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The mechanism of critical strain and serration type of the serrated flow in Mg–Nd–Zn alloy

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ABSTRACT

In present research the serrated flow has been observed successfully after a critical amount of strain. Two relationships between the critical strain and temperature i.e. normal and inverse, corresponding to each serration type were studied. In order to investigate systematically the onset of serrated flow and serration type in NZ31 alloy, samples in solutionized condition were tensile tested at the temperature ranging from 100 °C to 300 °C with the strain rate ranging from $1\times10^{-4}\,s^{-1}$ to $1\times10^{-2}\,s^{-1}$. Results showed that normal critical strain appeared with type A and B serrated flow at temperature from 150°C to 250 °C, and inverse critical strain appeared with type C at temperature from 275 °C to 300 °C. Through analyzing the mechanism of three serration types, we found that the production of serration required improvement in diffusion for solute atoms for pinning process at low temperature, and enhance the moving ability of dislocations for unpinning process at high temperature, which need the assistance of the strain and stress respectively. So, in this work, the critical strain for pinning and the critical stress for unpinning processes were defined, which give a better explanation to the variation tendency of two definitions in accordance with temperature. Furthermore, this relationship results in the critical strain for onset of serrated flow changing from normal to inverse and corresponding different serrations.

1. Introduction

Mg–3Nd–Zn alloy as traditionally cast Mg alloy with high strength and heat resistance, has been widely applied to aeronautics such as engine box and wing rib of airplane [1]. A serrated flow behavior was found in this alloy during high temperature deformation. The serrated flow, i.e. the Portevin–Le Chatelier (PLC) effect is always attributed to the manifestations of unstable yielding and flow under a suitable conditions [2–7]. It has been reported by many researcher in traditional industry of applied alloys including Al、Cu、Fe、Ti、Mg and Ni-based superalloy [8–19]. This phenomenon is generally explained as a consequence of an interaction of quasi-viscous moving dislocations with a solute atmosphere (or cloud), i.e. dynamic strain aging (DSA) mechanism proposed by Cottrell in 1953 [2]. This theory explains, when the diffusion velocity of solute atoms becomes equal to the dislocation mobility, the solute atoms can diffuse through lattice and can even pin the dislocations. However, subsequent researchers came with the idea that the diffusion rate of solute atoms is generally lower than the moving rate of mobile dislocations, which means that the effective pinning cannot be formed [20–24]. McCormick proposed a critical strain mechanism in the research on the PLC effect in 1972 [25]. He reckoned that diffusion ability of solute atoms was not enough to pin mobile dislocations at the beginning of the deformation process. Only by increasing the strain, the solute atoms pinning ability can be promoted and finally forms an effective pinning. The strain with which the first serrated yielding can be created is defined as critical strain ε_c.

On the basis of McCormick's critical strain theory, increasing in temperature promotes solute atoms diffusion, while decreasing strain rate reduces dislocations movement. Both of them can enhance the pinning ability of solute atoms. As a result, the critical strain should decrease with increase in temperature or the decrease in strain rate. However, a lot of experimental results manifest that, with the increase in temperature or decrease in strain rate, critical strain decreases first and then increases, instead of monotonously decreases [26–29]. The earlier decreasing process of critical strain corresponds to McCormick's theory, which is called normal critical strain, but the later increasing process of critical strain deviates from this theory, which is termed as inverse critical strain. Although some work has been done to reveal the mechanism of inverse critical strain, it is still not so clear. Brechet and Estrin, who assumed the nucleation and dissolution of precipitation during deformation could cause the inverse critical strain [31].

