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Influence of temperature and strain rate on serration type transition in NZ31 Mg alloy

Wen-hui WANG[1,2], Di WU[2], Rong-shi CHEN[2], Chang-sheng LOU[1]

1. School of Materials Science and Engineering, Shenyang Ligong University, Shenyang 110159, China;
2. Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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Abstract: The process of tensile test at different temperatures and strain rates was used to study the characteristics of serrated flow, i.e., Portevin-Le Chatelier effect (PLC), in NZ31 Mg alloy. The PLC effect in the tensile stress−strain curves was observed at the temperature range of 150−250 °C. Serrated flow during the deformation at 250 °C is prominent, and a lot of slip bands with a specific direction in each grain can be observed in the microstructure. The serration changes from type A to type C with the increase of temperature and the decrease of strain rate. One single serration of type A was described specifically by the processes of partial pinning, absolute pinning and unpinning. The enhancement of pinning ability at high temperature and low strain rate can promote the absolute pinning process and restrain the unpinning process, which explains the serration type transition.

Key words: NZ31 Mg alloy; Portevin-Le Chatelier effect; serrated flow; serration type

1 Introduction

Mg alloys containing rare-earth elements have been widely used in aerospace and aircraft applications due to their high specific strength and excellent mechanical properties at elevated temperatures [1,2]. As a heat resistant rare earth magnesium alloy Mg−3Nd−1Zn (mass fraction, %), denoted as NZ31, it shows high strength and low cost [3−5]. It has been known that Nd, one of the light rare earth elements, has a maximal solubility (normally 3.6%, mass fraction) in solid Mg at eutectic temperature of 545 °C. Mg−Nd binary alloys have significant strengthening effect [6]. Moreover, the small addition of Zn into Mg−3%Nd alloy would further increase its peak-aged hardness [7,8]. Therefore, this alloy as astronautic structure material has been applied successfully [3].

It was found that serrated flow, i.e., the Portevin-Le Chatelier (PLC) effect, occurred in this alloy during plastic deformation at a certain temperature and strain rate [9]. PLC effect has been commonly accepted as a consequence of dynamic strain aging (DSA), i.e., dynamic pinning and unpinning interactions between the mobile dislocations and solute atoms during plastic deformation, which was first proposed in Al alloys [10−12]. In recent past, serrated flow has also been reported in many Mg alloys, such as Mg−Al−Zn alloy [13], Mg−Y−Nd alloy [14], Mg−Gd alloy [15], Mg−Li alloy [16]. In these reports, many different serration types were found at different deformation temperatures and strain rates. According to the characteristic features, the classification of PLC effect was given by PINK [17] and BRINDLEY and WORTHINGTON [18]. Type A refers to serrations that the general stress raises at first then drops to the original level in curve, otherwise the stress−strain curve is smooth. Type B refers to continuous serrations that the serrate stress raises at first, and then drops to the original level. Type C refers to serrations that only drop below the position in general curve. FANG et al [19] reported that the serration type of PLC effect changed from type A to type A+B and then to type B+C with increasing the temperature from 150 to 300 °C in two Mg−Gd alloys. However, few reports in Mg alloys gave a sound and detailed explanation on the transition of serration type with changing the testing temperature and strain rate.

In this work, the NZ31 alloy after solution treatment,

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Corresponding author: Di WU; Tel: +86-24-23915891; Fax: +86-24-23894149; E-mail: dwu@imr.ac.cn
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which ensures a lot of solute atoms in the matrix, was tensile tested at elevated temperatures at different ranges of strain rate and the serrated flow was found under a certain condition. The corresponding mechanism of the serrated flow with different types was discussed on the base of DSA theory, which explained well the serration type transition with the increase of test temperature and strain rate.

2 Experimental

The chemical composition of NZ31 alloy was Mg−2.7Nd−0.6Zn−0.5Zr (mass fraction, %). It was prepared with Mg (purity 99.95%), Zn (99.9%), Nd (99.5%) and Mg−30Zr by melting them in an electric resistance furnace under the protection of RJ-6 anti-oxidizing flux, which was mainly composed of 54%−56% KCl, 27%−29% $CaCl_2$, 14%−16% $BaCl_2$ and 1.5%−2.5% NaCl (mass fraction) [20]. The ingots with dimensions of 75 mm × 200 mm × 200 mm were prepared by pouring the melted alloy into a preheated steel mold. They were homogenized at 525 °C for14 h, and then quenched in water.

