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The Portevin-Le Chatelier effect and strain-rate-induced plasticity enhancement in Mg-4Li and Mg-4Li-1Al alloys

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Abstract
The effects of strain rate on deformation behavior of the Mg-4Li and Mg-4Li-1Al alloys were investigated through tension testing and microstructure analysis. The Portevin-Le Chatelier effect was detected in tension testing of Mg-4Li alloy in the strain rate range of $5 \times 10^{-4}$ s$^{-1} \sim 1 \times 10^{-3}$ s$^{-1}$, and the effect was enhanced by the addition of 1% Al. The mechanism of Portevin-Le Chatelier effect was ascribed to the interaction between primary dislocations and pre-existing secondary forest dislocations. The strain rate sensitivity indexes of both Mg-4Li and Mg-4Li-1Al alloys were found as negative. With increasing strain rate, the yield strength and tensile strength of both alloys decreased, while the elongation increased.

In recent years, more and more studies on Portevin-Le Chatelier (PLC) effect of magnesium alloys have been reported [1–18]. All these studies prove the prevalence of PLC effect in magnesium alloys. However, some fundamental questions concerning the PLC effect in magnesium alloys need to be clarified. For example, PLC effect is found in some binary Mg alloy [19], while not found in other binary Mg alloys [5, 20]. The question is what kind of solute atom could trigger PLC effect in Mg alloys, and why. Earlier reports explain PLC effect through the mechanism of dynamic strain ageing (DSA), which could be classified into diffusional model. Recent studies prefer non-diffusional model, which is purely based on dislocation-dislocation interaction, excluding the necessity of solute-dislocation interaction for PLC effect [3, 4]. In the domain of Mg alloys, more proof should be provided to help discriminate between diffusional and non-diffusional models. Also, the relationship between PLC effect and the phenomena accompanying PLC effect, such as strain rate softening and strain-rate-induced plasticity enhancement (SRIPE), need further discussion.

In this paper, we fabricated two Mg-Li based alloys and studied the room temperature tensile behavior under different strain rates. The PLC effect was found in tensile deformation of both alloys. The underlying mechanism of PLC effect and the influence of strain rate on PLC effect were discussed.

1. Experimental procedure

The alloy ingots were cast in electrical resistance crucible furnace under atmospheric pressure and flux protection, with the smelting temperature of 750 °C. The actual chemical compositions (mass fraction, %) were measured as Mg-4.7Li and Mg-4.2Li-1Al for Mg-4Li and Mg-4Li-1Al alloys, respectively. After homogenizing annealing of 400 °C × 7 h, the cast ingots were processed by hot extrusion at the temperature of 300 °C with extrusion ratio of 5.7:1.

The observation of microstructural features and EBSD analysis were carried out by using optical microscope and scanning electron microscope. The etchant for microstructure observation was the solution of 5 g picric acid, 10 ml acetic acid and 100 ml ethanol, with the etching time of 45 s. Tensile tests were executed on a tensile testing machine, at the nominal strain rates of $1 \times 10^{-4}$ s$^{-1}$, $5 \times 10^{-4}$ s$^{-1}$, $1 \times 10^{-3}$ s$^{-1}$, $5 \times 10^{-3}$ s$^{-1}$ and $1 \times 10^{-2}$ s$^{-1}$. The sizes of the gauge section of tensile specimen were 28 mm × 6 mm × 3 mm, with longitudinal direction parallel with the extrusion direction.
2. Experimental results

The stress-strain curves of Mg-4Li and Mg-4Li-1Al alloys under various strain rates are shown in figure 1. In strain rate range of $5 \times 10^{-4} \text{s}^{-1} \sim 1 \times 10^{-2} \text{s}^{-1}$, serrated flow was found in the tensile curves of Mg-4Li alloy, which could be ascertained as PLC effect. Compared with Mg-4Li alloy, Mg-4Li-1Al alloy illustrated more obvious PLC effect at the same strain rate. We could observe the PLC effect at even lower strain rate in Mg-4Li-1Al alloy, with the lowest strain rate as $1 \times 10^{-4} \text{s}^{-1}$. During the process of tensile testing, the PLC effect occurred nearly from the beginning to the end of the deformation, and the intensity of the PLC effect decreased with increasing strain rate. Based on the insets (in figures 1(a) and (b), respectively) enlarged from the stress-strain curves with the same strain but different strain rates, the frequency of serrated flow was high at low strain rate, and low at high strain rate. In other words, the frequency of plastic instability decreased evidently in both alloys with strain rate increasing.

