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Microarticle

Kinematics of formation and cessation of type *B* deformation bands during the Portevin-Le Chatelier effect in an AlMg alloy

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ABSTRACT

Using digital image correlation technique, various stages of development of localized deformation bands caused by the Portevin-Le Chatelier (PLC) instability of plastic flow are examined at strain rates corresponding to abrupt stress drops akin to relaxation oscillations. Diffuse deformation bands are found prior to stress drops. Although the respective increase in the local strain rate is relatively weak, it is immediately observed over the entire region of the nascent PLC band. Moreover, diffuse bands are also detected at the beginning of reloading after the end of stress drops, thereby indicating that the termination of plastic instability proceeds through a progressive depletion of the strain localization. Weak transient strain localizations that do not develop into a PLC band are also observed during reloading.

Introduction

The Portevin-Le Chatelier (PLC) effect is a phenomenon of plastic instability in alloys, associated with brief strain localizations within deformation bands resulting in stress fluctuations [1] (for recent reviews, see [2,3]). The interest to this effect is not only sustained by the unceasing elaboration of new alloys but has recently taken a new turn from the viewpoint of self-organization in nonlinear dissipative systems [4]. At low and intermediate values of the applied strain rate with respect to the strain-rate domain of instability, the PLC bands last very shortly, often only several milliseconds, and give rise to abrupt stress drops. Recent occurrence of experimental techniques with a high time resolution made it possible to start investigations of the long-standing problem of the PLC band nucleation and relationship between the stress drop and the band development (e.g., [5–9]). In the present paper, attention is paid to both nucleation and cessation of the so-called type *B* deformation bands characteristic of intermediate strain rates.

Methods

Tensile specimens with the gage part $35 \times 7 \times 3\,\text{mm}^3$ in size were cut from cold-rolled sheets of an Al-3 wt%Mg alloy and annealed at 400 °C for 2 h. Polycrystalline grains had an approximately equiaxed shape with the average size about 40 μm. Tensile tests were performed with a constant grip velocity of 0.3 mm/min corresponding to the nominal applied strain rate $\dot{\varepsilon}_a = 1.43 \times 10^{-4}\,\text{s}^{-1}$. 2D digital image correlation (DIC) technique was applied to calculate local strain-rate maps over the specimen gage part and visualize deformation bands as described in [10]. Although the time resolution of the DIC technique was relatively low (1 frame per 65 ms) and, therefore, not adopted to a detailed mapping of a given band, a large number of stress serrations observed in each test (Fig. 1) allowed to select and examine various stages of the development of the PLC bands.

Results and conclusions

The example of a deformation curve in Fig. 1a and b illustrates overall tensile behavior of the studied material and magnify details of two stress drops. Fig. 1c and d display maps of the local strain rate $\dot{\varepsilon}$ for several time instants selected in Fig. 1b. Both the serrations and deformation bands show typical type *B* patterns: Each stress drop is produced by an individual deformation band; The subsequent bands form series of relay-race ("hopping") propagation along the gage length, giving rise to packets of regular stress serrations akin to relaxation oscillations; Such packets are separated by intervals of less regular behavior corresponding to attempts of nucleation of a new band in the work-hardened material (see, e.g., [4,5]).

Fig. 1c reveals two PLC bands at the instants corresponding to the

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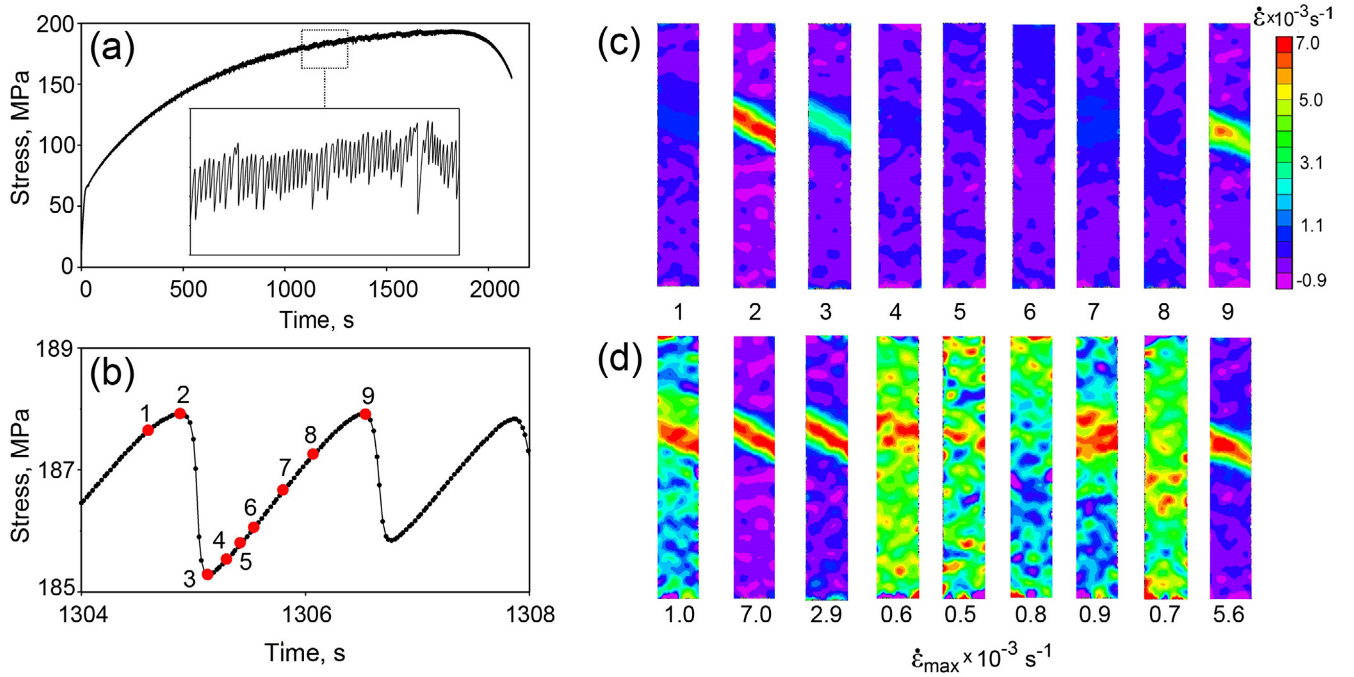

