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

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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. 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. 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.

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 and even some Ni-based superalloys. Generally, it is considered to be a consequence of dynamic strain aging (DSA), the dynamic interactions between mobile dislocations and diffusing solute atoms clustered around these dislocations during plastic flow. 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. The 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.

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.

As a kind of substitutional solutes, Mg is widely considered to be the solute element responsible for DSA in Al–Mg alloys. 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-
particularly 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.\textsuperscript{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.\textsuperscript{46} 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.\textsuperscript{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 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.

Tensile tests were performed at various applied strain rates in the range of $1.67 \times 10^{-4}$–$5.00 \times 10^{-3}$ 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\textsuperscript{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 με respectively\textsuperscript{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\textsuperscript{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 propagating 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. 1(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.\textsuperscript{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 (Δσ) 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,
were explored in the section.

(a) Schematic of the DIC system and (b) experimental scene diagram consisting of (1) two synchronized cameras with standard f50-mm lens, (2) a collection trigger; (c) Specimen with random speckles. PC-1 is used to control the loading process, while PC-2 is used to capture deformed images and perform correlation calculations.

Fig. 1. (a) Schematic of the DIC system and (b) experimental scene diagram consisting of (1) two synchronized cameras with standard f50-mm lens, (2) a collection trigger; (c) Specimen with random speckles. PC-1 is used to control the loading process, while PC-2 is used to capture deformed images and perform correlation calculations.

the critical strain, namely the onset of serrations in loading curves, is also heavily affected by the Mg content. As can be seen in Fig. 2, the critical strain is relatively small and the normal PLC effect is presented for low Mg content alloys; a big critical strain and the inverse behavior are exhibited in high Mg content alloys. In a word, with the change of serration type from A/B to C, the critical strain increases.

DSA theory indicates that the appearance of serrated flow is ascribed to the competitive mechanism between pinning and unpinning effects; the serration amplitude depends on the solute concentration clustered around the mobile dislocation during the waiting time. In general, the Mg solute is considered as the prominent factor responsible for DSA effects in Al-based alloys. From this perspective, high Mg concentration addition leads to a severer response of DSA effect, which correspondingly results in a severer heterogeneous plastic deformation in macro-scale. It can be seen that the inverse PLC effect (corresponding to type C serrations) easily appears in high Mg content alloys, revealing that the high solute concentration promotes a transition of PLC effect from normal to inverse. For Mg content, severe DSA stems from two factors: the direct and the indirect one. On the one hand, high Mg solute concentration enhances the interactions between the solute atoms and the mobile dislocations in itself, which can be regarded as the direct factor; on the other hand, Mg content can also affect the waiting time in DSA process\textsuperscript{[31]}, which has indirect effect on the solute diffusing behavior and therefore can be considered as the indirect factor.

Morphologically, it is well established that serrations of type A and B are upward, nevertheless type C serrations are downward. As such, the critical strain depends on the first pinning for the normal PLC effect, while it depends on the first unpinning for the inverse PLC effect\textsuperscript{[43]}. On account of this, the pinning process was completed ahead of schedule in the normal regime due to the severe solute diffusing behavior with the aid of Mg solute addition; to the contrary, the unpinning process was delayed in the inverse regime because of the highly required applied stress for escaping the potential trough ascribed to solute atmosphere. Seen from this perspective, high Mg content promotes a shift of the critical strain to the higher values of applied strain rate, which is in agreement with observations reported by Ait-Amokhtar et al.\textsuperscript{[31]}.\n
3.1.2. Propagation characteristics of the localized bands

Usually, with respect to the strain rate and the experimental temperature, plastic instability can be characterized by different types of strain localization which depend upon either the morphology of the stress–strain curves or the propagation of PLC bands. Generally, serrations associated with continual propagation of PLC bands are classified as type A serrations; type B serrations are discontinuous, or hopping, propagation of localized bands; type C serrations occur at random intervals along the gauge length. Here, we investigated the propagation characteristics of the localized bands in relation to Mg content by means of sequence DIC method. Experiments at 1.00 × 10\textsuperscript{−3} s\textsuperscript{−1} were explored in the section. Fig. 3 shows the propagative characteristics of bands, described by accumulated strain mapping (sequence DIC method), of these alloys at strain of ∼0.2 at 1.00 × 10\textsuperscript{−3} s\textsuperscript{−1}, where the continuous propagation appears in the low Mg content alloy, while alloys with high Mg content mainly exhibit disperse feature in propagation. Corresponding results reveal that the spatial correlation of propagative bands gradually decreases with increasing Mg contents.

