Journal of Materials Processing Technology 215 (2015) 251–263

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Analytical design and experimental validation of uniform pressure actuator for electromagnetic forming and welding

Ethan Thibaudeau, Brad L. Kinsey*

University of New Hampshire, Department of Mechanical Engineering, Durham, NH, USA

ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form 15 August 2014
Accepted 21 August 2014
Available online 1 September 2014

Keywords:
Electromagnetic forming
Analytical model
Velocity measurements

ABSTRACT

In this paper, an analytical model is used to design a coil, called a Uniform Pressure Actuator (UPA), for use during electromagnetic forming (EMF) and magnetic pulsed welding (MPW) by combining and extending past efforts by other researchers. The UPA offers increased forming efficiency and repeatability, as well as a robust design. Magnetic pressure applied to the workpiece and workpiece velocity are predicted to ensure impact conditions are sufficient for MPW. The UPA is constructed and tested experimentally to validate the accuracy of the analytical model, as well as verify assumptions made during modeling. The coupling coefficient introduced in the magnetic analysis is experimentally determined and compared to previous researchers' values. Workpiece velocities for various energy levels, workpiece thicknesses, and materials with various conductivities and densities are compared to analytical predictions and show good agreement for the initial acceleration in the process. Workpiece velocity measurements were obtained using a Photon Doppler Velocimetry (PDV) system, which provides a robust method for measuring velocities with submicron displacement and temporal resolution in the nanosecond range. Uniformity of the workpiece deformation is also examined, which is an advantage of the UPA.

1. Introduction

Lightweight sheet metal components and assemblies formed and joined electromagnetically are of interest in various industries such as automotive, aerospace, and electronics. In electromagnetic forming (EMF) and magnetic pulsed welding (MPW), a capacitor bank is discharged into a coil which creates a magnetic field in close proximity to the workpiece. Eddy currents are induced in the workpiece, which create an opposing magnetic field and a repulsive Lorentz force. The workpiece to accelerate away from the coil and plastically deforms at high velocity rates, typically on the order of 100–300 m/s. Benefits of EMF include higher strains prior to failure, more uniform strain distributions, reductions in wrinkling, active control of springback, and the possibility of local coining and embossing (Psyk et al., 2011).

If a second, stationary workpiece is impacted at a critical velocity and angle, large pressures are achieved, and a solid state weld is produced at the interface (i.e., a MPW process). Joining can be achieved even between base metals of vastly different material properties, and bond strength can be stronger than the parent components (Zhang et al., 2011). This allows joined components in an assembly to be tailored to a specific function according to material properties, and assembly weight is reduced from removing fasteners.

Typical control parameters of the EMF and MPW processes include the charge energy of the capacitor bank, the coil geometry, the standoff distance between the workpiece, coil, and die, etc. Typical measurements of the processes include primary current in the coil and induced current, velocity and displacement of the workpiece.

Fig. 1 shows a schematic of the MPW process (Blakely, 2008).

Past applications and modeling of EMF and MPW have typically focused on crimping and expansion of tubular workpieces. However, for lightweight automotive applications, forming and welding of flat sheets are of interest. Development of work coils and process analysis for sheet forming has been limited due to its complexity (Psyk et al., 2011). According to Daehn, this is caused by a gap between experts in sheet metal forming and pulsed power applications (Daehn, 2006). While some finite element analysis (FEA) packages exist that are capable of modeling these processes, there is a lack of simplified analytical modeling efforts, especially for sheet metal workpieces. Analytical modeling is attractive for its simplicity and cost in effectively determining e.g., an optimal coil design and workpiece velocities. Such modeling acts to bridge this gap and promote electromagnetic applications in manufacturing.

---

* Corresponding author. Tel.: +1 603 862 1811; fax: +1 603 862 1865.
E-mail address: bkinsey@unh.edu (B.L. Kinsey).

http://dx.doi.org/10.1016/j.jmatprotec.2014.08.019

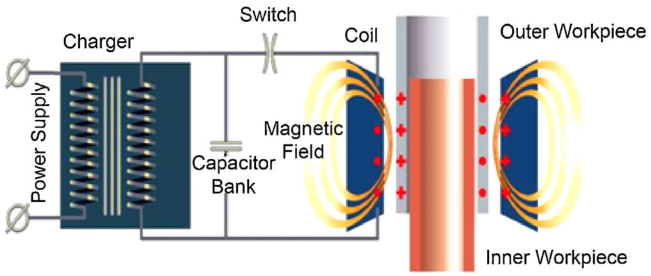

Fig. 1. Diagram of magnetic pulse welding (Blakely, 2008).

In past research, forming and welding of flat sheet workpieces was achieved with a few different coil designs. Flat spiral coils have been implemented, where a wire is wound in a flat spiral configuration on a plane parallel to the workpiece. However, this type of coil typically fails after a small number of forming operations (VanBenthysen et al., 2013). Additionally, the pressure distribution across the workpiece is non-uniform with the peak pressure at half of the coil planar radius which leads to ripples in the workpiece deformation (Psyk et al., 2011).

