in the sample.

It is commonly accepted that strain aging is responsible for this behavior: solute atoms tend to diffuse to arrested dislocations, which increases the unpinning stress up to the UYP level [4]. Dislocations are collectively unpinned at the UYP, but since the stress needed to accommodate the imposed strain rate is substantially lower, an abrupt multiplication of dislocations takes place, along with elastic relaxation of the rest of the sample. This unpinning mechanism has intricate connections with the spatial correlations responsible for band propagation. According to the Cottrell assumption [4], propagation occurs once the stress concentration due to dislocation pile-ups at grain boundaries is able to activate new dislocation sources in neighboring grains. At a somewhat larger scale of interpretation, long-range internal stresses are involved in the vicinity of the band, as incompatibilities in plastic

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strain with the adjacent material must be elastically accommodated. These internal stresses provide a mechanism for band propagation.

In a low-carbon steel, evidence of the role of internal stresses in the unpinning mechanism is also provided by the directionality of the yield point. If such a material is deformed beyond the Lüders strain, then aged and further strained, a sharp yield point phenomenon reappears provided straining is pursued in the same direction. Such a behavior can be explained within the framework of a local model coupling aging properties with isotropic strain hardening [5]. However, if the sample is strained in the direction opposite to that before aging, a Bauschinger effect is observed and the sharp yield point phenomenon is usually absent [6–8]. This phenomenon is shown in the tension–compression of a mild steel in Fig. 1. Such directionality of the yield point is of considerable practical importance. It may be useful, as it curbs the return of the sharp yield point in temper-rolled or bake-hardened steels, but it may also limit the benefits of strain aging as a strengthening mechanism. Further, it demonstrates that the strain aging and unpinning mechanisms are dependent on the gradients of the distribution of dislocations, which challenges local interpretations. Indeed, it has been recognized in recent decades that, in severely nonuniform conditions, conventional (local) descriptions of plasticity, which do not include internal length scales, are generally unable to describe patterning consistently (see Ref. [9] for a review).

Several attempts at modeling the sharp yield point phenomenon have been made by using gradient plasticity models [9–12]. Although they may account for several aspects such as band width and band velocity, none of these models is able to describe the directionality of the yield point, due to their isotropic character. In the present paper, it is our objective to present an interpretation of the yield point directionality by using the continuous framework of a field dislocation theory naturally involving internal length scales through lattice incompatibility and dislocation transport [13]. We strive to understand this phenomenon by coupling the evolution of polar and statistical dislocations with the kinetics of strain aging. Polar dislocations, also referred to as "excess dislocations" or "geometrically necessary dislocations", are a continuous manifestation of lattice incompatibility. They are associated with the development of lattice curvature and long-range internal stresses [14]. In contrast, statistical dislocations (or "statistically stored dislocations") are assumed to be arranged so as to render a net zero overall stress field. When they are predominant, short-range interactions prevail, which results in statistical forest hardening. In conventional plasticity theories, only statistical dislocations are considered. Both species contribute to plastic flow however. Their dynamics are coupled, because spatial gradients in the plastic distortion field may generate polar dislocations [15,16]. Lattice curvature due to point defects is not considered. The paper is organized as follows: the general field equations for dislocation dynamics are summarized in Section 2. In particular, a rate form of these equations and a two-dimensional idealization are shown. Section 3 deals with the kinetics of static aging and its connections with dislocation dynamics. Results obtained from this model by using a general three-dimensional (3D) approach and a reduced one-dimensional (1D) setting are presented and discussed in Section 4. Concluding remarks follow in Section 5.

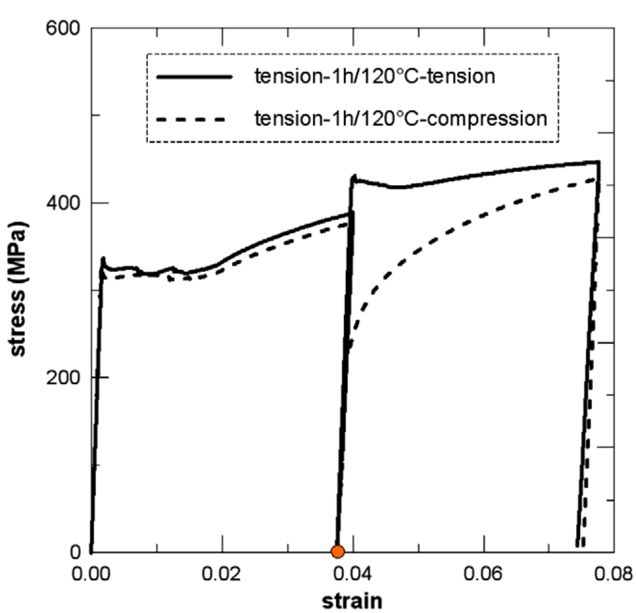

Fig. 1. Stress–strain curves during tension–aging–tension and tension–aging–compression experiments on a 1020 mild steel. The aging period is marked with an orange dot. For convenience the sign of the compression stress is reversed. Both tension and compression stresses are plotted against the same cumulative strain. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

2. Field equations for dislocation dynamics

The model uses the continuum description of dislocations based upon Nye's dislocation density tensor $\boldsymbol{\alpha}$ [18]. Operating on the normal $\mathbf{n}$ to a unit surface S in the deformed configuration, $\boldsymbol{\alpha}$ provides the net Burgers vector $\mathbf{b} = \boldsymbol{\alpha} \cdot \mathbf{n}$ of all dislocation lines threading S, i.e. the closure defect in plastic displacement found along the Burgers circuit surrounding this surface, in the natural (stress-free) configuration (the latter is derived from the deformed configuration by applying the inverse elastic distortion to its vectors). The net Burgers vector $\mathbf{b}$ may be zero if all individual Burgers vectors compensate statistically. Then the Nye tensor $\boldsymbol{\alpha}$ is zero and all these dislocations are deemed "statistical". For the same dislocation distribution, the characteristic size of the Burgers circuit, i.e. the scale of resolution of the dislocation ensemble, may be decreased to the point where only one dislocation line is threading the surface S. Such a situation occurs when this size amounts to the mean dislocation-to-dislocation distance $\rho_f^{-1/2}$ (ρ_f denotes the statistical forest dislocation density). Then $\boldsymbol{\alpha}$ is non-zero and the involved dislocation is labeled as a