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Electromagnetic forming of aluminum alloy sheet: Free-form and cavity fill experiments and model

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Abstract

A series of high-rate electromagnetic-forming experiments are presented that consider free-forming and two configurations of cavity fill operations, one with a flat-bottomed die and the other with a hemispherical protrusion on the bottom of the die cavity. The experiments are performed on 1 and 1.6 mm AA5754 and 1 mm AA5182 aluminum alloy sheet; all of which are candidates for lightweight automotive structural applications. Increasing energy levels of discharge resulted in increased cavity fill and strain level in the formed parts. The effect of die geometry on formability, strain state and location of failure is examined.

Numerical simulations of the high-rate deformation and structural impact that occur during electromagnetic forming are presented, and provide insight into the physics of the problem and the transient nature of this high-rate deformation process. A transient electromagnetic finite-element code is used to model the time-varying currents that are discharged through the coil in order to obtain the transient magnetic forces that are imparted to the workpiece. The body forces generated by electromagnetic induction are then used as the loading condition to model the high-rate deformation of the workpiece using an explicit dynamic finite-element code. A "two-way, loose coupling" of the electromagnetic analysis with the elastic-plastic structural analysis is utilized to account for the effect of changing workpiece geometry on the transient body forces. Validation of the numerical model is performed through comparison between predicted and measured strain distributions within the formed parts.

Keywords: Electromagnetic; Forming; Aluminum; Coupled; Simulation; High-strain rate

1. Introduction

Aluminum alloy sheet is a candidate material for use in lightweight automotive closure panel and structural applications. The viability of aluminum in such applications is hindered by the fact that aluminum has lower formability than conventional drawing quality steel, for example. High-rate forming processes, such as electromagnetic (EM) forming, can promote significant increases in strain to failure in low-ductility materials due to strain rate and inertial stabilization of material failure modes [1,2]. Such processes are of interest to the automotive body manufacturing community as a potential method to overcome inherent formability limitations in aluminum alloy sheet.

Electromagnetic forming refers to the high-velocity and high-strain rate deformation of a material driven by electromagnetic forces that are generated by the rapid discharge of electrical current through a nearby conductor. The time-varying currents pass through the inductor (coil) and generate a transient magnetic field. This magnetic field generates eddy currents in the workpiece which generates its own opposing transient magnetic field. The interaction of these two magnetic fields will create large repulsive electromagnetic forces that accelerate the workpiece to high velocities.

Boulger and Wagner [3] first described the industrial use of electromagnetic forming in 1960. Six years later, Lammeraner and Stafl [4] applied analytical methods, based on the magnetic vector potential, to develop specialized mono-

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graphs of eddy currents which play a significant role in the force distribution on the workpiece.

EM forming of axisymmetric parts continued to be developed throughout the 1970s and into the late 1980s with few publications during this period. One of the few published works during this time was by Gourdin [5], who analyzed and assessed EM ring expansion as a viable high-strain rate material test. With some assumptions, Gourdin developed simplified equations that could be integrated using numerical techniques [5]. Gourdin concluded that for materials with high conductivity, the maximum useful strain rate is limited by Joule heating of the specimen and that the contribution of adiabatic plastic work to the overall temperature rise is small in comparison [5].

Balanethiram et al. [6,7] and Daehn et al. [8] outlined three different mechanisms that may account for increased formability: (i) the material constitutive behaviour changes at high-strain rates, leading to an increase in the rate of strain hardening and/or rate sensitivity; (ii) it may be possible that inertial effects promote more diffuse neck development, hence leading to higher ductility; and (iii) the impact with the die wall at high velocity causes the material to plastically spread radially in a process that may be thought of as “inertial ironing”. Imbert et al. [9] examined the effect of tool/sheet interaction on damage evolution in EM forming through free-form and conical die experiments using 1 mm AA5754 sheet. In that study, they utilized a damage-based material model to demonstrate that the tool/sheet interaction had a significant effect in suppressing necking and damage evolution.

Furth and Waniek [10,11] made one of the earliest attempts to develop an analytical method by which EM forming may be investigated through establishing basic equations that describe the physical phenomena. An approximate solution to the equations governing the process was proposed by Baines et al. [12], who treated the coil and workpiece as a transformer mutually coupled to a short circuit. An improved approach was suggested by Al-Hassani et al. [13–15] and Belyy et al. [16], who combined the coil and workpiece into a single equivalent circuit.

During the early 1970s, Al-Hassani [17], attempted to theoretically determine the magnetic-field intensity and the magnetic-pressure distribution on a flat super-conducting plate due to a number of conductors. Until this point, most analytical treatments of EM-forming problems assumed that the pressure distribution on the workpiece was uniform. The equations reveal that for a perfect conductor, the magnetic field does not penetrate through the plate and is confined to the top surface while purely tangential to it.

Takatsu et al. [18] continued from the work of Gourdin et al. [5,19] and included magnetic diffusion effects to obtain an even more precise model of EM forming. One of the earliest finite-element models of EM forming, which took into account the effect of changing workpiece geometry in a tube-forming process, was developed by Lee and Lee [20]. A two-dimensional, uncoupled electromagnetic finite-element code was used to determine the magnetic-pressure distribution acting on the tube.

Work by Fenton and Daehn [21,22] demonstrated that a two-dimensional Arbitrary Lagrangian Eularian (ALE) finite difference code can accurately predict the dynamics of the EM-forming process. Bendjima [23] considered force due to motion of the workpiece utilizing two-dimensional finite-element techniques to model the transient phenomena in EM-forming systems.

The objective of the current research is to develop a basis from which the EM-forming process and material response may be better understood and quantified. The role of “hyperplasticity” in sheet-metal applications through the acquisition of basic material formability data and the dynamics of the high-velocity impact of the sheet and die are also assessed. The “loosely” coupled, three-dimensional finite-element modeling capability developed in this work is used to model free-form, flat insert and dome insert cavity fill experiments, which are driven by an EM coil.

2. EM-forming experiments

2.1. EM-forming tooling

Cavity fill experiments are conducted by forming aluminum alloy sheet into a rectangular die that allows the geometry of the bottom of the cavity to be reconfigured using two inserts, as depicted in Fig. 1. For the free-form experiments (Fig. 1a), the inserts were removed so that the dome did not contact the bottom of the die. A flat insert (Fig. 1b) was used in so-called “flat insert cavity fill” experiments, while a dome insert (Fig. 1c) was utilized in the “dome insert cavity fill” experiments. For both inserts, the depth of the die cavity can be adjusted using spacers, while the two insert types promote different stain distributions. The dome insert has a hemispherical protrusion of 25.4 mm radius at the center. The die cavity is 121.9 mm by 101.6 mm, with a die-entry radius of 7.75 mm and die corner radii of 12.7 mm. The die cavity is surrounded by a rectangular lock-bead (not shown in Fig. 1) such that when the casing holding the coil is pressed against the workpiece, the material is clamped along its edges. The die–workpiece–coil assembly was placed in a hydraulic press, which applied a clamping load of 130 kN.

A flat double spiral coil (Fig. 2) was adopted that relocates the “dead spot” (region of low magnetic pressure) that occurs at the center of the winding of a single spiral coil. With this double spiral coil, the dead spots are located away from the center of the workpiece and just outside of the die-entry radius, resulting in a more evenly distributed pressure on the workpiece [1]. The coil is wound from copper wire with a square cross-section of 5 mm. The distance between the windings is 2 mm. The profile of the coil is machined into a reinforcing and insulating block of G10-Garolite, which is covered by a thin layer of epoxy. The insulated coil is placed