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Constitutive analysis of electrically-assisted tensile deformation of CP-Ti based on non-uniform thermal expansion, plastic softening and dynamic strain aging

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A B S T R A C T

Electrically-assisted (EA) deformation has shown promising effects in increasing formability and reducing springback in sheet metal forming. This work experimentally and analytically investigated the influence of non-uniform and transient Joule heating on the plastic flow stress of titanium which evolved nonlinearity with time and deformation. Three-stage constitutive analysis was carried out in the present study. First, the pure influence of non-uniform Joule heating was investigated in terms of linear elastic thermal expansion, which then explained the measured drops in stress. Second, the Johnson-Cook model was adopted to interpret a plastic thermal-mechanical behavior of the material loaded at a constant quasi-static deformation rate under the uniaxial tension combined with a single pulse of electric current. Finally, it was revealed that the sudden change in strain rate and rapid heating rate due to an electric current pulse could give rise to the transient occurrence of dynamic strain aging (DSA) in materials. This resulted in an accumulated plastic strain as well as transient high-temperature strain hardening, which estimated the experimentally measured data well. The DSA contribution revealed in this work could help to explain many observations in the past studies in the field of EA deformation.

1. Introduction

The development of advanced electrically-assisted (EA) forming technologies has been one of the recent focuses in sheet metal forming research. It utilizes the effects brought by the high-density electric current passage through metals to assist the deformation of difficult-to-form materials, such as titanium and magnesium alloys (Guan et al., 2010). Utilizing electric current in a forming process gives rise to a primary benefit of rapid heating of material to a desired temperature for either a warm or hot forming process, while circumventing the need for expensive heating furnaces and long heating/cycle times (Karbasian and Tekkaya, 2010). Researchers have reported the advantages of EA forming for a decade including the reduction of bending force in bulk- and micro-scale sheet metals (Jordan and Kinsey, 2012; Salandro et al., 2011), the elimination of elastic springback after sheet bending (Green et al., 2009), and the increase of formability for AZ31 magnesium alloy (Xu et al.,

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2007) and 5052-H32 aluminum alloy (Roh et al., 2014). These improvements are often attributed to an athermal electroplasticity phenomenon between electrons and dislocations, either in addition or exclusive to thermal-mechanical plastic softening (Conrad, 2000; Harris, 1972).

The high-temperature plastic behavior of metallic materials has been widely investigated in the literature with respect to strain-rate sensitivity, deformation temperature, and strain hardening; nevertheless, these studies are usually under the conditions produced by a heating furnace with minimal temperature gradients across specimens (Bieler and Semiatin, 2002; Brown et al., 1989; Liang and Khan, 1999). Other than elevating temperature by furnace, applying a constant electric current to an electrical conductive material can also increase its temperatures during the deformation process (Magargee et al., 2013) or affect the necking behavior (Ross et al., 2007). However, the use of electric current to heat a material accompanies a number of unique mechanical considerations that may not be present during the typical high-temperature deformation. For example, the current might be applied in pulses in order to induce dynamic mechanical responses (Golovashchenko et al., 2009). It is also noted that the thermal and environmental conditions during EA deformation commonly lead to non-uniform heating profiles and temperature gradients (Ross et al., 2009), which are often not considered in the modeling of mechanical behavior (Salandro et al., 2011). Thus, a more in-depth analysis of the mechanics associated with this unique form of heating is required to advance the understanding of the plastic behavior of EA-deformed materials.

