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Forming limits of an age hardenable aluminum sheet after pre-straining and annealing

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ABSTRACT

A two-stage stamping with an intermediate annealing method was developed to improve formability of age hardenable aluminum alloys, which are more challenging than the non-age hardenable aluminum alloys because of the effects that intermediate annealing will have on dissolution of solutes, precipitation of strengthening particles, and the subsequent mechanical behavior of the materials. The process could readily be applied locally to highly strained areas of a complex panel for 6000 series aluminum alloys in order to form a good part without fracture; however, there will be a decrease of precipitation strengthening of those locally treated, highly strained areas. In this study, the strain-based forming limit curves (FLC) of as-received AAx610-T4PD alloy sheets were shown to increase after pre-straining to ~15% and annealing at 425 °C for 10 s. However, since strain-based FLCs are very sensitive to the pre-strain history, both stress-based FLCs and polar-effective-plastic-strain (PEPS) FLCs, which are path-independent, were used to evaluate the forming limits after pre-straining and annealing. Due to the change of mechanical behavior during annealing, this paper describes the procedure to calculate the stress-based FLC in which a residual-effective-plastic-strain (REPS) is determined by overlapping the hardening curve of the pre-strained and annealed material with that of material heat treated without pre-strain. After converting the strain-based FLCs using the constant REPS method, it was found that the stress-based FLCs and the PEPS FLCs of the post-annealed materials are quite similar and both tools are applicable for evaluating the forming limits of Al–Mg–Si alloys for the two-step stamping process with intermediate annealing heat treatment.

1. Introduction

Vehicle mass reduction is one enabler to improve fuel economy, and aluminum alloys are increasingly being considered as substitutes for steel in order to reduce weight of automotive bodies and structures. One impediment to widespread implementation of aluminum sheet is limited formability compared to steel when stamping complex panels and shapes at room temperature. Often the complexity of a single-piece steel stamping requires multiple-pieces for an aluminum replacement that leads to greatly increased cost of assembly in addition to the raw material premium. However, special forming technologies have been developed to improve aluminum formability in order to match the complex features achieved in steel products.

Preform annealing [1] is one promising technology developed to address the formability challenge that includes a two-step stamping process with an intermediate annealing heat treatment. Several investigations have described the effect of preform annealing technology on forming limits of non-heat treatable aluminum alloys (i.e. no phase transformation during heat treatment). Li et al. [2,3] studied the effects of pre-strain, strain paths and subsequent annealing on the mechanical behavior and forming limits of AA5182-O and showed that annealing can indeed significantly improve the material ductility after the first stage of forming. However, this technology has not been applied to heat treatable aluminum alloys that are more challenging than the 5000 series because of the effects that intermediate annealing will have on dissolution of solutes, precipitation of strengthening particles, and the subsequent mechanical behavior of the material. The primary objective of this research is to study the effect of preform annealing technology on the forming limits of age hardenable aluminum alloys.

The strain-based forming limit curve (FLC), which is plotted with critical major and minor principal strains, has been a valuable

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tool for assessing sheet metal formability since first proposed by Keeler and Backofen [4]. Intensive studies [5–16] have been conducted to understand and predict the FLCs of sheet metals. It has been found that strain-based FLCs are not static. They are intrinsically dynamic limits, and the variation of strain path significantly affects the shape and location of the FLCs, as explained by Graf and Hosford [7].

In order to account for the effect of strain path on the FLC, some authors [17–21] have proposed that assessing the formability of sheet metals should be based on the states of stress rather than the states of strain. It is found that if the material is described by an isotropic hardening model, the stress-based FLCs are path-independent and applicable without modification to analyze forming situations.

Li et al. [22] have studied the application of stress-based FLCs to a non-heat treatable aluminum alloy, AA5182-O, after preform annealing. It was found that the stress-based FLC of post-annealed materials, calculated based on a constant hardening model, were identical to that of the as-received material, irrespective of the pre-strain levels and annealing treatments. However, annealing can significantly change the microstructure and mechanical properties of age hardenable Al–Mg–Si alloys, which leads to different hardening behaviors. Hence, the stress-based FLC of AAx610-T4PD alloy sheets after preform annealing is investigated in this research.

