INVESTIGATION OF PORTEVIN-LE CHATELIER EFFECT IN COARSE-GRAINED Al-Mg ALLOYS

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Abstract

The behavior of deformation bands associated with the Portevin-Le Chatelier (PLC) effect was studied in an Al-Mg alloy. The microstructure of the alloy consisted of coarse grains with approximately equiaxed shape and average size of 40 μm. A series of tensile tests was carried out at room temperature and initial strain rates of 1×10^{-3} s^{-1} and 5×10^{-3} s^{-1}. Comparing different propagation characteristics of the PLC bands (the velocity of the PLC band propagation, the local strain rate within the band, the band width, and the angle of band) for the model coarse-grained alloy reveals numerous unusual features of spatiotemporal behavior observed at various stages of strain hardening the alloy. The specific mechanisms of plastic deformation at various stages of strain hardening are considered in some detail.

Keywords: Aluminum alloys, mechanical testing, microstructure, Portevin-Le Chatelier effect

1. INTRODUCTION

Al-Mg alloys are widely used materials exhibiting jerky flow or repetitive yielding, associated with heterogeneous localization of plastic deformation within the bulk of a material. It is referred as the Portevin-Le Chatelier (PLC) effect [1-3]. The PLC effect is known to result in a reduction in ductility and the formation of deformation bands that leave undesirable traces on the surface of the sheet product [2].

Different authors studied this phenomenon using various methods. However, there are still many questions. For example, Shabadi et al. [4,5] investigated the PLC band width using the laser speckle technique and found that band width increases with strain and reaches a plateau in Al-based alloys. However, in research from Ait-Amokhtar et al. [6], band width was measured as a function of strain during the test and it was noted that band width decreases during the test.

In this paper, the micro-deformation or macro-deformation behaviors of an object will be characterized via digital image correlation (DIC). This method has been widely used for several decades. Thanks to the DIC method, it is possible to have access to the width, the height or transported strain, the angle and band velocity. Therefore, a new experimental database can be achieved to better understand the PLC phenomenon.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

An alloy with a chemical composition of Al-3Mg (wt.%) was produced by semi-continuous casting. The ingots were subjected to homogenization by annealing for 4 h at 500 °C and cooled with the furnace. Rectangular samples with dimensions of 40 mm × 120 mm × 200 mm were machined from the central part of the ingots and rolled at an ambient temperature with a total reduction of 70 % which provides a final thickness of ~4 mm. The rolled sheets were annealed for 2 h at 400 °C to produce a recrystallized microstructure. The microstructure obtained after such thermomechanical processing consisted of coarse equiaxed grains with an average size of about 40 μm. The fraction of high-angle boundaries (HABs) was near 47 %. The average misorientation Θ was ~21°. The density of lattice dislocations was $\sim1\cdot10^{13}$ m^{-2}. Other details of the structural and processing were reported in previous work [7].

Tensile specimens with 35 mm gauge length and 3 × 7 mm^2 cross-section were cut parallel to the rolling direction of the sheets. Tensile tests were performed at room temperature and initial strain rates of 1×10^{-3} s^{-1} and 5×10^{-3} s^{-1} were measured in a Zwick 1476 testing machine. Three samples were tested for each set of conditions. A strain gauge extensometer with 0.5% accuracy of strain measurement was applied to examine yielding behavior. A digital image correlation (DIC) method was used to observe the PLC band kinematics. The calculations were performed using Vic-2D software. The DIC system also provided a channel for recording the output signal of the testing machine. The accuracy of these measurements was relatively low but they served to synchronize the series of images with the deformation curve recorded by the load cell.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The engineering σ-ε curves at strain rates of 1×10^{-3} s^{-1} and 5×10^{-3} s^{-1} are presented in **Figure 1**. The Al-Mg alloy exhibits mechanical behavior similar to other dilute Al-3% Mg alloys with a grain size of ≥30 μm in a recrystallized condition. The material manifests an elastoplastic behavior in which a short yield plateau at a very low strain in the σ-ε curves appear shortly after the elastic regime. The following deformation is characterized by pronounced strains hardening up to the onset of necking. The deformation curves exhibited stress serrations, which are shown in **Figure 1**. This phenomenon is caused by the dynamic strain aging (DSA) of dislocations and is associated with heterogeneous localization of plastic strain. The strain rate sensitivity (SRS) of the flow stress is one of the central elements of DSA models of the PLC effect in the description of stress serrations. The deformation curves of the Al-Mg alloy tend to lie below the curves measured at lower strain rates (see **Figure 1)**. This indicates negative strain-rate sensitivity of stress, which is a necessary condition for the onset of the PLC instability. A close-up observation on the jerky flow shows the temporal aspects of type A at both strain rates.

