Journal of Materials Science & Technology ■■ (2016) ■■–■■

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Investigation of Portevin–Le Chatelier Band Strain and Elastic Shrinkage in Al-Based Alloys Associated with Mg Contents

Yulong Cai [1], Suli Yang [1], Shihua Fu [1,*], Di Zhang [2,**], Qingchuan Zhang [1,***]

[1] CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei 230027, China
[2] State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form
3 May 2016
Accepted 26 May 2016
Available online

Key words:
Mg content
Al–Mg alloy
Portevin–Le Chatelier effect
Digital image correlation
Elastic shrinkage

The Portevin–Le Chatelier (PLC) effect in Al–2.30wt%Mg, Al–4.57wt%Mg and Al–6.91wt%Mg alloys has been investigated at various applied strain rates at room temperature in this study. Three-dimensional digital image correlation (3D-DIC) technique was applied to obtaining the further insight into the spatiotemporal characteristics, in particular the influence of Mg content on deformation behaviors. Mg content has a pronounced effect on serration characteristics, including the serration type and amplitude; Mg content tends to weaken the spatial correlation of the propagative bands. Additionally, the serration amplitude linearly increases with the maximum PLC band strain; high Mg content generates a higher PLC band strain at a given serration amplitude compared with low Mg content. Mg content is found to be effective to enhance the serration amplitude, the maximum PLC band strain and also the amount of elastic shrinkage outside PLC bands.

1. Introduction

With a great intensity, a good formability and an excellent corrosion resistance, Al–Mg alloys are extensively used in the aerospace industry and the automotive manufacture[1]. However, the Portevin–Le Chatelier (PLC) effect, a kind of plastic instability, always appears even at room temperature in columnar or plate specimens subjected to tension, compression and torsion[2–4]. Previous studies have shown that repeated serrations in the plastic regime are a predominant feature in the deformation over a broad range of strain rates[5–7].

The PLC effect, always referred to as jerky flow or serrated flow, is manifested as a repetitive yielding (serrations) in stress–strain curves and a localized deformation band in specimens of Al/Mg-based alloys[4,8–10] and even some Ni-based superalloys[11–13]. Generally, it is considered to be a consequence of dynamic strain aging (DSA), i.e., the dynamic interactions between mobile dislocations and diffusing solute atoms clustered around these dislocations during plastic flow[14–16]. This theory stipulates that the mobile dislocations are blocked and released repeatedly by the solutes, resulting in repeated serrations in the stress–strain curves and corresponding PLC bands. For Ni-based superalloys, the interactions between the mobile dislocations and solute atoms might be different compared with Al/Mg-based alloys due to the γ' precipitates. Tian et al.[17] and Han et al.[18,19] investigated the jerky flow at various strain rates and temperatures in Ni-Co-based superalloys, and all found that the normal PLC effect occurs at low temperatures, whereas the inverse PLC effect occurs at high temperatures.

Usually, PLC bands cause undesirable visible traces on the surface of the final products due to high strain gradient effect[20]. Therefore, as a remarkable feature in the space-domain, PLC bands have attracted extensive attention on the direct observation of deformations. In the past two decades, many investigations of the spatial features of the PLC effect have been reported. Various optic methods, such as shadowgraph technique[21], laser scanning extensometer method[22], digital speckle pattern interferometry[4,23–25], infrared thermography[26–29], digital shearography[30] and digital image correlation (DIC)[4,7,31], were applied to obtaining the deformation information of PLC bands.

As a kind of substitutional solutes, Mg is widely considered to be the solute element responsible for DSA in Al–Mg alloys[32,33]. Indeed, Mg content itself affects the solute concentration in DSA; as such, the magnitude of stress drops and even the deformation behaviors should be influenced. Recently, several researchers, par-

* Corresponding author. Tel.: +86 551 63601248; Fax: +86 551 63606459. *E-mail address:* fushihua@ustc.edu.cn (S. Fu).
** Corresponding author. Tel.: +86 010 82375844; Fax: +86 010 82375844. *E-mail address:* zhangdi@skl.ustb.edu.cn (D. Zhang).
*** Corresponding author. Tel.: +86 551 63607613; Fax: +86 551 63606459. *E-mail address:* zhangqc@ustc.edu.cn (Q. Zhang).

http://dx.doi.org/10.1016/j.jmst.2016.05.012
1005-0302/

ticularly Ait-Amokhtar and Kang, focused their attention on and made a great contribution to the effect of Mg content on the PLC effect. Ait-Amokhtar et al.[34,35] investigated the spatiotemporal aspects and the critical strain of jerky flow in relation to Mg content; they found that the instability characteristics were influenced by the Mg content, and the critical strain rate (corresponding to the minimum of the critical strain vs. applied strain rate curve) shifts to larger values when the Mg content increases. The aforementioned behavior can lead to an enlargement of the strain rate domain of inverse behavior of the critical strain. Since analyses of Ait-Amokhtar et al. are almost based on loading curves, Kang et al.[36] studied Al–Mg sheets with Mg content between 1.8 wt% and 4.5 wt% by using DIC method and discovered that the band strain values in all the samples follow a common linear relationship with the loading procedure, which reveals that the linear relationship is only independent of solute content. Ma et al.[37] investigated the effects of alloying elements and processing parameters on the mechanical properties and PLC effect of Al–Mg alloys, and found that the addition of Mg or Zn enhances the work-hardening rate, which leads to an increase in both strength and ductility. Besides, the influence of the addition of Mg or Zn solute atoms on the serration characteristics is also analyzed. Nevertheless, there are very few investigations devoted to the influence of Mg content on the deformation behaviors of PLC bands in connection with the corresponding serrations so far.

