Portevin-Le Chatelier effect of LA41 magnesium alloys

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Abstract Uni-axial tensile deformation of LA41 magnesium alloy has been carried out and the Portevin-Le Chatelier (PLC) effect, also known as serrated flow or plastic instability, is observed. This kind of alloy exhibits negative strain rate sensitivity (SRS) at room temperature, that is, SRS is negative at the strain rate range from \(3.33 \times 10^{-4}\) to \(6.66 \times 10^{-3}\) s\(^{-1}\) at ambient temperature. Both ultimate stress (\(\sigma_u\)) and 0.2% proof stress (\(\sigma_{0.2}\)) decrease when strain rate (\(\dot{\varepsilon}\)) increases, whilst critical strain (\(\varepsilon_c\)) of serrated flow is found to rise with enhancing \(\dot{\varepsilon}\). A new explanation for this unusual phenomenon is presented. The model of dynamic strain aging (DSA) is established through diffusion of solute atoms to mobile dislocations, which are temporarily arrested at obstacles. Such interaction renders the movement of mobile dislocations more difficult so as to necessitate the required force to overcome the obstacles.

Keywords magnesium alloy, Portevin-Le Chatelier phenomenon, strain rate sensitivity, dynamic strain aging

1 Introduction

Portevin-Le Chatelier (PLC) effects have been extensively reported in some kinds of alloys oriented for industrial applications. Because the successive localization process of strain will occur when PLC effect is dominant, the stress–strain curves exhibit serrations or plastic instability. Macroscopically, polished surfaces of tested samples will become rippled and the overall plasticity will be reduced dramatically. Generally speaking, PLC effects ought to be avoided in structural alloys.

Recently, Mg-Li alloys have drawn great attention from material scientists due to their excellent mechanical, electronic and magnetic properties, and related researches are being conducted all over the world. According to firmly-established reports, the addition of some elements such as Al, Zn or Ag can drastically enhance the mechanical properties of such alloys [1].

One point that deserves great attention is that the PLC effect mainly occurs in the face centered cubic (FCC) alloys [2−14] and is seldom reported in the hexagonal close packed (HCP) alloys. Zhu et al. [15] found serrated flow in WE 54; Corby et al. [16] presented excellent evidence in commercial AZ91. This paper, however, brings about some new insight on PLC effect that occur in HCP Mg–Li alloys and aims to broaden the application of this promising material series.

2 Experimental

High purity Mg (99.7%), Li (99.9%) as well as Al (99.9%) were melted in a vacuum induction furnace under an argon atmosphere, then, alloys were solidified in a steel mould. Subsequently, ingots were extruded at 673 K with an 8:1 ratio and then annealed at 723 K for 1 hour. Finally, homogenized extruded sheets were quenched in air at room temperature. Chemical analysis revealed that the employed alloy was composed of 4.32wt% Li, 0.97wt% Al and 94.71wt% Mg and was named as LA41 according to the nomenclature.

Cylindrical tensile specimens, which had gauge dimensions of 5 mm in diameter and 25 mm in length, were prepared and tested (Fig. 1). Uni-axial experiments were performed on an MTS-880 machine with initial strain rates of \(3.33 \times 10^{-4}\), \(6.66 \times 10^{-4}\), \(3.33 \times 10^{-3}\) and \(6.66 \times 10^{-3}\) s\(^{-1}\) at 293 K. Cu Kz radiation was used to complete phase identification on a Rigaku D/max-rA X-ray diffractometer. Leica MEF4M optical microscope was employed to make microstructure revelation. The etchant is composed of 3 g picric, 10 mL distilled water, 10 mL acid and 50 mL ethanol with the etching time as long as 30 s.
3 Results and discussion

The stress–strain curves, which are subjected to four different strain rates, are plotted in Fig. 2. It is clear that both the ultimate tensile strength and the yielding stress decrease with enhancing strain rate (Fig. 3). Besides, serration intervals tend to be prolonged with increasing strain rate. That is, serrations are more intense under low strain rate while they become less serrated under higher strain rate. According to the classification of Baird [17], such serration can be named as A type (Fig. 4).

The strain rate sensitivity (SRS), which is defined as $n = \Delta \sigma / \Delta \ln \dot{\varepsilon}$, remains negative throughout deformation history (Fig. 5). Based on classical explanations [18–22], negative SRS signifies the predominance of dynamic strain aging (DSA). In other words, it is most likely that DSA contributes to the occurrence of PLC effect in LA41 alloy.

The movement of dislocations inside crystals is not continuous [21,22]. When the moving ability of mobile dislocations and solute atoms becomes equal, mobile dislocations will be arrested by obstacles such as particular forest dislocations. Therefore they should temporarily reside over obstacles [23] (Fig. 6). Due to thermal fluctuations, mobile dislocations can break out the pinning stress and move towards the next obstacle. The average velocity of mobile dislocations can be expressed as follows:

$$v_L = \frac{L}{t_w + t_f}$$  \hspace{1cm} (1)

where $L$ is the average distance between obstacles, $t_w$ is the waiting time of mobile dislocation and $t_f$ is the flight time among obstacles. Gills et al. [24] made it clear that $t_f$ is always several orders less than $t_w$, then the above equation can be simplified as:

$$\overline{v} = \frac{L}{t_w}$$  \hspace{1cm} (2)