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Modeling of thermal and mechanical behavior of a magnesium alloy AZ31 during electrically-assisted micro-tension

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Many researchers have used a material response function termed "electroplasticity" to account for the mechanical behavior of metals subjected to electric current during plastic deformation. However, other researchers claimed that the electrically-assisted (EA) deformation behavior of metals could be successfully characterized using thermal-mechanical constitutive models without the need for electroplasticity theories. In order to examine the controversial mechanisms and determine which dominates the flow stress behavior under EA forming, this work established a flow stress model including the effects of strain hardening, rate hardening, thermal softening, solute–dislocation interaction and electron wind, where the latter three effects were assumed to contribute to the stress drop due to electric current. Additionally, an analytic thermal model was also established to capture the temperature variations during EA tension based on the energy balance between the heat generation due to Joule heating, and the heat losses due to conduction and convection. Also, the evolutions of strain rate and strain at specimen center were incorporated into both models to capture the effects of diffuse necking on thermal and mechanical behaviors during EA tension. Uniaxial micro-tension tests were conducted on AZ31 magnesium alloy specimens subjected to continuous electricity with various current densities to verify the proposed models. Results show that the thermal and mechanical models can effectively predict the thermal and mechanical behaviors of the AZ31 magnesium alloy at various current densities in EA micro-tension, respectively. The modeling results also demonstrate that Joule heating is the major factor to affect the deformation behavior under micro-tension subjected to continuous electricity.

1. Introduction

Recently, there has been growing interest in the experimental and modeling study of the forming limit of metals during micro/meso-scale plastic deformation (Ran and Fu, 2014; Ran et al., 2013). It was found that the formability decreased with

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the reduction of thickness-to-grain-size ratio due to the so-called "size effect" (Fu and Chan, 2011; Xu et al., 2015b). This undesirable effect on formability would be more severe for hard-to-form lightweight materials, especially magnesium alloys. Due to very few active slip systems in hexagonal close packed (HCP) crystal structures, plastic deformation of magnesium and its alloys is usually accommodated by both slip and twinning. As a result, magnesium and its alloys show very limited formability caused by significant flow asymmetry and heterogeneity, which is significantly affected by temperature, strain rate, strain path and micro-texture (Khan et al., 2011; Lévesque et al., 2010; Neil and Agnew, 2009). An increase in forming temperature can greatly reduce the degree of asymmetry and anisotropy (Jain and Agnew, 2007; Piao et al., 2012), which is still the most effective way to enhance the formability of magnesium alloys so far, like superplastic deformation (Babu et al., 2014; Watanabe et al., 2001). However, in most traditional processes including micro/meso-scale plastic forming, materials should be heated up to recrystallization temperatures by conduction/convection, which is energy consuming as well as time consuming. Therefore, a more economical and ecological technique that can also overcome forming difficulties for hard-to-form metals, is desirable.

Previous research has shown that the mechanical behavior of a metal can be modified by passing high densities of electric current through the metal during plastic deformation, i.e., EA forming. EA forming has been considered as an alternative to hot/warm forming (Perkins et al., 2007)as it can overcome various forming difficulties. Typical advantages associated with EA forming include improved formability (Salandro et al., 2010), reduced flow stress (Perkins et al., 2007) and decreased springback (Green et al., 2009), etc., for high strength or hard-to-form materials at relatively lower temperatures.

It is necessary to understand the mechanism behind the current-induced effects so that it can be modeled and effectively applied within metal forming industries. Trotskii and Likthman (1963) first found a significant electron-induced stress drop and an improvement in ductility with electron irradiating Zn single crystals during plastic deformation. This current-induced effect on plastic flow was termed as the electroplastic effect (EPE), which was then attributed to an interaction between drift electrons and elastic fields of dislocations by Troitskii (1969). Afterward, the influences of the drift electrons were extended by Sprecher et al. (1986) to other material parameters such as the vibration frequency of dislocation segments, the obstacle strength and the stacking fault energy. Note that most of the earlier studies were focused on the electron–dislocation interaction by means of reducing Joule heating and increasing the action of drift electrons using liquid nitrogen cooling or short-duration high-current pulses, which were reviewed in Kir'yanchev et al. (1983). As a result, classical theories were mainly established in terms of the electron–dislocation interaction including: (i) drift electrons can exert a "wind" on dislocations, i.e., electron wind, depending on the difference between the drift electron velocity and the dislocation velocity (Roshchutkin et al., 1979; Sprecher et al., 1986); (ii) drift electrons can enhance dislocation slipping velocity by influencing internal local stress field (Li and Yu, 2009); (iii) drift electrons can facilitate dislocation depinning by the magnetic field induced by current (Molotskii and Fleurov, 1995).

However, some recent experimental studies show that the above nonthermal EPE may be insignificant when continuous electricity was applied. For example, Kinsey et al. (2013) applied a high strain rate (i.e., ~10^3 s^{-1}) in the EA tension of 304SS and Ti–6Al–4V using a Kolsky bar with DC current supply (at current densities of 60–180 A/mm^2), and found no EPE occurred during the tests, and flow stress was strongly temperature-dependent. Jordan and Kinsey (2015) also did not observe the EPE during the EA three-point bending of brass sheets, and it was found that the variations in the bending force were caused by temperature effects. Magargee et al. (2013b) cooled the Joule heating temperature down to room temperature during the EA tension of commercially pure (CP) titanium sheets using forced air, and found that the measured flow stress was consistent with that at room temperature, which led them to conclude that Joule heating dominated the plastic flow in EA forming, while the EPE was negligible.

More recently, the current-induced mechanism was extended for EA forming using pulsed current. Kim et al. (2014) observed the microstructure of an aluminum alloy before and after necking in tension with 0.5s duration, 110 A/mm^2 current pulses, and found that the microstructure before necking was similar to that of non-EA samples, while the other showed recrystallization after necking due to the dominant effect of Joule heating. Moreover, the comparison among the degrees of X-ray diffraction (XRD) line broadening for initial, nonpulsed, heat treated and pulsed samples at the strain of 0.075, demonstrated that the pulsed sample included the lowest dislocation density and indicated that current could induce annealing without exceeding the critical annealing temperature of the aluminum alloy. Similar results were also observed using electron backscatter diffraction (EBSD) by Roh et al. (2014) for aluminum alloy samples in pulsed EA tension, and they also concluded that the EA deformation behavior cannot be simply explained by Joule heating since dynamic strain aging (DSA) (Kabirian et al., 2014) may influence the stress–strain curves. Magargee (2014) claimed that favorable conditions for DSA existed in pulsed EA tension since the sharp temperature increase caused by Joule heating and the enhancement of the strain rate could improve the mobility of solute atoms. Therefore, it is still unclear whether the EA deformation is exclusive to thermally activated plastic flow resulting from the temperature rise due to Joule heating, or combined plastic flow also taking account of the direct electron–dislocation interaction and DSA.

Due to the considerable debate regarding the existence of the EPE, modeling of the plastic flow during EA forming is a challenging task and the reported models vary from case to case. Sprecher et al. (1986) experimentally found that the passage of electric current pulses during the tension of metals could enhance the rate of deformation. Then the strain rate enhancement associated with stress drops were modeled based on different current-induced effects, which found that skin, pinch and magnetostrictive effects were of less importance, and elastic strains caused by the thermal expansion due to Joule heating only made a partial contribution to the enhancement of the strain rate. In order to account for a significant contribution to the enhanced rate of plastic flow due to the direct effect of drift electrons on dislocation motion, a rate-controlled