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The mechanical behavior of 5052-H32 aluminum alloys under a pulsed electric current

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ABSTRACT

The electroplasticity of an aluminum 5052-H32 alloy under a pulsed electric current is investigated experimentally. A pulsed electric current is applied to a specimen simultaneously with a quasi-static uniaxial tensile load. The experimental result shows a ratchet shape stress–strain curve under a pulsed electric current. The formability of the selected aluminum alloy is significantly improved at near room temperature depending on the electric pulse parameters. An empirical expression to describe the upper boundary of the ratchet shape stress–strain curve of the aluminum alloy under a pulsed electric current is suggested. Two electroplastic coefficients are used in the suggested empirical expression: one is a material constant and the other accounts for the effects of the electric energy density and the electric pulse period. The result of the present study is expected to provide a basis to develop sheet metal forming processes using electroplasticity.

1. Introduction

Recent efforts in the automotive industry to improve fuel efficiency are reflected in the increasing use of lightweight materials, especially aluminum alloys. However, a general disadvantage of aluminum alloys is their limited formability at room temperature compared with conventional ferrous alloys (Khan and Liu, 2012; Li et al., 2013).

A traditional method to increase the formability of a metal is to deform the material at elevated temperatures, for example, by hot forming or warm forming. However, elevated-temperature forming methods have a few noticeable drawbacks, such as increased adhesion between the specimen and the die, reduced effects of lubrication, and decreased die strength (Salandro and Roth, 2009). Also, for some aluminum alloys, which strengths are not generally increased by heat treatment (for example, 5xxx aluminum alloys), the elevated-temperature forming process may induce an additional issue of inadequate post-process strength of manufactured parts for automotive applications. As alternatives to hot forming or warm forming, various forming methods such as hydroforming (Hartl, 2005; Dunand et al., 2012) and incremental forming (Golovashchenko and Krause, 2005) have been introduced. Although these recently introduced alternatives provide various technical advantages, they are still far from being perfectly satisfactory. Their drawbacks include that they are still time consuming and often require a significant amount of initial capital investment. Therefore, forming methods that can enhance

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the formability of a given metal alloy and reduce the required forming force without an excessive increase in temperature or a high capital investment are still desired.

Various studies have shown that the material property of a metal can be modified by simply applying electricity to the metal during deformation. In addition to the classical work by Troitskii (1969), which suggested that the flow stress of certain metals can be lowered by pulsed electricity, studies by Conrad (2000a,b) provide good background knowledge regarding the effect of electricity on the material property of metals. The studies of Conrad (2000a,b) also showed that the plasticity and phase transformation of various metals and ceramics are affected by pulsed or continuous electric current.

More recently, efforts have been made to implement the effect of electric current on the mechanical property of metals (electroplasticity) in metal forming processes (Electrically Assisted Manufacturing: EAM). According to Ross et al. (2007) and Perkins et al. (2007), the presence of a continuous electric current during plastic deformation of a metal can significantly reduce the flow stress of the metal. However, a continuously applied electric current may reduce the maximum achievable elongation of a metal under tension (Ross et al., 2007), while the formability of a metal increased significantly with continuous electric current under compression (Perkins et al., 2007). The decrease in the maximum elongation of a metal under continuous electric current may be explained by that, under tension, the cross-sectional area of the specimen continuously decreases, thus causing a continuous increase in the electrical current per unit area (electric current density). The increased current density yields excessive heating and eventually contributes to premature failure of the specimen. It is evident that a decrease in the maximum elongation of a metal under continuous electric current under tension imposes a significant disadvantage in sheet metal forming processes. Fan et al. (2013) investigated the influence of grain size and grain boundaries on the thermal and mechanical behaviors of 70/30 brass during tension tests with a continuous DC current. It was observed that decreasing grain size increased stress reductions during tension with a continuous DC current. The result of Magargee et al. (2013) suggested that the thermal effect may play a significant role in the electroplastic behavior of thin commercially pure titanium sheets under tension with a continuous DC current.

Even though a completely satisfactory explanation for the electroplasticity mechanism of metals has not been provided yet, the phenomenon of electroplasticity is very attractive to researchers and industries in the metal forming field. Regarding the electroplasticity of metals under tension, attempts to overcome the disadvantage of the reduced maximum elongation under continuous electric current have led researchers to pulse the electric current instead of applying it continuously to a specimen under tension (Roth et al., 2008; Salandro et al., 2009, 2010). Roth et al. (2008) applied pulsed electric current (or periodic electric current) to 5754 aluminum alloy specimens under tension and achieved elongation close to 400% of the gage length. Salandro et al. (2009) investigated the effect of pulse duration and current density on the electroplasticity of Mg-AZ31BO tensile specimens and suggested process parameter sets to reliably achieve optimal specimen elongations. Salandro et al. (2010) also investigated the effect of pulsed electric current on the mechanical behavior of tensile specimens of various 5xxx aluminum alloys with different heat treatments. According to Salandro et al. (2010), the effectiveness of a pulsed electric current on the tensile behavior of the selected aluminum alloys depends on both the alloy and the heat treatment. In addition, Green et al. (2009) found that the electroplasticity of metals can be used to reduce or even eliminate springback during the metal forming processes by applying a single pulse of high-current electricity at the final moment of deformation before removal of the forming load.

Even though the effect of pulsed electric current on the mechanical behavior of various metals is receiving rapidly increasing interest from many researchers and industries, quantitative descriptions of the effects of electric pulse parameters, including the electric current density, pulse duration, and pulse period, on the mechanical behavior of metals are very limited. Salandro et al. (2011) investigated the effects of pulsed electric current on the bending (electrically assisted bending: EAB) of 304 stainless steel sheets and suggested an analytical model to describe three-point bending force profiles for non-electrical baseline tests and various EAB tests. In a study by Salandro et al. (2011), an electroplastic bending coefficient was introduced and used for modeling the EAB process. Their model was in good agreement with the experimental results, and was able to predict the bending forces to within a difference of 10–15%. However, in order to design a commercial electrically-assisted sheet metal forming process, a quantitative description of the effect of pulsed electric current on the mechanical behavior of a metal is still required.

In the present study, the effect of a pulsed electric current on the mechanical behavior of a typical automotive aluminum alloy under tension is investigated. First, the effect of the electric pulse parameters on the local and global stress–strain behaviors of the aluminum alloy is discussed. Next, based on the experimental result, a mathematical expression describing the global stress–strain behavior of the aluminum alloy under a pulsed electric current is suggested, and then validated experimentally using randomly selected electric pulse parameters. Finally, the microstructural aspect of the electroplastic behavior of the selected aluminum alloy is briefly discussed.

2. Experimental set-up

Aluminum 5052-H32 alloy sheets 2 mm in thickness were used for experiments. The chemical composition of the selected aluminum alloy is listed in Table 1. For normal quasi-static tensile tests (baseline tests) and quasi-static tensile tests under a pulsed electric current, typical tensile specimens with a 9 mm gage width and a 50 mm gage length were fabricated by laser cutting along the rolling direction of the sheet. For the quasi-static tensile test under a pulsed electric current, the electric current was created using a Vadal SP-1000U welder (Hyosung, South Korea) with a programmable pulse controller