In what follows, three alloys of Al–2.30wt%Mg, Al–4.57wt%Mg and Al–6.91wt%Mg were fabricated to investigate the PLC effect at various applied strain rates at room temperature. The influence of Mg concentration on deformation behaviors (the spatiotemporal characteristics) is studied by using three-dimensional digital image correlation. The dependence of the serration amplitude and the domain of PLC effect on the Mg content are analyzed in relation to the microscopic DSA mechanism. Additionally, another attention is particularly focused on the variation of the relationship between the serration amplitude and the maximum PLC band strain (i.e., the maximum strain within PLC band) with Mg contents. The elastic shrinkage outside PLC bands, an accompanied phenomenon, is discussed with various Mg contents as a balancing term under the condition of deformation compatibility.

2. Experiment

The investigated materials are laboratory-scale chill-casting alloys with different Mg contents, with nominal chemical compositions shown in Table 1. These three alloys were labeled based on the increasing trend of Mg content. For these alloys, prior to the tensile test experiments, plates of the three alloys were subjected to a three-step aging heat and rolling treatment, as follows: first-step homogenizing at 450 and 540 °C for 5 and 10 h, respectively, and then hot-rolling to 6-mm-thick plate with at least 90% reduction; second-step cold-rolling to 4 mm followed by an annealing process at 450 °C for 1 h; third-step cold-rolling to 1 mm followed by an annealing process at 450 °C for 1 h, and then air cooling to room temperature. The specimens for tensile tests of alloy 1–3, with gauge length of 50 mm, width of 12.5 mm, were machined from the 1-mm-thick plate along the rolling direction.

Table 1
Chemical compositions of three investigated alloys (wt%)

Alloy	Mg	Mn	Fe	Si	Ti	Cu	Cr	Al
Alloy 1	2.30	0.22	0.24	0.10	0.02	0.17	0.05	Bal.
Alloy 2	4.57	0.22	0.24	0.10	0.02	0.17	0.05	Bal.
Alloy 3	6.91	0.22	0.24	0.10	0.02	0.17	0.05	Bal.

Tensile tests were performed at various applied strain rates in the range of 1.67×10^{-4} –5.00×10^{-3} s^{-1}; all tests were carried out by using a hard testing machine (RGM-4050) at room temperature. The force data were recorded at a sampling rate of 25 Hz. The accuracy of DIC method is a coupling factor associated with the image noise, the interpolation bias and the calculation algorithm parameters[38]. Note that it is much more difficult in establishing the theoretical measurement resolution in the high gradient deformation situation (e.g., the PLC band) than the homogeneous deformation situation. Specifically, the experimentally measured value of the displacement and strain measurement error are about 0.01 pixel and 150 $\mu\varepsilon$ respectively[39]. Our group explored the influence of DIC parameters, including the patch size, the shape function and the strain gradient, on measurement error, and gave an effective suggestion (i.e., the moderate patch size) for high gradient inhomogeneous deformations[40].

The self-developed DIC system, referred to as PMLAB DIC-3D (Nanjing PMLAB Sensor Tech Co., LTD, Nanjing, China), was used to continuously capture the deformed images via synchronous image acquisition. Sequence DIC and equal-interval DIC were both used in this work. In the case of sequence DIC, the correlation between a fixed reference image and the deformed image is determined; with equal-interval DIC, however, the correlation between frame n and frame $n+g$ is determined ($g = 1$ is the image interval in this work). In this work, the sequence DIC was only used in the acquisition of PLC band propagative characteristics. Before the tensile tests, specimens were sprayed in flat white lacquer oversprayed with random black spots. The defined right-handed coordinate and the experimental schematic were presented in Fig. 1. The horizontal distance between the specimen and the optical center of the left- and the right-camera was about 600 mm; the stereoscopic angle of each camera was about 10°. In the 3D-DIC system, deformed images were captured continuously by synchronous image acquisition technology using a collection trigger. The image sampling rate was about 7 fps. The array dimensions of each image = 2048 × 2048 pixel^2; calculation grid size = 1 pixel; patch size = 29 × 29 pixel^2; and strain calculation window size = 9 × 9 point^2.

3. Results and Discussion

3.1. Stress–strain curves

3.1.1. Serration morphology and the critical strain

Fig. 2 shows the engineering stress vs. engineering strain curves obtained with different Mg contents at applied strain rate; magnified views of the data in sections A, B and C (corresponding to Fig. 2(a)–(c) respectively) are shown as Fig. 2(d)–(f), respectively. It can be seen that the Lüders strain (i.e., the flat in the stress–strain curves at the end of the elastic part) is observed systematically in the increasing tendency of Lüders strain with increasing applied strain-rate, which accords with the theoretical prediction proposed by Sun et al.[41]. Moreover, the serration morphology also obviously changes with different Mg contents and strain rates. The unstable plastic flow with serrations appears in all experiments beyond a certain critical strain of the serration onset, which becomes especially apparent in the high Mg content alloy (Alloy 3). As these figures show, the variation of Mg content and strain rate leads to a crossover of the serration type and a corresponding change of the serration amplitude. Specifically, Fig. 2(d)–(f) shows that the serration type switches from type A to type B and then to type C, and simultaneously the serration amplitude ($\Delta\sigma$) gradually increases with decreasing applied strain rate or increasing Mg content. The serration density, defined as the number of serrations per 100% strain, decreases with increasing Mg content for type B/C serrations, which is ascribed to increasing reloading time. From another viewpoint,

Please cite this article in press as: Yulong Cai, Suli Yang, Shihua Fu, Di Zhang, Qingchuan Zhang, Investigation of Portevin–Le Chatelier Band Strain and Elastic Shrinkage in Al-Based Alloys Associated with Mg Contents, Journal of Materials Science & Technology (2016), doi: 10.1016/j.jmst.2016.05.012