Table 1 lists the mechanical parameters for Mg-4Li and Mg-4Li-1Al alloys at different strain rates. With the same testing condition, Mg-4Li-1Al alloy had higher yield strength ($\sigma_{0.2}$) and tensile strength ($\sigma_b$) in comparison with Mg-4Li alloy, demonstrating 18% to 21% increase in yield strength and 13% to 16% increase in tensile strength. The elongation ($\delta$) was maintained at similar level between the two alloys. For both alloys, the increase in strain rate led to strength softening and elongation increase in the strain rate range of $1 \times 10^{-4} \text{s}^{-1} \sim 1 \times 10^{-2} \text{s}^{-1}$.

3. Discussion

3.1. The PLC Effect in Mg-4Li and Mg-4Li-1Al Alloys

PLC effect is not found in binary Mg-Al alloy [20] and Mg-Zn alloy [5]. However, it is found in binary Mg-Ag alloy [19]. PLC effect was also found in the binary Mg-4Li alloy in this study. All these experimental results challenge the DSA mechanism which is based on solute atom diffusion and solute-dislocation interaction. If the interaction between solute atoms and dislocations is the basic principle for PLC effect, the conclusion could be drawn that PLC effect must happen when concentration of solute atoms exceeds specific level. Unfortunately, the facts contradict.

The very important proof for non-diffusional theory for PLC effect is the work by Basinski and Jackson [21, 22], in which they found that unstable flow occurs in very pure copper single crystals if predeformed on slip.
systems secondary with respect to that which is being tested. Trojanova et al. thought that the primary slip system of Mg and its alloys is basal slip, while the secondary slip system is the prismatic slip. Due to the addition of specific solute atoms, prismatic slip is activated to form a forest of dislocations. This type of forest dislocations could be regarded as ‘alien’ dislocations relative to the primary slip system. During the following deformation, newly-activated primary dislocation must escape the impedence from the alien forest dislocations to maintain gross deformation process. This is the essence of non-diffusional theory for the PLC effect in Mg alloys. The addition of lithium into magnesium apparently lowers the axial ration \( c/a \), and then activates non-basal slip systems. Regarding the Mg-4Li alloy in this study, the critical resolved shear stress (CRSS) for prismatic slip was lowered evidently by the addition of Li atoms, providing conditions for the formation of forest prismatic dislocations. The addition of Li atoms altered the difficulty of activation for prismatic slip system, and promoted the formation of forest prismatic dislocations. The interaction between primary basal dislocations and alien prismatic forest dislocations leaded to PLC effect. The role of Li addition for PLC effect was not through the direct interaction between Li solute atoms and dislocations.

The comparison between figures 1 (a) and (b) shows that PLC effect was more obvious in Mg-4Li-1Al alloy than in Mg-4Li alloy. In other words, the addition of 1% Al strengthened the oscillation of PLC serrations. In Mg alloys exhibiting PLC effect, the role of solute atoms in solid solution is twofold: on the one hand, solute atoms may lower the CRSS of prismatic slip system, promoting the activation of prismatic dislocations; on the other hand, solute atoms may influence dislocation dynamics on basal planes, impacting the procedure of PLC effect. As the binary Mg-Al alloys do not show PLC effect, the former role of Al addition could be neglected. So, the addition of Al atoms in the Mg-4Li-1Al alloy was thought to influence PLC effect through changing the dislocation dynamics of basal planes.

Figure 2 gives the relationship between initiating strain for PLC effect and strain rate of the two alloys. The initiating strain increased monotonously with increasing strain rate in both Mg-4Li and Mg-4Li-1Al alloys. According to Trojanova et al.’s analysis, at low strains the forest of alien dislocations is not very dense, and the PLC bands carry very little strain and are unable to trigger macroscopic jerky flow. Hence, they propagate in a smooth fashion and no macroscopic serrations are observed on stress-strain curves. As the forest of dislocations becomes denser, the successive bands increase their share of the strain until the burst of strain trigger macroscopic serrations in the curves. So, the transition from smooth to jerky band propagation occurs at a larger strain for higher strain rates.