Fig. 1. (a) Typical stress-time deformation curve displaying type *B* serrations at $\dot{\varepsilon}_a = 1.4 \times 10^{-4}\,s^{-1}$. (b) Magnification of two stress drops. (c) Series of DIC images of the specimen surface at the instants indicated in Fig. 1b. Color bar quantifies the $\dot{\varepsilon}$ scale. The image height is approximately 34 mm. (d) The same as Fig. 1c, but the color scale is recalculated for each frame independently. For quantitative comparison, the maximum $\dot{\varepsilon}$-value is indicated under each frame. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

maximum load at the onset of the respective stress drops (frames 2 and 9). Frame 3 illustrates the band weakening at the end of the first stress drop. A relatively uniform $\dot{\varepsilon}$ field with weak heterogeneities is observed during reloading between stress drops (frames 4–8).

Fig. 1d presents the same series of images after maximization of the contrast through determination of the $\dot{\varepsilon}$ scale range independently for each frame. The image contrasting allows to visualize three particular features of such kinematic patterns found at various work-hardening stages. First, frame 1 reveals a diffuse deformation band corresponding to the commencing slowing-down of the reloading prior to the abrupt stress drop. Although the intensity of this heterogeneity is weaker than in the well-developed PLC band, it covers the entire area of the PLC band (cf. frames 1 and 2 and the maximum $\dot{\varepsilon}$-values indicated underneath). It can be suggested that the band is nucleated quasi-instantaneously, but the strength of the strain heterogeneity grows progressively and prepares the catastrophic instability. Furthermore, frame 4 displays a diffuse band in the wake of the PLC band, thus testifying that the termination of the instability also involves a gradual change (a decrease in this case) in the strain localization intensity. Therewith, the ratio between the local and applied strain rate is high enough for a certain detection of the band, $\dot{\varepsilon}/\dot{\varepsilon}_a > 4$, even if it is an order of magnitude lower than in frame 2. Finally, frame 7 displays a diffuse band that appears during reloading but is "healed" up (frame 8) enough to not lead to a stress drop.

The usually discussed scenarios of the PLC band nucleation were formulated in [5,11]. Two extreme cases consider the occurrence of either a relatively large embryo on a side surface of the specimen, followed by its transversal growth, or a thin (several atomic planes) transversal band that grows in the lateral direction. Besides, a mixed scenario can be envisaged, such that a band arises on a side surface and is thickened laterally during the transverse propagation, thus acquiring a wedge shape. The above results testify that the instability may not imply the nucleation of an embryo. Indeed, frame 1 shows that the initial weak deformation band already has dimensions close to its final size.

The conjecture of a quasi-instantaneous nucleation of deformation bands across the specimen width agrees with the conclusions [6,7], albeit the authors of these works only surveyed the time interval corresponding to the fast stress drop but not the prior stage. Both the immediate nucleation and the mixed scenario were detected in [6]. Only mixed scenario was reported in [9]. The observation of different scenarios leads to a suggestion that the PLC band formation is microstructure dependent (cf. discussion in [12]). It is therefore necessary to investigate the band kinematics in materials with different microstructures. It would also be interesting to examine the formation of type *C* bands that occur at low $\dot{\varepsilon}_a$, give rise to very deep and abrupt stress serrations, and are virtually uncorrelated in space [13].

Whereas the nucleation of a band through the entire width of the specimen could be anticipated from the literature data [6–8], the observation of a diffuse band in the wake of the PLC band was unexpected. It can be suggested that this symmetry between the band nucleation and termination is due to the dominating role of internal stresses in both processes (cf. [14]). Such stresses are generated due to plastic strain incompatibilities in differently strained material sites and are controlled by second order gradients of strain [15]. This suggestion conforms to the observation of the "healing" of a weak deformation band, which can be attributed to elastic reaction of the material outside the band. Moreover, such a healing was predicted (unpublished) in a block-and-spring model of the PLC effect, which used a second gradient term to mimic the spatial coupling between strain heterogeneities [16]. So far, modeling of the PLC effect was mostly aimed at reproducing overall spatiotemporal patterns of jerky flow. The results presented motivate efforts towards modeling of the kinematics of individual PLC bands.

In summary, the present results allow for the following suggestions. The formation of a short-duration PLC band giving rise to an abrupt stress drop may follow different scenarios in different materials. The observation of diffuse bands prior to abrupt drops bears evidence that the strain localization may take place quasi-simultaneously in various grains over the entire cross-section of the sample. This weak strain heterogeneity can be healed up without resulting in a "catastrophic" process, i.e., a deep stress drop associated with intense strain localization in a well-delineated PLC band. The latter may not terminate instantly but be depleted progressively, so that the initial part of reloading does not necessarily correspond to a uniform quasi-elastic deformation. These results point out to an important role of spatial coupling between differently strained material elements in the kinematics of the PLC instability.

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