Various methods have been proposed in regards to the modeling of EA-deformed materials. For example, previous works have focused on the estimation of dislocation-slipping velocity (Li and Yu, 2009) as well as the computation of plastic strain rate due to changes in dislocation activation energy from electron-ion collisions (Li and Yu, 2011) in the field of electroplasticity. Empirical determination of electroplastic coefficients has been also studied to quantify the stress reduction under electric current environment (Bunget et al., 2010). A recent work has investigated the contribution of Joule heating and electroplasticity to the deformation behavior of a magnesium alloy under pulsed electric current (Lee et al., 2016). A high contribution of Joule heating was confirmed for the EA-deformed AZ31B alloy using finite element analysis based on a thermo-mechanical-electrical model. Meanwhile, other researchers have paid attention to viscoplasticity-based models as an alternative to the electroplasticity theory. For example, a temperature-dependent viscoplastic model calibrated by quasi-static and dynamic mechanical tests successfully predicted experimentally measured stresses for a pure titanium under uniaxial tensile deformation with short pulses of high current density; the temperature and strain rate obviously affected the apparent stress drops in this work (Bilyk et al., 2005). The further development of this approach revealed the relationship between the apparent stress drops and thermal expansion, rather than strain rate effects (Unger et al., 2006). A viscoplastic model also well described the deformation behavior of aluminum alloy and copper alloy subjected to mechanical load and electric load with high-density current pulsing (Gallo et al., 2012).

A common EA deformation applies electric current using single or periodic DC current pulses with 'on-time' durations of 1–10 s. However, the aforementioned thermal-mechanical models focused on predicting the dynamic mechanical response of a material subjected to short (i.e., μs-to ms-scale durations) electric current pulses. It is of particular note that the influence of pulse with longer duration (~1 s) has yet to be analyzed with respect to thermal-mechanical behavior. Therefore, the present study aims to investigate the unique mechanics and plastic deformation behaviors of a commercially pure titanium (CP-Ti) subjected to mechanical load and a single pulse of 1-s DC current. This work focuses on three aspects of EA deformation that have received little attention thus far: (1) the influence of non-uniform temperature gradients on the thermoelastic response of the material; (2) a characterization of flow stress during a single 1-s electric pulse; and (3) an analysis of dynamic strain aging (DSA) behavior accompanied by the DC pulsing environment.

2. Experimental procedures

The present study used CP-Ti (Grade 2) sheet with a thickness of 0.1 mm. A table-top mechanical testing machine (SEMTester 1824LM, MTI Instruments/Fullam Inc.) was employed to conduct EA tensile tests. Motor-driven lead screws were precisely aligned in the machine to carry out uniaxial tension, during which an attached load cell (Model 31, Honeywell Sensotec) with 1112-N capacity and 0.1-N resolution measured deformation forces. A linear displacement transducer (240 DC Linear Variable Displacement Transducer LVDT, Transtekinc) with a resolution of 1 μm was used to measure tensile grip displacement.

DC current was supplied to tensile samples during EA experiments using a rectifier-based DC power supply (MicroStar CRS-LFP12-300, Dynatronix Inc.). The maximum DC current and power outputs were 300 A and 3.6 kW, respectively. This power supply was connected to the tensile grips of the experimental machine. Teflon-coated steel screws and Macor ceramic layer insulated the tensile grips from the other parts of the machine, and thus protected electronics, such as sensors and motor, from any damages.

Tensile strain was measured using a non-contact digital image correlation (DIC) method. Prior to the tensile test, the front side of each specimen was coated by high-temperature black and white paint (Zynolyte Hi-Temp Paint, Aervoe Industries Inc.) to create a speckle pattern required for the digital image analysis. The image of the specimen during tensile deformation was captured by a high-resolution CCD camera (CMLN-13S2M-CS, Point Grey Research) and telecentric lens (0.3× TECHSPEC, Edmund Optics). These data were processed using DIC software (Icasoft, provided by INSA-Lyon) to compute two-dimensional strain fields for all images (Mguil-Touchal et al., 1997). Meanwhile, the backside of specimens was coated by high-temperature black paint (Zynolyte Hi-Temp Paint, Aervoe Industries Inc.) to prepare a uniform surface for temperature measurement. Direct and local temperature was measured during the tensile test using an infrared camera (TIM160 Imager,