Obviously, a crossover from chaos to self-organized criticality (SOC) has been identified as the serration type switches from type C/B to type A within the PLC regime\textsuperscript{[49]}. Generally, the appearance of type A serrations is believed to be induced by SOC dynamics in specimen, as the corresponding serration amplitude distribution is highly consistent with the power-law form. On the basis of the interpretation proposed by Ananthakrishna et al.\textsuperscript{[40]}, the spatial coupling is responsible for the propagation of bands, and the change of band propagation feature can reflect the variation of spatial coupling strength. Bigger serration amplitude signifies more reloading time for the plastic relaxation process, guaranteeing that the incompatibilities arising from the heterogeneous deformation can be sufficiently relaxed. Thus, with excluding the influence of the incomplete relaxation, interactions or multiplications of dislocations lead to chaos of the avalanche deformation within one stress drop in nonlinear ways. For small serration amplitude, the reloading time is too short to sufficiently complete the plastic relaxation process, which causes formations of new small inhomogeneities. As such, this results in a recurrence of partial relaxation processes, which enhances the dislocation propagation into the neighboring material elements and
leads to a SOC-type dynamics. In a word, higher reloading time induced by bigger serration can provide more time for plastic relaxation of the internal stress, which results in a less spatial coupling force. Exactly, the spatially continuous propagation requires higher coupling force than discontinuous propagation. Therefore, based on the strength of coupling force, type A, B and C serrations correspond to continuous, hopping and random propagations, respectively. Similarly, it is evident that the Mg content addition favors a switch of band propagative feature, i.e., from continuous to hopping and finally to random.

3.2. Effect of Mg content on the width of localized bands

The band width is defined as the distance between the two closest extremum points on opposite sides of the PLC band, as depicted in Fig. 4. The variation of band width with Mg contents at $1.00 \times 10^{-3}$ s$^{-1}$ was shown in Fig. 5, in which each experimental data point was averaged by 6 sets of data. The band width maintains a constant value of $-4.95$ mm. It is evident that the band width was hardly influenced by Mg content and serration amplitude. Some researchers[27,44,45] also investigated the PLC band width by full width at half height.

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Fig. 2. Variation of engineering stress vs. engineering strain curves at various applied strain rates of $1.67 \times 10^{-4}$ - $5.00 \times 10^{-5}$ s$^{-1}$ for 2.30 wt% Mg addition (a), 4.57 wt% Mg addition (b) and 6.91 wt% Mg addition (c). Magnified views of the data in sections A, B and C are shown as Fig. 2(d), (e) and (f), respectively. For clarity, all curves are separated vertically by a stress interval of 15 MPa.
For example, Shabadi et al. investigated the PLC band width using the laser speckle technique, and found that band width increases with strain and reaches a plateau in 1-mm-thick Al-based alloys, although the results are somewhat discrete.

In consideration of the measuring principle of the test machine, the stress drop (Δσ, i.e., the serration amplitude) can be expressed as a function of the relative displacement within the PLC band and the amount of elastic shrinkage outside the localized band. Besides, under the assumption that the strain distribution within localized bands can be characterized by a Gaussian function, the deformation within the bands can be determined by the maximum PLC band strain (εmax) as the band width is constant. Therefore, the serration amplitude can be determined by the maximum PLC band strain and the amount of elastic shrinkage outside the PLC band.

