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

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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.

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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 gliding 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
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 \( \theta \) symmetrically (in practice, this condition can be realized expeditiously 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

\[
\Delta I(x, y) = |I_\text{cur}(x, y) - I_\text{ref}(x, y)| = \frac{I_0(x, y)}{2} \left| \gamma(x, y) \sin (\phi_0 + \frac{2\pi}{\lambda} \Delta v(x, y) \sin \theta) \right|
\]

where \( I_0(x, y) \) is the bias intensity, \( \phi_0 \) the random phase of the speckle field, which varies very rapidly in the spatial domain, \( \gamma(x, y) \) the modulation factor, \( \lambda \) 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

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

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 \( K \)

\[
K = \frac{\lambda}{2 \sin \theta}
\]

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 \( t \)
The recorded speckle patterns are divided into regions. Each region is denoted by \( S_{mn} \). The intensity of a selected point on the specimen is known to vary sinusoidally with time, as plotted in Fig. 2. And each period corresponds to the fringe sensitivity. Therefore, the displacement at selected point can be measured by tracing the evolution of speckle intensity.

\[ I(x, y, t) = I_0(x, y)(1 + \gamma(x, y)\cos(\varphi(x, y) + \varphi(x, y, t))) \]  

(4)

where \( I_0(x, y) \) is the bias intensity, \( \varphi(x, y) \) the initial phase and varies randomly across the interference field rapidly, \( \gamma(x, y) \) the modulation factor and \( \varphi(x, y, t) \) is the temporal phase sequence caused by the object deformation [19,20]. The relationship between \( \varphi(x, y, t) \) and displacement \( V(x, y, t) \) is expressed in

\[ \varphi(x, y, t) = \frac{4\pi}{\lambda} \sin \theta V(x, y, t) \]  

(5)

Actually, \( I_0(x, y) \) and \( \gamma(x, y) \) also depend on time, but they vary quite slowly compared with the temporal phase. Therefore, the effect of time on \( I_0(x, y) \) and \( \gamma(x, y) \) is neglected. According to Eq. (4), the intensity of a selected point on the specimen is known to vary sinusoidally with time, as plotted in Fig. 2. And each period corresponds to the fringe sensitivity. Therefore, the displacement at selected point can be measured by tracing the evolution of speckle intensity.

2.3. Digital speckle correlation

Digital speckle correlation has been widely used to measure in-plane displacement [21,22]. By this technique a whole field distribution of displacement on the surface of specimen can be obtained. In our experiments, the speckle pattern is formed from diffuse reflection of specimen surface, which is illuminated by incoherent light, as shown in the left part of Fig. 1. The recorded speckle patterns are divided into \( M \times N \) regions. Each region is denoted by \( S_{mn} \), for \( 1 \leq m \leq M \) and \( 1 \leq n \leq N \) (notice \( k=1,2 \) denotes the status before and after a small deformation, respectively). The discrete correlation function

\[ C_{uv}(u, v) = \sum_i \sum_j S_{mn}(i, j) S_{mn}^*(i-u, j-v) \]  

(6)

The \((u, v)\) corresponding to the max \( C_{uv}(u, v) \) represents the average displacement along \( X \) and \( Y \) coordinates in the selected region \( S_{mn} \). Eq. (6) can be computed either directly in the space domain or in the frequency domain by FFT. In practice, the Gaussian curve-fitting method is used [23] in order to locate the correlation peak more precisely. Generally speaking, the correlation peak has a shape of Gaussian distribution approximately. Thus, the accurate location of correlation peak can be expressed as

\[ u = u_0 + \frac{\partial \log C_{uv}(u_0, v_0) / \partial u}{\partial^2 \log C_{uv}(u_0, v_0) / \partial u^2} \]

\[ v = v_0 + \frac{\partial \log C_{uv}(u_0, v_0) / \partial v}{\partial^2 \log C_{uv}(u_0, v_0) / \partial v^2} \]

where \((u_0, v_0)\) is the integral-pixel location of correlation peak. All the above partial derivatives can be evaluated by numerical methods.

3. Experimental

A schematic illustration of whole experimental set-up is shown in Fig. 1. The specimen is deformed in a special tensile machine with crosshead speed ranging from 0.5 to 250 \( \mu \)m/s at room temperature. The signals of load cell and extensom-eter are recorded with the resolution in time of 50–100 Hz. One of the specimen surfaces, which are both polished as plane for diffuse reflection, is illuminated with two parallel Nd:YAG laser beams at angle \( \theta \) respectively. Two CCD cameras are set to collect the interference speckle patterns. CCD camera 1 is used to monitor the deformation process in the whole testing area of the specimen with a sampling rate of 2 frames/s. The results of DSPI (equal-interval subtracting) are displayed in real time. CCD camera 2 is used to capture the interference speckle pattern sequences with a high sampling rate of 30 frames/s. It is triggered to work as soon as the PLC deformation band is found by CCD camera 1, and 1200 frames are recorded each time. The adjustment of the
It is found that the main factors influencing the type of the band are imposed strain rate and testing temperature. When the strain rate is decreased or the testing temperature is increased the band evolves from type A to type B and to type C.