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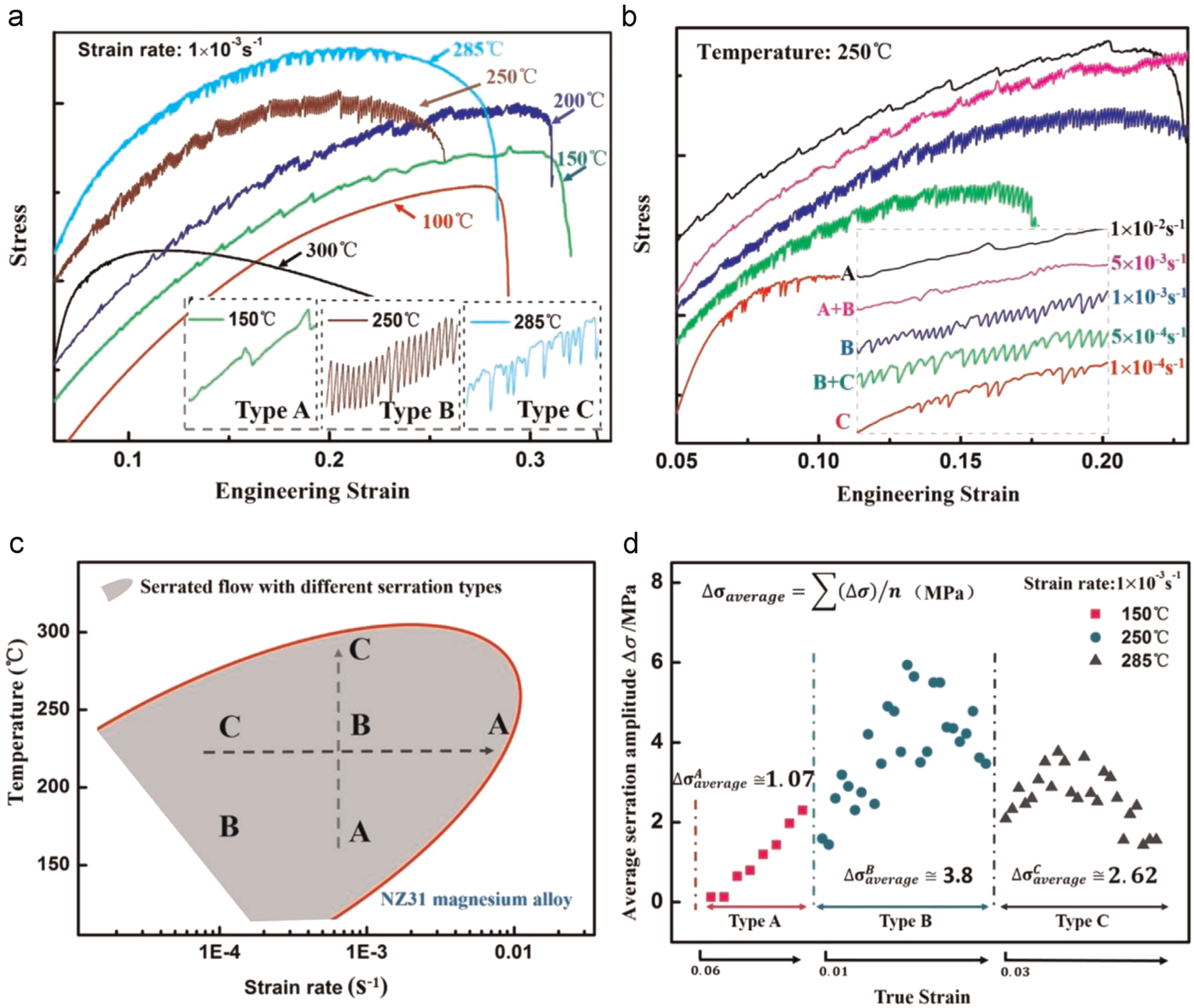

Fig. 1. Segments of engineering strain-stress curves, (a) at a temperature range from 100 °C to 300 °C with a strain rate of 1×10^{-3} s^{-1}; (b) at different strain rates and at the temperature of 250 °C. (c) Schematic of serration types with temperature and strain rate. (d) Variation in average serration amplitude of different serration types at corresponding temperature: type A, B, and C serrations have average amplitudes of 1.07 MPa, 3.8 MPa and 2.62 MPa respectively.

However, Chmelik who took advantage of sound emission experiment described that precipitates were not able to trigger the PLC effect [32]. Fu et al., believed that the process by which dislocations broke away from solute atoms contributed to the beginning of inverse behavior for the onset strain of serrated flow [29]. Recently Cui, et al., found that high stacking fault densities are correlated to the inverse critical strain [9,33].

Researchers classify the serrated flow into A, B and C three types according to their different characteristics [17,30,34]. Experimental results indicated that the types of serration often transformed from type A to type B then to type C with the increase in temperature [17,35,36]. Following research found that the normal critical strain behavior went along with type A serration and was observed at high loading rates or low temperatures, whereas inverse critical strain behavior was associated with Type C and observed at low loading rate and high temperature [37]. However, the inherent relationship between critical strain and corresponding serration type is not found.

Our recent works have analyzed the serration type transformation [38]. Based on these works, we believe that the appearance of a serration in serrated flow must meet two conditions. First is the pinning process which causes up stress, and then the unpinning process triggers down the stress respectively. Recent studies mainly focus on the pinning process, which associate the diffusion ability of solute atoms with strain, discussing the beginning of serrated flow. However, when the serrated flow begins with the unpinning process, the main factor of the appearance of serration is whether pinned dislocation can getting rid of solute atoms or not. Therefore, it is a premise for analysis of serration production to determine whether the pinning ability of solute atoms or the unpinning ability of dislocations is dominative factor.

This paper characterized the serrated flow of Mg–3Nd–1Zn alloy in detail in the tensile test with different temperatures and strain rates. The concept of critical strain for pinning (ε_{cp}) and critical stress for unpinning (σ_{cu}) was proposed to distinguish the DSA and serrated flow. Moreover, the relationships between temperature, critical strain ε_c, ε_{cp}, σ_{cu} and serration type were thoroughly discussed. A good explanation of the serration type transforming from A to C and the critical strain behavior for the serrated flow changing from normal to inverse with increasing temperature was obtained.

2. Experimental procedures

The NZ31 (Mg–2.7Nd–0.6Zn–0.5Zr (wt%)) alloy was used in present study. It was prepared with pure Mg (99.95 wt%), Zn