Single or half turn coils have also been used for welding sheets, but the pressure distribution is localized in a small region (Watanabe and Kumai, 2009). Kamal and Daehn (2007) developed a coil design, i.e., a Uniform Pressure Actuator (UPA), which has a more uniform pressure distribution over a larger area and is robust enough to last hundreds of forming operations. The design consists of a helical coil with a rectangular cross-section. A surrounding conductive channel allows induced eddy currents in the sheet to form a closed circuit around the coil. A cross-section schematic of this assembly is shown in Fig. 2 (Kamal and Daehn, 2007).

The return path integrated into the coil design has multiple advantages. Since eddy currents generated in the workpiece flow in a closed circuit, edge effects of the sheet are eliminated as eddy currents flow throughout the workpiece. Also, additional eddy currents are generated from the coil and return path, which create a higher magnetic pressure. By including the return path, the magnetic field generated around the entire coil is utilized in the forming process increasing the process efficiency (Kamal and Daehn, 2007). Finally, replusive forces generated between the helical coil and return path help to resist the radial forces generated by the coil on itself, thus increasing the strength of the actuator.

In this paper, the design analysis for a UPA was achieved by combining past research, (Kamal and Daehn (2007) for coil design and Al-Hassani (1975) for magnetic pressure calculations) and extending the analytical model in order to calculate the magnetic pressure and workpiece velocity and thus optimizing these parameters. The pressure distribution over the workpiece and a rigid body motion assumption were investigated. Also, finite element (FE) analysis was used to access the robustness of the coil design. Finally, the coil was constructed and implemented in a free forming process. The results show that velocities are accurately predicted for the initial acceleration for various materials and sheet thicknesses provided that the thickness to skin depth ratio is sufficient. This ratio was found to be lower than specified in past research efforts to achieve effective magnetic coupling between the coil and workpiece. Also, the magnetic coupling coefficient was shown to be dependent on the geometry of the coil and workpiece and independent of the workpiece thickness and material properties.

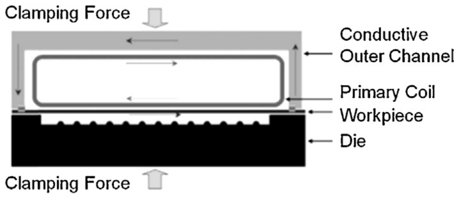

Fig. 2. Cross-section of the uniform pressure actuator (Kamal and Daehn, 2007).

2. Uniform pressure actuator

Prof. Glenn Daehn's group from The Ohio State University developed multiple generations of UPA as shown in Fig. 3. Initially, their construction consisted of soft copper windings around an insulating mandrel. Further generations moved to a stronger design, with a thicker coil cross-section, machined out of a solid block of high strength copper alloy. The coils were then potted in urethane for electrical insulation.

Kamal (2005) presented an EMF coil design methodology comprised of an analytical model and FE magnetic modeling in Maxwell 2D. The deformation of the workpiece was solved separately in LS-DYNA. The analytical model predicted rigid body workpiece acceleration and is attractive for its simplicity and cost in effectively determining an optimal coil design.

A large coil turn count results in a stronger magnetic field, and thus higher magnetic pressure. However, a small turn count allows for a shorter rise time to peak current (Kamal, 2005). Therefore, it is important to specify whether the coil design is to create maximum pressure or maximum sheet velocity. Forming shallow features or embossing requires larger magnetic pressures, whereas deep features with large deformations require higher velocities to create large inertial effects and high impact pressures (Kamal and Daehn, 2007).

For the model presented here, the research by Kamal (2005) and Al-Hassani (1975) is combined and extended. The goal is to determine, for a given sheet geometry, a coil geometry that maximizes pressure or sheet velocity, while maintaining structural integrity and uniform pressure on the workpiece.

Compared to Kamal and Daehn (2007), an alternative design process is conducted that consists of an analytical model and a FEA structural analysis. Analytical electromagnetic solutions from Al-Hassani (1975) are implemented to determine the pressure distribution on the workpiece. The analytical model is then used to evaluate the electromagnetic coupling coefficient for various materials and thicknesses. Lastly, the modeling effort is verified experimentally by measuring workpiece velocity for various energy levels, workpiece thickness, and materials.

The analytical model calculates the initial workpiece acceleration of the EMF/MPW process. The magnetic pressure distribution on the workpiece and rigid body workpiece acceleration are solved for a given UPA geometry, workpiece length, and coil turn count. A FE mechanical analysis determines if the resultant geometry is strong enough to withstand the predicted magnetic pressure. If the mechanical simulation shows material failure, the analytical model is used to modify the geometry. For a given workpiece length, a larger conductor cross-section, and thus lower turn count, produces a more robust coil.

3. Analytical model

The analytical model used in this research can be divided into stages based on the type of physical interactions involved. First, electrical theory is used to determine the current out of the EMF machine and through the coil. Second, magnetic calculations determine the magnetic field distribution and magnetic pressure developed. Lastly, classical mechanics theory is used to find rigid body motion of the workpiece caused by the magnetic pressure.