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Three types of Portevin–Le Chatelier effects: Experiment and modelling

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Abstract

By employing the dynamic digital speckle pattern interferometry (DSPI) technique, three types of Portevin–Le Chatelier (PLC) effects are investigated systematically, with emphasis on the temporal and spatial dynamic features. A new model based on the dynamic strain aging (DSA) mechanism is proposed, and three types of PLC effects at different applied strain rates are reproduced by it when the spatial coupling is included. The dynamic interaction between dislocation and diffusing solutes is also studied through the developed constitutive model. The results self-consistently exhibit three branches of the dislocation–solute interaction, two stable branches at low and high strain rate (or dislocation velocity), which correspond to the effective aging or unpinning of dislocation, respectively, and a metastable one at the intermediate strain rate, where negative strain rate sensitivities result from the dynamic strain aging.
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Keywords: Portevin–Le Chatelier effect; Dynamic strain aging; Negative strain rate sensitivity; Numerical simulation

1. Introduction

The Portevin–Le Chatelier (PLC) effect [1–3], which occurs in many dilute alloys under appropriate conditions, is one of the most prominent examples of plastic instabilities. In particular, this effect manifests itself as a serrated flow in the stress–strain curve and static or propagating strain localization in the sample. Since it was discovered a century ago, the PLC effect has attracted much attention from experimental and theoretical researchers. Abundant reviews are provided on this subject, e.g., Bell [3], by Kocks [4], by Neuhäuser [5], by Estrin et al. [6,7], by Zaiser and Hähner [8], Rizzi and Hahner [9]. As an intrinsic property of materials, the PLC effect is generally attributed to the dynamical strain aging (DSA) [10–15] associated with the interactions between mobile dislocations and diffusing solute atoms.

While the kinetics of DSA has been thoroughly studied by plentiful experiments in the evolution of stress/strain histories [16–21], the kinematics characteristics of the localized deformation bands are also important. Up to now, there are two representative experimental means for direct observation of the PLC bands, i.e., the shadowgraph method and the laser extensometer method. By the traditional shadowgraph method, which was developed by Chihab et al. [22], the band kinematics information can be obtained from the polished specimen surface. As the specimen surface becomes rough in response to the passage of deformation bands, this method meets difficulty in observing the repetitively generated PLC bands. The laser extensometer method, by which the specimen surface is covered by markings 1 mm wide using white and black lacquers and the local strain within each zone is scanned by a laser beam, is exploited by Ziegenbein et al. [23] to monitor the kinematics feature of the PLC deformation bands. By this method, one-dimensional deformation of the PLC bands can be measured with a spatial resolution of 1 mm. In the present paper, a realtime two-dimensional observation method, the dynamic digital speckle pattern interferometry (DSPI) technique, is used to measure the geometric and

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kinetic aspects of the PLC bands with a spatial resolution of several tens of microns and a deformation resolution of laser wavelength.

At a qualitative level, the DSA mechanism is responsible for the macroscopic negative strain rate sensitivity (SRS) of the flow stress. By assuming that the strain rate hardening is negative over a finite interval of strain rates, i.e., the N-shaped relationship between the plastic strain rate and flow stress, Penning [24] first proposed the concept of negative SRS and elegantly explained the existence of the PLC effect. Based on this, Kubin and Estrin [25,26] and Lebyodkin et al. [19–21] carried out their constitutive models through instantaneous jumps algorithmically prescribed in the computational code. However, enforcing such behavior may be questionable from a dynamic point of view [27].

