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A coupled electric–magnetic numerical procedure for determining the electromagnetic force from the interaction of thin metal sheets and spiral coils in the electromagnetic forming process

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ABSTRACT

In this paper, a numerical procedure is proposed that is both coupled electromagnetic and uncoupled magnetic-mechanical, and enables the calculation of electromagnetic force in thin circular flat plates by using a spiral coil as an actuator. Its inductances, which link the electric and magnetic phenomena, can be calculated by treating the problem as an electric circuit. The influence of system parameters, such as pulse energy, workpiece and coil geometry and material properties, are considered in the calculation of electromagnetic force. The calculation routine models the problem as a system of ordinary differential equations to obtain the discharge (actuator coil) and induced (workpiece) currents. Free bulging experiments with discharge current acquisition were performed to demonstrate satisfactory correlation with the calculation method, which provides valuable feedback for system design.

1. Introduction

An electromagnetic forming (EMF) system is essentially a mutual induction system composed of an actuator coil and a conductive workpiece [1]. In other words, an EMF system is a discharge circuit that consists of a pulse unit, connecting lines, a discharge device (switch) and an actuator coil coupled to the metallic part to be deformed. A model of the system is shown schematically in Fig. 1.

This process is based on a repulsive force generated by opposing magnetic fields in adjacent conductors [2]. Although several studies were derived from this premise, the majority of studies involve the deformation of tubular parts by solenoid coils. Few studies have analyzed the sheet metal forming caused by flat spiral coils [3,1,4–6]. The main reason for this limitation is that the EMF of flat plates usually involve larger areas than in tube forming applications, thus requiring considerably higher pulse energies [7].

Electromagnetic forming is a high-speed process that only requires a few hundred microseconds to deform the workpiece [8]; some authors advocate that this may improve the formability of strain-rate-dependent materials. Furthermore, the EMF

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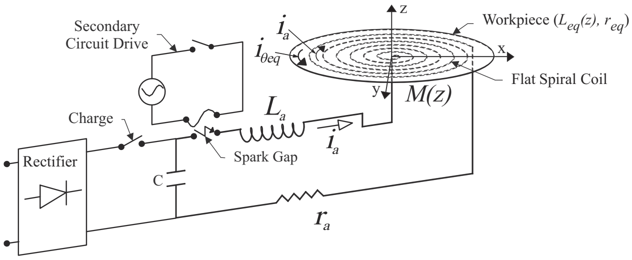

Fig. 1. Schematic of the electromagnetic forming system.

controllability is superior to other high-speed forming processes. The process currently employs aluminum or copper alloys, but this technology has also been applied to magnesium alloys, which have low density and high mechanical strength but demonstrate low formability at moderate strain rates [9]. The mechanical and electromagnetic phenomena of the process are strongly interrelated because the movement/deformation of the sheet metal affects the inductances (self and mutual), magnetic field and, consequently, the resulting Lorentz forces. An approximate but more feasible approach is to treat the process as a weakly coupled problem by disregarding the influence of workpiece movement on the magnetic field, and then applying the forces generated by the electromagnetic field to the mechanical problem [4]. This assumption remains valid if the electromagnetic force occurs within a short time interval compared with the total deformation time, and if the effect of the sheet metal displacement is less significant than other EMF conditions, such as tube compression and expansion. Most of the sheet deformation is caused by inertia forces from the pulse of electromagnetic force [6]. Examples of a coupled model for analyzing the EMF process of flat plates can be found in the work of [8,10]. By employing the finite element method (FEM), the mechanical force of electromagnetic sources is calculated initially and then applied to the plate to verify the mechanical deformation.

The analysis and modeling of EMF processes requires prior knowledge of interdisciplinary areas, including electromagnetism, dynamics of deformable bodies, viscoplasticity of materials, and advanced numerical methods, to address highly nonlinear coupled problems. This requirement inhibits a simple explanation of the process and prevents the implementation and development of this technology in industrial and academic environments. Analysis of the EMF process is a very complex task; it has been the subject of recent studies because it can offer insight into a branch of potentially original applications where conventional forming methods typically fail. A method of analysis for EMF should provide a concise understanding of the physics involved in the process by applying relevant data to the design of devices such as actuator coils, dies, and capacitors, as well as by identifying parameters and their influence on the process. A comprehensive review about this subject is presented in [11].

The main objective of this paper is to propose a methodology for analysis of an EMF system configured with a flat spiral coil as the actuator, in contrast with others already presented [1,4,6]. In the presented method the mutual and self-inductances of the system are numerically computed and such inductances are responsible for the electromagnetic coupling. Therefore, the discharge (actuator coil) and induced (workpiece) currents are numerical predicted by solving a coupled system of ordinary differential equations. This is the main difference when comparing this procedure with others in literature, especially in EMF predictions as for instance in [3,1,4–6], that need to inform the discharge function, what is or hypothetical or measured in an experimental manner, to posteriorly calculate the electromagnetic force. Particularly, the theoretical contribution for the determination of the magnetic field intensity and pressure distribution on a flat workpiece made by Al-Hassani [3] is valid for densely winded flat coils and when a small gap between the coil and the workpiece exists.

In a more detailed way, the proposed numerical procedure discretizes the workpiece in an electric circuit by calculating the inductances with the Biot–Savart law, which couples the electric and magnetic phenomena. The influence of system parameters, such as pulse energy, workpiece and coil geometry and material properties, are considered in the calculation of electromagnetic force. This method solves the problem by considering both the coil and the workpiece as rigid materials, approximating the flat spiral coil in circular coplanar concentric conductors and approximating the sheet metal by discrete elementary segments of circular coplanar concentric conductors. This discretization leads to a system of second-order ordinary differential equations (ODE) that couple the electric and magnetic phenomena. As a result, the discharge and induced currents are dependent on circuit parameters. This method serves as a basis for the design and selection of several components of the EMF system. Another special feature of the proposed model is the potential for changing the process parameters and easily identifying its influence on electromagnetic force.

2. Description of the electrical circuit and its numerical discretization

2.1. Electrical circuit

Applying *Kirchhoff*'s law we obtain the Eq. (1) and (2), which describes the electric primary and secondary circuits of the EMF system in Fig. 1,