The sheets for tensile tests were cut from the casting ingots with a gauge length of 10 mm, width of 4 mm and thickness of 2.5 mm. They were tested using a Sans type tensile testing machine equipped with a heating chamber. Tensile tests were conducted at temperature from 100 to 300 °C with a strain rate of 1×10^{-3} s^{-1}. At the temperature of 250 °C, tensile tests were conducted with the strain rates ranging from 1×10^{-4} to 1×10^{-2} s^{-1}. A tensile test with repeatedly varying strain rates of 1×10^{-4} and 1×10^{-3} s^{-1} at 250 °C was completed. During the tensile test, the specimens were kept at a given temperature with the deviation less than 2 °C. The samples were held for about 10 min prior to the test to eliminate the temperature gradient. To ensure the accuracy of results, the final data of tensile tests were based on the average results of three specimens.

For microstructure observation, the samples were cut from the gauge part of the tensile test bars with the observation plane perpendicular to the thickness direction and then etched by a solution of HNO_3 (5%, volume fraction) in ethanol after mechanical polishing to observe the grain boundaries. The microstructures were examined using an optical microscope (OM), a confocal laser scan microscope (LEXT, Olympus OLS4100), a scanning electron microscope (SEM, Philips XL30 ESEM−FEG/EDAX) equipped with an energy-dispersive X-ray (EDX) spectroscopy analysis system, and a transmission electron microscope (TEM, JEM−2100F) operating at 200 kV. The thin foil specimens for TEM observation were prepared by punching discs of 3 mm in diameter, followed by dimple grinding and Ar^+ ion milling in a precision ion polishing system (PIPS, Gatan) operating at accelerating voltage of 4.5 kV and incident angle of ~8°.

3 Results

The typical engineering stress−strain curves at a temperature range of 100−300 °C are shown in Fig. 1(a). The results show that the serrated flow (PLC effect) is present only within the temperature range of 150−250 °C, and the curves are smooth at 100 and 300 °C. As shown in Fig. 1(b), type A serration dominates at 150°C, and the period and amplitude of serrations are longest and lowest, respectively, in comparison with those of serrations at other temperatures. At 200 °C, the serration type changes to A+B that exhibits an increase of the frequency of serrations. As the temperature increases to 250 °C, the serrations evolve into type B, where the frequency and amplitude of serrations become the most intense.

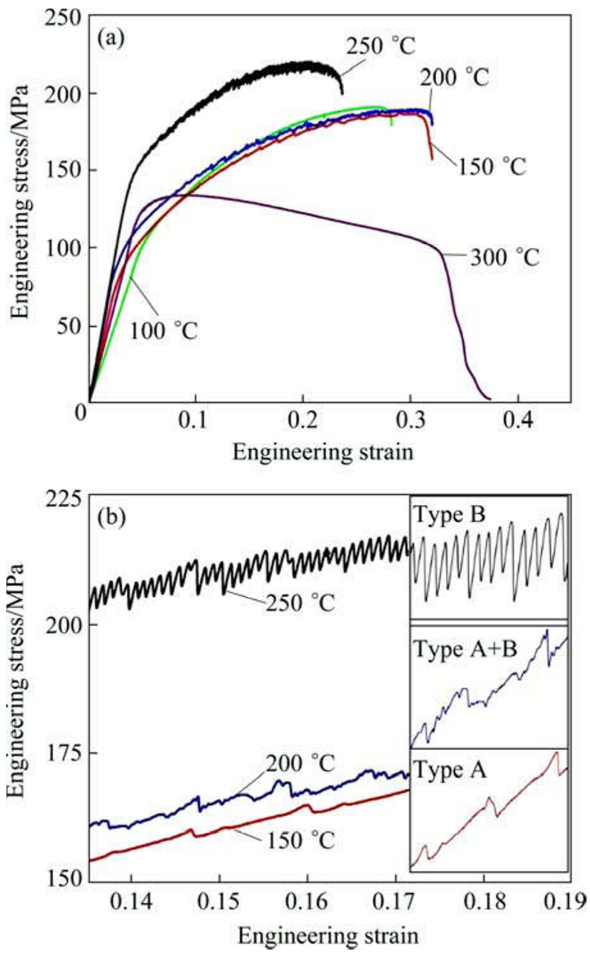

Fig. 1 Engineering stress−strain curves (a) and types of serration (b) at temperature range of 100−250 °C with strain rate of 1×10^{-3} s^{-1} for NZ31 alloy

The typical engineering stress−strain curves at 250 °C with the strain rate ranging from 1×10^{-4} to