The spatiotemporal aspects of three types of PLC effects are the main concern of the present paper. According to the load serrations or band propagation characteristics, three types of PLC effects have been commonly distinguished [16,22,28–30]. In the following (Section 2), the correlation fringe patterns depicting the PLC bands are presented, vividly characterizing the different spatial kinematics features for three types of PLC bands. Three types of serrated flow on stress–time curves, combined with the corresponding position–time plots for static or propagating PLC bands, will clearly classify three types of PLC effects. The material and the experimental method used are also described in Section 2, together with the experimental results. In Section 3, a phenomenological model that includes spatial coupling is developed on the basis of McCormick's constitutive equations [11,31] and the above-mentioned N-shaped relationship can be naturally deduced without additional prescription. Furthermore, motivated by the phenomenon detected in previous work [32], i.e., shrinkage deformation takes place outside an avalanche-like PLC deformation band, elastic deformation is considered in the boundary conditions of the present model. Then, numerical simulations are carried out for three types of PLC effects at different constant applied strain rates. The simulated results are found to be in good agreement with the experimental observations.

2. Experimental

2.1. Experimental procedure

The material used in the tests is A2017 aluminum alloy which has a 4 wt.% copper element as its main solute component. Before heat processing, the specimens with a gauge of $50 \times 20 \times Th$ mm^3 ($Th = 1$, 2 and 3 mm, respectively) were cut from a *Th*-mm-thick plate along the rolling direction. To reduce the residual stress, the specimens were annealed at 723 K for 4 h and then furnace cooled to ambient temperature before tension. With the aid of an optical microscope, the average grain size of the specimen was estimated to be 30 μm.

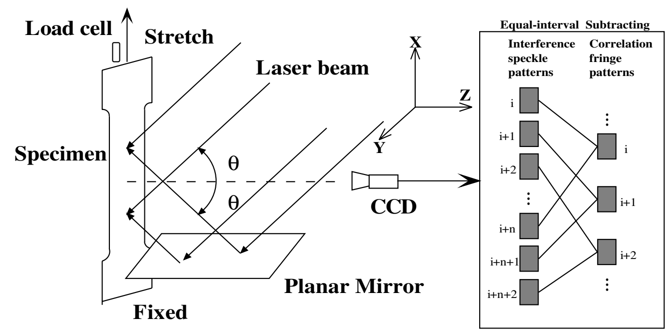

Fig. 1. Principle of dynamic digital speckle patterns interferometry (DSPI) and data processing method.

Fig. 1 shows the principle of DSPI and the data processing method. A vibration-resistant testing machine was specially designed for optical interferometry observations during the tensile tests. A specimen was clamped at two ends with the lower end fixed and the upper end stretched along the *x*-direction at a constant strain rate ranging from 10^{-5} to 5×10^{-3} s^{-1}. A CCD camera was placed in front to collect the interference speckle patterns formed on the specimen surface. The load and displacement data were recorded at a rate of 100 Hz. The sampling rate of the CCD camera was in the range 0.5–30 Hz, depending on the imposed strain rates. For more details, refer to previous work [32–34].

2.2. Experimental results

Although specimens with thicknesses of 1, 2 and 3 mm were deformed at applied strain rates from 10^{-5} to 10^{-3} s^{-1}, only representative results for three types of PLC effects are presented in the following, i.e., results for type A with applied strain rate $\dot{\varepsilon} = 5 \times 10^{-3}$ s^{-1} in specimen of thickness $Th = 3$ mm; for type B with $\dot{\varepsilon} = 10^{-5}$ s^{-1}, $Th = 3$ mm; and for type C with $\dot{\varepsilon} = 5 \times 10^{-5}$ s^{-1}, $Th = 1$ mm.

2.2.1. Type A

Fig. 2 shows the characteristics of type A PLC effect. As shown in Fig. 2a, a few upper yield points, between which the PLC bands of type A propagate continuously from one end of the specimen to the other, hump up the stress profile accompanied by slight stress fluctuations. Since the focus here is mainly on the plasticity portion of deformation, the elasticity fraction of the stress curve has been cut off for convenience. A distinct yield point corresponds to the nucleation of a new band, which is always initiated near one specimen grip, as depicted in Fig. 2b.

A series of correlation fringe patterns are given in Fig. 2c, vividly showing the continuous propagation progress of type A bands, with the corresponding deformation time being given under each pattern. Table 1 gives the corresponding experimental processing parameters of the original digital speckle patterns for three types of PLC effects. Note that one pixel in the correlation fringe patterns repre-

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