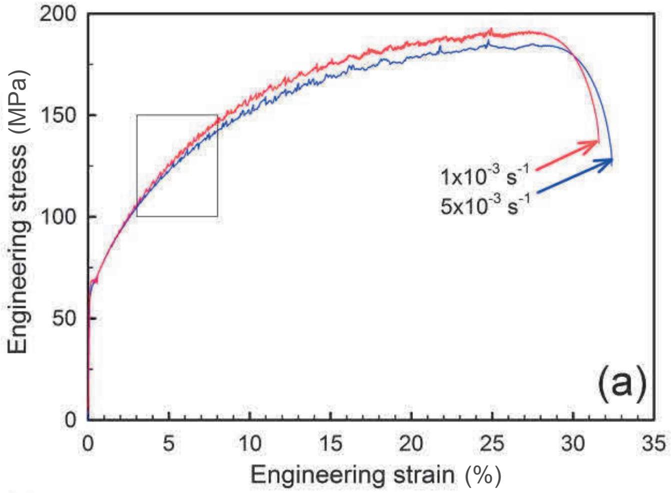

Figure 1 Typical engineering σ-ε curves of the Al-Mg alloy for two strain rate values

The propagation characteristics of the localized bands in relation to strain are investigated by the DIC method. **Figure 2** shows the strain-rate maps of the Al-Mg alloy tested at a strain rate of 5×10^{-3} s^{-1} where the continuous propagation appears at various deformation stages of the alloy. The time interval of the strain-rate maps corresponds to regions of the time-load curve of the alloy marked with rectangles on the top graph of **Figure 2**. It should be noted that the strain-rate maps show some differences in the various stages of deformation.

The yield plateau is related to nucleation and fast propagation of a deformation band from one specimen edge to the other (see **Figure 2a**). As can be seen in **Figure 2a** at t = 1.05 s, the central part of localized deformation appears to be a rounded contour. Even though this aspect is less pronounced after complete formation of the deformation band, it can be recognized on all images. The deformation within the bands can be determined by the maximum. It should be noted that the maximum at the yield plateau has a PLC band strain only four times higher than the applied strain rate. This means the localization of plastic flow is low in comparison with the PLC bands. The last three frames capture the plastic flow homogenization after the band passage through the specimen. They demonstrate delocalization of the high local strain rate zone in the sense that the area of intense color spreads all over the sample while the maximum value decreases.

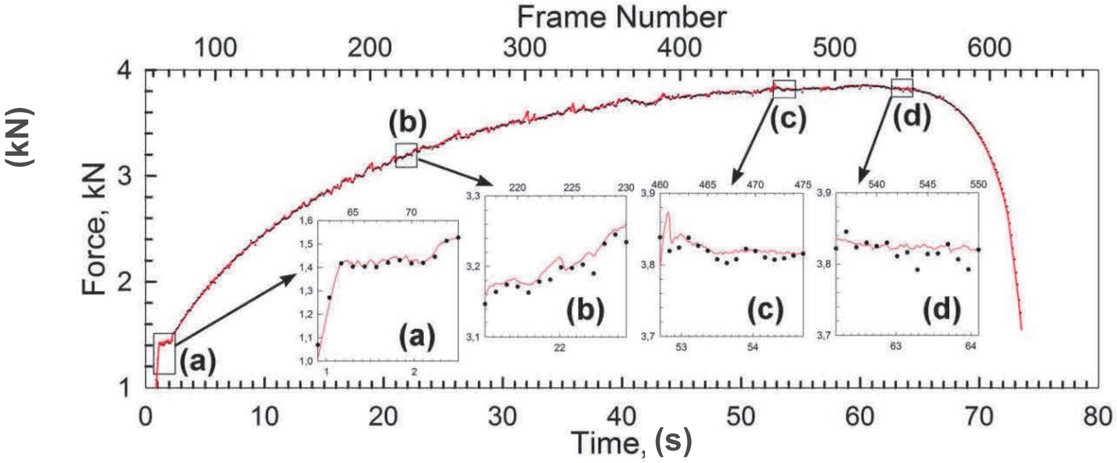

Figure 2 Strain-rate map demonstrating propagation of a type A PLC band at different stages of deformation including during the yield plateau (a), on an early deformation stage (b), after significant deformation (c) and during necking (d) in Al-Mg alloy tested at 5×10^{-3} s^{-1}