3.3. Relationship between δσ and εmax in relation to Mg content

As presented above, the PLC band width has been explored. This section devotes to the investigation of relationship between the serration amplitude and the maximum PLC band strain associated with the variation of Mg content. The self-developed 3D-DIC method, where equal-interval correlation was employed here, was applied to the acquisition of the spatial distribution of the full-field strain field within one serration. Fig. 6 shows the typical plots of serration amplitude vs. maximum PLC band strain for different specimens with various Mg contents at room temperature. Evidently, the serration amplitude linearly increases with the maximum PLC band strain with different rectilinear slopes. Data-points of different Mg content alloys belong to different regression lines; to be more specific, the corresponding slope of the regression line increases with decreasing Mg contents. Therein, data of both 5456 alloy with different thicknesses and alloy 3 with 6.91 wt% Mg addition concentrates in a narrow strip region (the orange box in Fig. 6), demonstrating two things: (1) the linear law does not rely on the specimen thickness, and (2) macro-deformation behaviors of alloy 3 and 5456 Al-based alloy are quite similar.

Fig. 6 indicates that the stress drop reaches the maximum in the alloy with the lowest Mg content at a given maximum PLC band strain. This phenomenon can be considered as the consequence of the elastic shrinkage outside the PLC band. Taking the measuring principle of the test machine into consideration, the serration amplitude relies on both the maximum PLC band strain and the amount of elastic shrinkage outside PLC bands as the PLC band width is invariable. Subsequently, the elastic shrinkage associated with Mg content is investigated. Here, we select two similar serrations pertaining to Alloys 2 and 3 with approximated amplitude (~24 MPa) to investigate the influence of Mg content on macroscopical localized deformations. Fig. 7 presents the detailed DIC results, where (a) is two selected serrations and the corresponding DIC-calculated strain mappings and (b) the strain and displacement distributions in Y-axis of the center lines corresponding to serrations present in (a). Surface strain mappings indicate that the severer localized deformation appears in higher Mg content alloy with a similar serration amplitude. The relative displacement in Y-axis within the localized band of alloy 3 is much bigger than alloy 2, which suggests that a high gradient deformation appears in the high Mg content alloy. One step further, the least-squares approximation results (see inset of Fig. 7) reveal that the averaged strain of high Mg content alloy is also bigger than that of low Mg content alloy. That is to say, at a given maximum PLC band strain, both the biggest serration amplitude and the smallest elastic shrinkage appear in the alloy with the lowest Mg content. In fact, the elastic shrinkage can be taken as the balancing item for maintaining a constant stress drop. As
Fig. 4. Schematic for calculating the PLC band width and the maximum PLC band strain.

Fig. 5. Variation of band width with Mg contents at $1.00 \times 10^{-3}$ s$^{-1}$. The band width is calculated from the equal-interval correlation results. Specimens of 5456 Al-based alloy are 1 mm-thick.

Fig. 6. Relationship between serration amplitude and maximum PLC band strain in the PLC band with various Mg contents.

Fig. 7. Variation of the amount of elastic shrinkage with Mg contents: (a) two selected serrations with amplitude of about 24 MPa and the corresponding DIC-calculated strain mappings; (b) the strain and displacement distributions in $Y$-axis of the center lines corresponding to serrations present in Fig. 7(a). The inset of (b) shows variation of the averaged strain outside PLC bands with Mg contents.
such, the influence of Mg content on the deformation behaviors of PLC band can be classified into two aspects: the PLC band strain and the amount of elastic shrinkage outside PLC bands.

4. Conclusions

In summary, this paper presents a detailed investigation about serrated flow of Al-based alloy at various applied strain rates in relation to the Mg content. The influence of Mg content on deformation behaviors, including the spatiotemporal characteristics and the relationship between the serration amplitude and the strain increment within PLC bands, was studied by using 3D-DIC. The major conclusions can be summarized as follows:

(1) Mg content has a pronounced effect on the serration characteristics (the serration type and amplitude) and shifts the region in which the PLC effect occurs to high strain rate.

(2) Mg content weakens the spatial cohesion of propagative bands.

(3) The serration amplitude linearly increases with the maximum PLC band strain for all the alloys with various Mg contents; high Mg content generates a higher PLC band strain at a given serration amplitude compared with low Mg content.

(4) Both the serration amplitude and the amount of elastic shrinkage outside PLC bands increase with increasing Mg content.

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