In order to investigate the role of twinning, microstructure features of the two alloys after tensile testing were analyzed (see figure 3, the arrow direction represents tensile direction). Deformation twinning could be found in deformed microstructures of the two alloys. The increase in strain rate promoted the occurrence of deformation twinning in the two alloys. Twinning behavior is well known to be sensitive to strain rate. As the strain rate increases, the velocity-controlled dislocation slips are suppressed, leading to the stress concentration near grain boundaries and secondary phases. This contributes to enhanced twinning tendency and increases the amount of deformation twinning.

Figure 4 illustrates EBSD patterns of Mg-4Li-1Al alloy at two different strain rates, in which blue represents tension twinning, red compression twinning and yellow secondary twinning. With strain rate increasing, the amount of tension twinning increased while that of compression and secondary twinning did not change (see figure 4). The CRSSes for compression and secondary twinning are relatively high. With increasing strain rate, the flow stress of Mg-4Li-1Al alloy decreased (see figure 1). As a result, the occurrence of compression and secondary twinning was inhibited. Based on the fact that the amount of twinning increased while the intensity of PLC effect decreased with increasing strain rate, twinning was not the actual cause for PLC effect in Mg-4Li and Mg-4Li-1Al alloys.
3.2. Effect of strain-rate-induced plasticity enhancement (SRIPE)

Several studies show the correlation between PLC effect and negative strain rate sensitivity index. Both the two alloys in this study showed simultaneously PLC effect and the negative strain rate sensitivity indexes. At the same time, the two alloys also demonstrated SRIPE. Strain rate softening and SRIPE are macroscopic features of tensile curves. PLC effect is microscopic interaction between primary and alien forest dislocations and very local fluctuation on the tensile curves. The concurrence of strain rate softening, SRIPE and PLC effect could not guarantee the causal relationship among them. Based on the experimental results in this study, no causal relationship could be concluded among strain rate softening, SRIPE and PLC effect of Mg-4Li and Mg-4Li-1Al alloys.

The insets in figures 1 (a) and (b) shows that, with increasing strain rate, the frequency of PLC serrations and the amplitude of stress oscillation decreased. According to the theoretical features of non-diffusional model of PLC effect, the results meant that the intervals of forest dislocations increased, and the density of forest dislocations decreased, under higher strain rates.

The mechanism for SRIPE is commonly related with the initiation of twinning, transition of micro-fracture mechanism and temperature increase caused by high strain rate deformation [23, 24]. Obviously, the initiation of twinning promotes and coordinates the deformation mode of dislocation slip and, thus, contributes to the plasticity enhancement. For Mg-4Li and Mg-4Li-1Al alloys, the amount of twinning increased with increasing strain rate, proving the importance of twinning to SRIPE effect. Especially, the occurrence of tension twinning released the concentration of tension stress and contributed to SRIPE effect. The fracture mechanism did not change for both low strain rate and high strain rate, with cleavage as dominating fracture mode accompanied by
small amount of inter-granular fracture. With the addition of Al element, the fracture mechanism also did not change. Considering the strain rate range of $1 \times 10^{-4} \text{s}^{-1} \sim 1 \times 10^{-2} \text{s}^{-1}$, the increase of strain rate could not produce effective adiabatic heat. Therefore, both fracture mechanism and temperature increase from adiabatic heat exerted little influence on SRIPE effect of Mg-4Li and Mg-4Li-1Al alloys.

4. Conclusion

1) The observable PLC effect happened in tensile testing of Mg-4Li alloy, within the strain rate range of $5 \times 10^{-4} \text{s}^{-1} \sim 1 \times 10^{-2} \text{s}^{-1}$. After the addition of 1% Al, the strain rate range in which the PLC effect could occur changed to $1 \times 10^{-4} \text{s}^{-1} \sim 1 \times 10^{-2} \text{s}^{-1}$. The non-diffusional model based on dislocation-dislocation interaction was adopted as the mechanism of the PLC effects for two alloys.

2) With increasing strain rate, the initiating strain for PLC effect increased in both Mg-4Li and Mg-4Li-1Al alloys. Meanwhile, the frequency of the PLC effect decreased with strain rate increasing. The strain rate sensitivity index of flow stress was negative for two alloys.

3) The yield strength and tensile strength of the Mg-4Li and Mg-4Li-1Al alloys decrease gradually with increasing strain rate. While the elongation of both alloys increased slightly with increasing strain rate. Both alloys showed the effects of strain rate softening and SRIPE.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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