A further strain hardening stage is characterized by continuous propagation of bands associated with type A serrations (see **Figure 2b** and **Figure 2c**). In most cases, especially at low strains (see **Figure 2b**), bands are nucleated near one specimen end and escape at the other end. The bands observed at low strains have a usual plane shape corresponding to simple shear. However, they can turn symmetrically during propagation through the specimen. Importantly, this process does not occur as an abrupt flip but seems to involve a competition between two shear orientations, which was particularly well seen at t = 21.9 seconds. The band shape becomes similar to the one observed on the yield plateau in **Figure 2a**. This aspect is intensified in the course of deformation, which is illustrated in **Figure 2c**. The results reveal that the average band velocity and width gradually decreases with tested values while the local strain rate within the band is increased. This testifies to stronger strain localization. At large strains (see **Figure 2c**), the ratio exceeds 10. The final necking retains a sense of continuity with the above-described trends. It correlates with the termination of the propagation mode, which is substituted with strain localization in a restricted area over which the deformation band performs slow movements back and forth (see **Figure 2d**).

Other parameters such as width of the band can also be determined thanks to DIC. For a given time, the strain is plotted as a function of the position along the axis of the specimen (see **Figure 3**). The strain distribution within localized bands is characterized by a Gaussian function. The band width is defined as the distance between the two closest extreme points on opposite sides of the PLC band, which is depicted in **Figure 3**. This analysis was carried out on all the visible bands during the tensile test of the Al-Mg alloy. **Figure 3** shows the strain distributions of four bands taken from characteristic intervals of the curve: at the beginning of the tensile test (during the yield plateau) with an average width of 14 mm, on an early deformation stage with an average width of 11 mm, after significant deformation with an average width of 8 mm, and at the end of the tensile test (during necking) with an average width of 7.8 mm (see **Figure 3**). The deformation within the bands can be determined by the maximum PLC band strain (max). Therefore, **Figure 3** clearly shows that the maximum PLC band strain increases with the test, which was noted above.

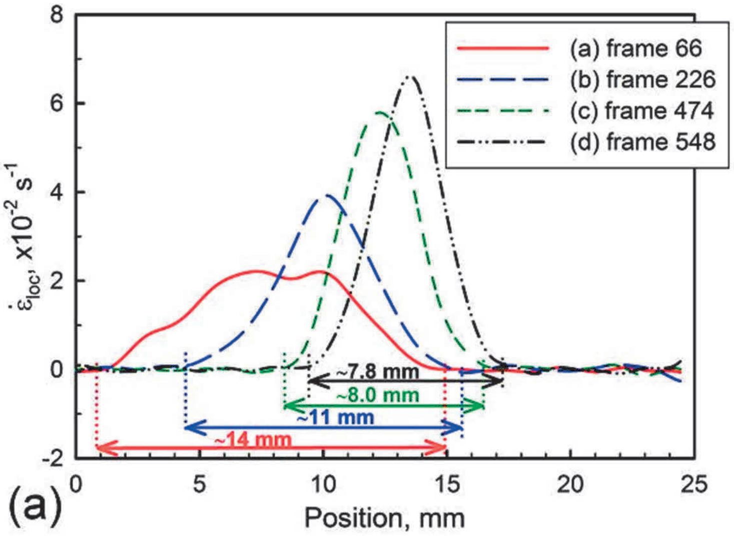

Figure 3 The strain distributions of frames along selected lines for four characteristic stages of the deformation curve are marked with rectangles in **Figure 2**

4. CONCLUSION

The Al-Mg alloy exhibits type A stress serrations at a strain rate of ~10^{-3} s^{-1} and an ambient temperature; these characteristics are associated with the dynamical mechanism that propagates deformation bands. It was established that the PLC band velocity and the band width on the true strain dependence is described by a linear decreasing function. The normal orientation of the band to the tensile axis is observed during the yield plateau. However, the average angle to the axis is 60° after the yield plateau (from the early deformation stage to necking).

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