It has been argued that stress-based FLCs are not significantly sensitive at large strains close to the necking limit because of the saturation of the true stress-true strain relation. To address this concern, Stoughton and Yoon [23] proposed a path-independent polar-effective-plastic-strain (PEPS) FLC, which utilizes the effective plastic strain as one of the metrics to assess formability and has a one-to-one mathematical correspondence to the stress-based FLC. In addition, the PEPS FLCs have nearly the same shape as the strain-based FLCs, which is an attractive feature for engineers who are familiar with the strain-based FLC. Hence, the PEPS FLCs of post-annealed materials are also investigated in this research.

Generally, the forming limits of a 6000 series aluminum alloy after preform annealing are studied using strain-based, stress-based, and PEPS FLCs. Initially, the improvement of forming limits after preform annealing is evaluated using the strain-based FLCs. Then in order to remove the strain path effect and use the FLC as a tool in stamping formability analysis, the stress-based FLC and PEPS FLC are developed for AAx610-T4PD.

2. Experimental procedure

AAx610-T4PD alloy sheets were pre-strained, annealed and deformed using the Marciniak test to measure the strain-based FLCs. Large, specially designed sheets were pre-strained along two different strain paths; and then smaller specimens were cut from the center of the pre-strained sheets in different geometries, followed by annealing. Finally, the smaller specimens were deformed in a Marciniak testing system at room temperature to obtain the forming limits and all the strains were measured via a stereo digital image correlation (DIC) system. Additionally, the tensile properties of as-received and post-annealed materials were measured in uniaxial tension tests.

Table 1
Chemical composition of AAx610-T4PD (weight %).

Si	Mg	Fe	Cu	Mn	Cr	Zn	Ti	Other	Al
0.71	0.60	0.22	0.19	0.13	0.04	0.02	0.05	0.04	Remainder

2.1. Materials

The materials used in this study were 1.0 mm thick AAx610-T4PD sheets. Table 1 lists the chemical composition of the alloy for this study. All material was stored in a freezer at $-20\,^{\circ}$C until testing in order to preserve the as-received properties and state of aging.

2.2. Digital image correlation (DIC)

In this research, a 3D DIC system was used to measure *r*-values and forming limits, which uses full field, non-contact, and considerably high accuracy imaging for measurements of displacement and strain (accuracy of the strain measurement is up to 0.005%) [24]. Prior to testing, each specimen was cleaned, lightly coated with a white spray paint, and then small black spray paint droplets (ranging from approximately 0.5–1.0 mm) were applied followed by a short drying period so that physical testing occurred while the paint was still "tacky." After calibrating the DIC system, a sequence of images was captured with time during testing to obtain the deformation history. Generally, the first image before deformation was taken as the reference image, which was used to calculate the accumulated strain by comparing with the subsequent images.

2.3. Tensile testing

Tensile properties of as-received and post-annealed materials were measured in uniaxial tension using ASTM standard methods [25,26]. Dog bone shaped tensile specimens with the dimensions included in Fig. 1 were cut in 15-degree increments to the rolling direction (RD) of the sheet with edges of the gauge section ground to a smooth finish with a sharp rectangular cross section. Tensile tests were conducted in a universal testing machine with a constant cross head speed of 5 mm/min at room temperature.

The anisotropy coefficient *r* is defined by

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{1}$$

where ε_w and ε_t are the true strains in the width and thickness directions, respectively.

2.4. Pre-straining and annealing

Generally, an automotive outer panel accumulates approximately 10–15% strain from the stamping process. In this study, large sheets were pre-strained in equi-biaxial tension and in plane-strain along the transverse direction (TD) of the sheet to

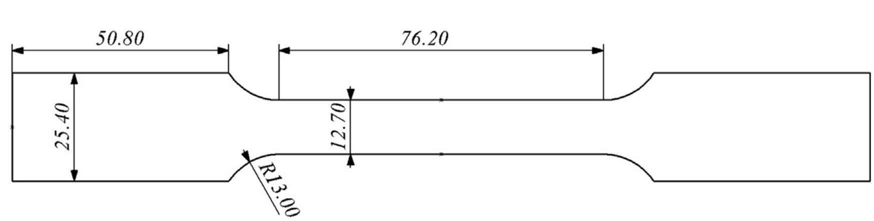

Fig. 1. Schematic of the tensile specimen geometry: dimensions in millimeters.