Spatiotemporal aspects of the Portevin–Le Chatelier effect in annealed and solution-treated aluminum alloys

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Received 21 September 2005; received in revised form 7 February 2006; accepted 6 March 2006

Abstract

By employing the dynamic digital speckle pattern interferometry technique, spatiotemporal aspects of the Portevin–Le Chatelier (PLC) effect in both annealed and solution-treated Al–4%Cu alloys are investigated. The effect of dynamic strain aging is enhanced in response to increased solute concentration in solution-treated materials. Influence of aging on the critical strain of the PLC effect is also reported.

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Keywords: Portevin–Le Chatelier effect; Dynamic strain aging; Solution treatment

1. Introduction

Under appropriate deformation conditions, many interstitial and substitutional solid solutions exhibit the Portevin–Le Chatelier (PLC) effect [1–6], one of the most prominent examples of plastic instability. The phenomenon represents material instability and is also referred to as “serrated flow” or “repetitive yielding”. This instability results in inhomogeneous deformation (strain localization) and a serrated stress–strain curve. During the last few decades, the PLC effect has been extensively studied and is generally considered to be the result of dynamic interactions between gliding dislocations and mobile solute atoms [7–12], i.e., dynamic strain aging (DSA). On the microscopic scale, the dislocation glide is intermittent, which has been proved by both acoustic emission measurements and numerical simulations [13]. After a mobile dislocation has been impeded by obstacles such as forest dislocations, precipitates and grain boundaries etc., a solute cloud may form around it in response to solute segregations by preferred pipe diffusion. The mobile dislocation is effectively pinned. With applied stress, obstacles can be conquered by thermally activated dislocation motion. This unpinning process of the dislocation may cause a stress drop on the macroscopic stress curve. Therefore, the PLC effect is in response to dynamic repeated pinning and unpinning processes between mobile dislocations and solute atoms.

For commercial aluminum alloys at ambient temperature, most solute contents in the Al matrix exceed their solubility limits. By conventional annealing treatment, the superfluous solute atoms will precipitate out in grains, forming coarse equilibrium phases [14]. However, by solution treatment, solute concentration in the bulk can be improved remarkably and a supersaturated solid solution will be created. We found extensive experimental work has been done to investigate the PLC effect in as received [15,16], annealed [17–20], solution-treated [21] and other heat-treated [22] materials and some of researchers [16,20] have focused their efforts on the spatiotemporal, especially spatial, aspects of the PLC effect for certain heat
treatments. However, the influence of different heat treatments on the PLC effect is also important, since solute concentration plays a key role in the DSA mechanism. In this paper, spatiotemporal features of the PLC effect in both annealed and solution-treated Al–4%Cu alloys are investigated. The difference between them is in response to the change of solute concentrations. Using the dynamic digital speckle pattern interferometry (DSPI) technique, interesting experimental results are obtained. The influence of aging on the critical strain of the PLC effect is also reported.

2. Experimental procedure

The material used in our tests is A2017 aluminum alloy which has 4 wt.% copper element as its main solute component. In this alloy, the copper content far exceeds the solubility limit of Cu in Al (typically 0.2%) at room temperature. Before heat processing, samples with a gauge of 55 x 20 x 3 mm³ were cut from a 3 mm-thick plate along the rolling direction. Half of these samples were annealed at 723 K for 4 h and then cooled naturally to room temperature. The rest were solution treated at 773 K for 3 h and then quenched in water. The solution-treated samples were divided into two groups with one group tested within 5 min in tension and the other tested after different natural aging durations, 3, 4.6, 6.5, 7, 10 and 24 h.

In our tests, the DSPI technique, a real-time two-dimensional observation method, was used to measure the geometric and kinetic aspects of the PLC deformation bands. 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 tensile tests. A sample was clamped at two ends with the lower end fixed and the upper one stretched along the X-direction at a constant speed. The range of the applied strain rates was from 10⁻⁵ to 5 x 10⁻³ s⁻¹. A charge-coupled device (CCD) camera was placed in front to collect the interference speckle patterns formed on the specimen surface. More details were shown in our previous work [19,23,24]. The sampling rate of the CCD camera was in the range 0.5–30 HZ depending on the strain rate imposed. The load and displacement data were recorded at a rate of 100 HZ.

![Fig. 1. Principle of dynamic digital speckle patterns interferometry and data processing method.](image)

3. Results

Fig. 2 shows the plots of stress and band position vs. time for annealed and solution treated Al–4%Cu alloys at a strain rate of 5 x 10⁻³ s⁻¹. As reported in other papers [15,19], the PLC effect in annealed materials will change from type C to B to A with increased applied strain rates. From that experience the representative type A PLC effect, characterized by both type A serrated flow and continuous band propagation as shown in Fig. 2(a), is expected in solution-treated materials at the same imposed strain rate. In fact, as shown in Fig. 2(b) and (c) for the solution-treated specimen the PLC band propagates continuously through one end of the sample to the other, indicating the type A behavior. At the same time, the heavily serrated flow with abrupt oscillations observed in the stress–time curve of these figures depicts a traditional type C serrated flow all the time. In addition, with further plastic deformation the spatial correlation of the PLC bands weakens, and the bands nucleate randomly in the sample, as shown in Fig. 2(d).