With the DSPI fringe pattern sequence recorded by CCD camera 1, the propagation of the PLC bands throughout the tensile process is traced. Fig. 3(a) demonstrates a type A band propagating from the bottom to the top of the specimen gauge. The statistics of the band location along F-axis during the test is plotted in Fig. 3(b). where the triangle signs denote that the inclination angle of the band turns from \( \text{“} / \text{”} \) to \( \text{“} \text{”} \) symmetrically. Fig. 3(c) gives the temporal evolution of the propagation velocity. In the initial stage of DSA (the deformation of the specimen reaches about 5%), the PLC band travels from one end of the testing area to the other quickly and continuously. The velocity of the band decreases gradually with the increasing deformation, and the band stops at the necking point eventually. In the late stage the band does not traverse the whole testing area and the inclination angle of the band changes sign occasionally. A discontinuous propagation of type B band is shown in Fig. 3(d–f). In contrast to the type A band, the propagation velocity of type B band is slow down distinctly. And the movement is limited in a local region, viz. the band hardly traverses the whole testing area. The alteration of the inclination angle occurs since the initial stage of DSA. In Fig. 4 (plotted in a log-log grid), a more detailed statistics of propagation velocity has been carried out with various imposed strain rate sequences plotted in Fig. 3(b), where the triangle signs denote that the inclination angle of the band turns from \( \text{“} \text{”} \) to \( \text{“} \text{”} \) symmetrically. The statistics of the band location along F-axis during the test is plotted in Fig. 3(b).

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the waiting time mobile dislocations spend at obstacles $t_w$ ($t_w = \frac{\epsilon}{\dot{\epsilon}}$, where $\dot{\epsilon}$ is the plastic strain rate) increases with $\Omega$, which represents the elementary plastic strain corresponding to the activation of all mobile dislocation ($\Omega = \rho_m b/\sqrt{\rho_f}$, where $b$ is the magnitude of Burgers vector of the gliding dislocations, $\rho_m$ and $\rho_f$ are mobile and forest dislocation densities) [30]. This conjecture is also sustained by the statistic analysis of the load history. Fig. 5(a) is the load history corresponding to Fig. 3(d–f). According to this plot, reload time and load drop are defined, respectively. Fig. 5(b and c) are the statistic results of the evolution of reload time and load drop, both of which shows an increasing trend. The former indicates that the magnitude of the time the dislocation spend to overcome the obstacles increases (Fig. 5(b)). The latter, namely

![Image](image.png)

**Fig. 3.** Dynamics of type A band ($\dot{\epsilon} = 0.91 \times 10^{-3} \text{s}^{-1}$), type B band ($\dot{\epsilon} = 1.0 \times 10^{-3} \text{s}^{-1}$) and type C band ($\dot{\epsilon} = 8.6 \times 10^{-6} \text{s}^{-1}$). In (a), (d) and (g), the “white band” represents the PLC deformation band. (a) A sequence of DSPI fringe pattern showing the continuous propagation of type A band. (b) Statistics of band location vs. time, where the triangle signs denote that the incline angle of the band turns from "\" to "\" symmetrically. (c) Temporal evolution of the propagation velocity of type A band demonstrating a decreasing trend. (d) A sequence of DSPI fringe pattern showing the discontinuous propagation of type B band. (e) Statistics of band location vs. time, where the triangle signs denote that the incline angle of the band turns from "\" to "\" symmetrically. (f) Temporal evolution of propagation velocity of type B band also demonstrates a decrease tendency. (g) A sequence of DSPI correlation fringe pattern showing the random nucleation of type C band. (h) Statistics of band location vs. time.
the increasing amplitude of nominal stress oscillation, proves enhanced strength of the obstacles (Fig. 5(c)).

Fig. 3(g and h) shows the stochastic nucleation of type C PLC band. It is obvious that the spatial correlation of the bands has broken down. The band appears randomly in the specimen.

The detailed migration process of the type A band can be visualized by the DSPI correlation fringes in a zoomed field, as displayed in Fig. 6(a). It shows that a new fringe forms at the left side of the specimen, and then develops through the cross-section along the inclination angle. Fig. 6(b) is a schematic illustration of this migration. When the band propagates from below to above, the shearing deformation in the band causes the upper and lower parts of the specimen to rotate in opposite directions. Once shearing stress reaches the critical level, a new slip occurs in front of the band from one side of the cross-section of specimen to the other gradually. Thereupon the type A band completes one step of migration. From this instance, we derive that the propagation of the PLC bands can be understood as a sequence of stepping process even if they seems to move continuously under relatively high strain rate.

