Materials Science and Engineering A 403 (2005) 154–164

MATERIALS SCIENCE & ENGINEERING A

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Spatial characteristics of the Portevin-Le Chatelier deformation bands in Al-4 at%Cu polycrystals

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Received in revised form 26 April 2005; accepted 11 May 2005

Abstract

The Portevin-Le Chatelier (PLC) effect represents a typical plastic instability in many metallic alloys of industrial interest. In space domain, this effect commonly consists of repeated nucleation and propagation of band structure, in which the plastic deformation concentrates, along the tensioned specimen. In this paper, a novel digital speckle pattern metrology technique including digital speckle pattern interferometry (DSPI) and digital speckle correlation (DSC) has been applied to investigate the spatial features (geometrical shape, localized plastic deformation in band) and dynamic characteristics (propagation of the bands, details of the band migration) of the PLC deformation bands in Al-4 at%Cu polycrystals simultaneously and quantitatively.

Keywords: Plastic instability; Portevin-Le Chatelier effect; PLC deformation bands; Digital speckle pattern interferometry; Digital speckle correlation

1. Introduction

When many alloys are tested under various loading conditions, such as tension, compression, torsion or sheet forming applications, an oscillatory plastic flow may exhibit in a certain range of strain, strain rate, testing temperature and pre-deformation states. This irregular plastic flow displayed as serrations on stress–time curves and steps on strain–time curves is one of the most prominent examples for plastic instabilities. It results in inhomogeneous deformation characterized by the band structure of strain localization for flat specimen. This phenomenon is generally called "jerky flow" or "repetitive yielding". According to the discoverers, it is named as the Savart–Masson effect [1,2] or more commonly as the Portevin-Le Chatelier (PLC) effect [3,4]. The PLC effect is understood as an intrinsic property of metallic alloys, for it is widely accepted that the physical origin of this instability is dynamic strain aging (DSA) associated with the dynamic interaction between mobile dislocations and diffusing solute atoms [5–7]. In the course of the plastic deformation, the mobile dislocations are arrested temporarily at localized obstacles (generally forest dislocations). During the waiting time, which the gliding dislocations spend to overcome these obstacles by the aid of thermal activation and correspondingly the flow stress, solution atoms diffuse towards the dislocations and impose an additional pinning on them. The aging by diffusing solute atoms and the unpinning of mobile dislocations from the surrounding solute clouds constitute dynamic and local competing processes. These processes repeat themselves when the mobility of solute atoms becomes comparable to that of gilding dislocations. On the macro-scale, these processes can be observed as the oscillation of plastic flow and corresponding PLC band.

Extensive experimental studies on PLC the effect have been presented in the literature since the last century [8–14]. While some information can be obtained from the evolution of stress and strain histories, the investigation on spatial features and dynamics of PLC deformation bands need direct observation. In this experimental work, we report the observation of PLC bands in Al-4 at%Cu polycrystals using a novel speckle pattern metrology technique that consists of digital speckle pattern interferometry (DSPI) and digital speckle correlation (DSC). This technique allows

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doi:10.1016/j.msea.2005.05.059

the temporal and spatial evolution of the deformation in whole testing area of specimen to be followed with a high resolution in time and in space. The observed spatial features and the dynamic characteristics of the PLC deformation bands are shown to be in good agreement with accepted theoretical and experimental results [9,12,15]. Moreover, some interesting results never published before are reported.

2. Experimental techniques

Following Ref. [16], in which the DSPI technique is first applied to observe the PLC bands, we improved three methods of the digital speckle pattern metrology and used them to analyze the characteristics of PLC bands [17,18].