With the aid of the DSPI technique, the deformation distribution of the specimen containing PLC deformation bands can be visualized as fringe patterns. Several typical fringe patterns which are subtracted with an interval of 2 s are shown in Fig. 3(b), (c) and (g). Here the correlation fringe represents the contour line of the displacement in the X-direction and the fringe sensitivity is about 0.38 µm [19]. In annealed materials, the PLC deformation band generally nucleates at one side of the lateral sample surfaces and then develops transversally through the cross section [15,19]. In solution-treated materials, the PLC band nucleates near the middle of the front surface at the initial stage of plastic deformation, as shown in Fig. 3(e). Fig. 3(d) presents the corresponding serrated flow in an amplified fraction of the whole stress–time curve. Furthermore, with the development of deformation one serrated stress drop in stress–time curve is associated with three to five PLC bands existing in the sample simultaneously as depicted in Fig. 3(f). Compared with band configurations in annealed materials shown in Fig. 3(b), the PLC bands are narrower. Moreover, we found the onset of the PLC effect is earlier in solution-treated material than annealed material, as shown in both Figs. 2 and 3.

When the applied strain rate is lowered to 10⁻⁵ s⁻¹, the stress–time curve of the solution treated material possesses a smooth profile compared with distinct serrations in the annealed one, as shown in Fig. 4(a) and (b). However, through DSPI fringe patterns, some PLC deformation bands were observed to nucleate at the initial stage of plastic deformation and to disappear with further deformation. Correspondingly, an amplified portion of the whole stress–time curve for solution treated Al–4%Cu alloys, Fig. 4(c), showed the serrated stress fluctuations depicting temporal behavior of the PLC effect. Note the first critical strain of the PLC effect is still less than that in annealed alloys. With development of deformation the PLC effect will die out (no
PLC deformation bands can be seen), leaving some tiny serrations in the stress–time curves as shown in Fig. 4 (d)–(f). Additionally, the frequency of stress serrations will decrease with deformation, while the amplitudes will remain almost unchanged, i.e., about 1.8 MPa.

Fig. 5 shows the serrated stress–time curves of solution-treated samples with different aging durations. For clarity, each curve has been shifted up 30 MPa from the neighboring one with a shorter aging duration. At an equivalent imposed strain rate, i.e., $5 \times 10^{-3} \text{ s}^{-1}$, the onset of serrated...
flow was delayed with increasing aging durations. With further increases of the aging time, the stress serrations will gradually diminish and completely vanish in the stress–time curves, as shown in the curve of natural aging (NA) for 420 min. Moreover, when the aging duration is less than 300 min, the average amplitude of serrated stress drops will slightly increase with longer aging durations. For lower applied strain rates, i.e., \(5 \times 10^{-5} \text{ s}^{-1}\), the characteristics of serrated flow with different aging durations are similar to the case discussed above but not shown here.

4. Discussion

By solution treatment, supersaturated solid solution can be obtained. Although the PLC bands propagate continuously, compared with annealed materials the effect of DSA is enhanced in solution treated materials as a result of more solutes diffusing to dislocations temporarily impeded by obstacles. As a result, strong regular load drops representing type C temporal behavior may occur associated with type A spatial behavior, i.e., the anomalous behavior shown in Fig. 2.

For solution treated materials, large numbers of defects are kept in grains, such as dislocations, vacancies, etc. The defects distort the surrounding lattice and cause an increased stress concentration impeding the dislocation motion. With deformation, the materials become harder so thinner bands are observed when plastic instabilities occur. Since a single band is unable to carry the imposed strain rate, the phenomenon of multiple bands emerges as shown in Fig. 3(f).

The occurrence of the PLC effect is governed by the strain rate sensitivity of material and the latter decreases with increasing solute concentration in the bulk [25]. Additionally, other ingredients should be considered, such as initial dislocation densities and precipitation during deformation. In solution treated materials, distinguishing the influences of all types of defects is complicated. However, it is reasonable to attribute the decreasing critical strain (as shown in both Figs. 2 and 3) to the remarkable increase in solute concentration, i.e., from 0.2% in annealed materials to nearly 4% in freshly solution treated ones. Moreover, the experimental result in Fig. 4, i.e. the PLC effect emerges at the initial stage of plastic deformation and vanishes with further strain, confirms the simulation deduction in the dislocation model of Kubin [26].

In freshly quenched Al–4%Cu alloys, copper atoms will aggregate in the (110) plane of supersaturated solid solution to form the Guinier–Preston (GP) zone by natural aging. In particular, the formation of the GP zone appears to be quite effective in delaying the onset of the PLC effect [26–28]. In our tests a similar result, i.e., the onset of ser-
rated flow is delayed by prolonging the aging duration, is shown in Fig. 5. Furthermore, according to the conventional DSA mechanism based on the dislocation-solute interactions, the amplitudes of serrated stress drops would diminish with increased aging duration as a result of the decreased solute concentration caused by formation of the GP zone. Since the inverse experimental results cannot be explained by the above-mentioned mechanism, it might be attributed to the additional interaction between dislocations and precipitates.

In our opinion, additional detailed research work should focus on the following two aspects: (i) the influence of each type of defect on the PLC effect; (ii) the nucleation mechanism for the PLC bands.

5. Conclusions

(1) In solution-treated Al–4%Cu alloys, the onset of the PLC effect is earlier than that in annealed materials. The PLC band nucleates near the middle of the front sample surface at the initial stage of plastic deformation and the phenomenon of multiple bands emerges with further deformation.

(2) By solution treatment, the effect of DSA is enhanced in response to the increased solute concentration in the bulk.

(3) With aging, the formation of GP zone appears to be very effective in delaying the onset of the PLC effect.

Acknowledgement

The authors are grateful for the financial support received from the National Natural Science Foundation of China under Grant Nos. 10232030, 10372098, and 10372119.

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