4.2. Spatial features of PLC the deformation bands

In flat specimen, the plastic deformation of the specimen commonly concentrates in an oblique band structure and forms a so-called PLC deformation band when jerky flow occurs. In the DSPI correlation fringe patterns obtained by CCD camera 1, the PLC deformation band is visualized as a “white band”, as displayed in Fig. 3. The appearance of the “white band” is due to the avalanche-like shearing
deformation, which makes the fringes in the band too dense to be distinguished. This process is accompanied by a serration on the stress–time curve.

However, by CCD camera 2 zoomed in on the specimen with a high sampling rate, the deformation distribution in the PLC band can be obtained for analysis. Fig. 7(a) shows a DSPI correlation fringe pattern while a band appears. The white square represents the field range of the CCD camera 3 through a microscope on the opposite side. For the purpose of describing the shearing deformation in the band accurately, the order of correlation fringe should be ascertained according to the results of PTPA and DSC. Fig. 8 shows the process of PTPA. During a serration on the stress–time curve, the intensity at points A–H in Fig. 8(a) are traced to plot the displacement chart at these points (Fig. 8(b)). It is obvious that the center of the band almost hold still, whereas the displacements at other points experience a dramatic change. This result is consistent with that obtained with DSC from the incoherent speckle patterns recorded by CCD camera 3 (Fig. 7(b) and c)). Consequently, the central correlation fringe in Fig. 7(a) can be defined to be order 0, and the others are orders \(-2, -1, 1, 2, 3\). Here, the sign represents the direction of displacement.

We define a discrete equivalent strain at the clearance of the correlation fringes as

\[
\varepsilon(n) = \frac{K}{\Delta L(n)}
\]

where \(K\) is fringe sensitivity and \(\Delta L(n)\) is the distance between the fringe of order \(n\) and order \(n - 1\). The equivalent strain distribution in the band is plotted in Fig. 7(d). In this plot, the equivalent strain decreases from the center to the boundaries of the band. The variation of equivalent strain in the front part of the band along the propagating direction is found to be steeper than that of the rear part. It may imply the strain hardening of the area the band has passed through.

According to the displacement distribution, the width of the PLC deformation band in the 1 mm thick specimen is approximated to be 1.9 mm. Fig. 9 shows the band width in the specimen of three kinds of thickness and with \(5.8 \times 10^{-6} \text{ s}^{-1} < \dot{\varepsilon} < 6.0 \times 10^{-4} \text{ s}^{-1}\). It can be estimated that the width of the band increases in proportion to the thickness, and the proportion factor ranges from 1.5 to 2.0. The band width does not display a distinct association with the imposed strain rate.

Fig. 5. Statistic analysis of the load history corresponding to Fig. 3 d–f. (a) Load–strain curve. Reload time \(t_{\text{reload}}\) and load drop \(\Delta F\) are defined, respectively, according to the serration, as shown in embedded plot. (b) Evolution of reload time and (c) evolution of load drop.
Fig. 6. The detailed migration process of type A band. The shearing deformation in the band causes the upper and lower parts of the specimen to rotate in opposite directions. (i) Once the shearing stress reaches the critical level, a new slip occurs at the front of the band. (ii and iii) The slip traverses from one side of the cross-section of specimen to the other gradually. (iv) The type A PLC band completes one step of migration and starts another. (a) A sequence of zoomed DSPI fringe patterns displays the detailed migration of type A band. (b) Schematic view of the band migration process.
Fig. 7. Analysis of the localization plastic deformation in the PLC band in a 1 mm thick specimen. (a) A zoomed DSPI correlation fringe pattern. The order of central fringe is defined to be 0, and the others are $-1, -2, 1, 2$ and 3, where the sign represents the direction of displacement. (b) microscopic incoherent light speckle pattern in the PLC band (field: 1.6 mm × 1.2 mm), (c) displacement distribution calculated by digital speckle correlation technique and (d) spatial distribution of equivalent strain in the band. Notice that the equivalent strain in the front part of the band along the propagating direction decreases steeper than that of the back part.
5. Conclusion

The present work on the spatial characteristics and the dynamics of the PLC deformation bands has shown that the digital speckle pattern metrology technique consisting of DSPI and DSC is a valuable method for direct observation of the spatial and temporal features of the PLC bands. With the analysis of the correlation fringe patterns obtained with DSPI, a precise measurement of the spatial characteristic parameters of the PLC band (geometrical shape, localized plastic deformation in the band) are carried out to obtain more comprehensive pictures of dynamics of the band (evolution of the propagation velocity, the details of migration process) of three types of the PLC deformation bands. However, the underlying mechanism of some observed results remains indistinct yet. This topic requires further research.

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