2.1. Digital speckle pattern interferometry

The right part of Fig. 1 illustrates the DSPI arranged to measure the in-plane displacement. One surface of the tensioned specimen is illuminated with two laser beams at angle θ symmetrically (in practice, this condition can be realized expediently by a planner mirror placed horizontally at the fixed end of the specimen). Several CCD cameras are set in normal direction to record the resulting interference speckle pattern in the X–Y plane. The speckle pattern before and after deformation are defined as reference frame and current frame, respectively. When the deformation is very small and the change of surface microstructure is omitted, the subtraction for these two frames of interference speckle patterns can be expressed as

$$\Delta I(x,y) = |I_{\mathrm{cur}}(x,y) - I_{\mathrm{ref}}(x,y)| = 2I_0(x,y)\gamma(x,y)\left|\sin\left(\varphi_0 + \frac{2\pi}{\lambda}\Delta v(x,y)\sin\theta\right)\sin\left(\frac{2\pi}{\lambda}\Delta v(x,y)\sin\theta\right)\right| \quad (1)$$

where $I_0(x,y)$ is the bias intensity, φ_0 the random phase of the speckle field, which varies very rapidly in the spatial domain, $\gamma(x,y)$ the modulation factor, λ the wave length of the laser and $\Delta v(x,y)$ represents the displacement along Y coordinate between two states of deformation. The black correlation fringes take place when the displacements of these pixels satisfy

$$\Delta v(x,y) = \frac{n\lambda}{2\sin\theta}, \quad (n = 0, \pm 1, \pm 2, \ldots) \quad (2)$$

where n is the order number of correlation fringe. Therefore, the correlation fringes represent the displacement contour of specimen before and after deformation. Commonly, the displacement difference between the adjacent correlation fringes is defined as fringe sensitivity K

$$K = \frac{\lambda}{2\sin\theta} \quad (3)$$

Two methods of subtraction to obtain correlation fringe patterns in practical experiments are illustrated in Fig. 1. The first method, called sequential subtracting, is to fix one frame as a reference frame, and subtract it sequentially with the following speckle patterns. This method is usually applied to analyze small deformation. The second method, called equal-interval subtracting, is to subtract two speckle patterns with a constant interval sequentially. This method can avoid the de-correlation of two speckle patterns caused by large deformation and be used to observe a complete tensile process. The deformation distribution of the specimen containing PLC deformation bands can be visualized by the above methods (see, e.g. in Fig. 3(a), (d) or (g), the "white band" represents the PLC deformation band).

2.2. Point-wise temporal phase analysis (PTPA) for DSPI

During the slow tensile process, the instantaneous interference speckle pattern on the surface of specimen at time t

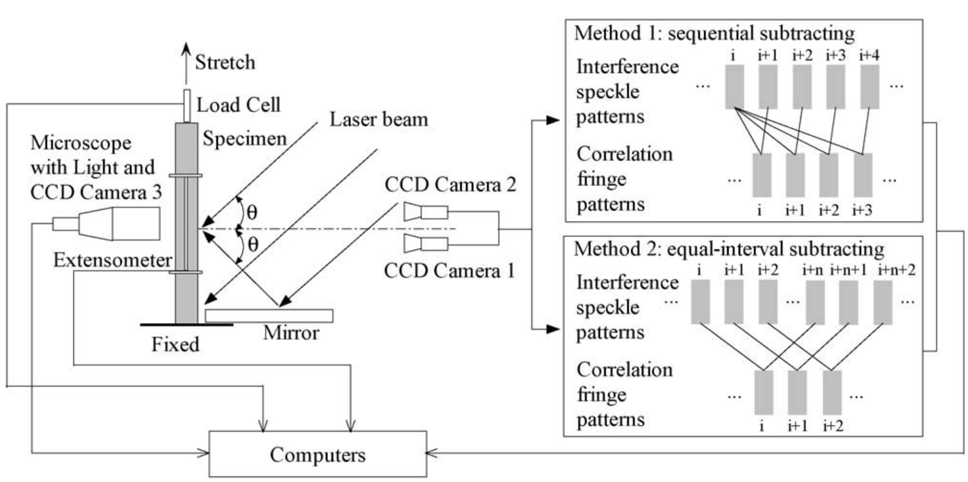

Fig. 1. A scheme of experimental set-up and principle of DSPI for in-plane deformation measurement.