Design, Construction, and Applications of the Uniform Pressure Electromagnetic Actuator*

M. Kamal[1], V. Cheng[2], J. Bradley[3], S. Hatkevich[4], G. S. Daehn[1]*

[1] Department of Mat. Sci. and Eng., The Ohio State University, Columbus, OH, USA
[2] Metals Industry Research and Development Center, Kaoshung, Taiwan
[3] General Motors R&D, Detroit, Michigan, USA
[4] American Trim Corporation, Lima, OH, USA
*Corresponding Author: Daehn.1@osu.edu, 614-292-6779

Abstract

High velocity forming can lead to better formability along with additional benefits. The spatial distribution of forming pressure in electromagnetic forming can be controlled by the configuration of the actuator. A new type of actuator is discussed which gives a uniform pressure distribution in forming. It also provides a mechanically robust design and has a high efficiency for flat sheet forming. Key quantitative concepts are presented that help in the design of the system. Examples of uses of the actuator are then presented, specifically with regard to forming shapes and surface embossing. This paper emphasizes the approaches and engineering calculations required to effectively use this actuator.

Keywords:

Sheet metal forming, High velocity forming

1 Introduction

Electromagnetic forming (EMF) is a non-contact forming technique where large forces can be imparted to a conductive metallic workpiece by pure electromagnetic interaction [1]. When properly applied, this can accelerate the sheet to velocities on the order of 200 m/s over a distance of a few millimeters. This high velocity forming can be quite beneficial. It can provide: improved formability, improved strain distribution, reduction in wrinkling, active control of springback, and the possibility of local coining and embossing [1, 2].

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* *This work is largely based on the Ph.D. Thesis of Manish Kamal. It can be accessed at http://www.ohiolink.edu/etd/view.cgi?osu1127230699.*

If one is to use conventional electromagnetic forming actuators to form directly, it is important that the EM pressure distribution is appropriate for the part that one would wish to form. It has been found that the velocity distribution within the sheet metal during forming significantly influences the result [3]. Risch et al. [3] have shown that puckers can form when the launch velocity is not uniform.

The spatial distribution of forming pressure can be controlled by the configuration of the actuator [4-6]. Traditionally, EM actuators have been used to form axisymmetric parts as in tube expansion and compression. Sheets have been formed with flat spirals. One issue with spiral actuators of any configuration is that the pressure distribution is not uniform. Figure 1 shows the typical example where a flat spiral actuator was used to accelerate a circular disk. Here, the magnetic pressure is zero at the center of the part and the edges and reaches a maximum midway between them.

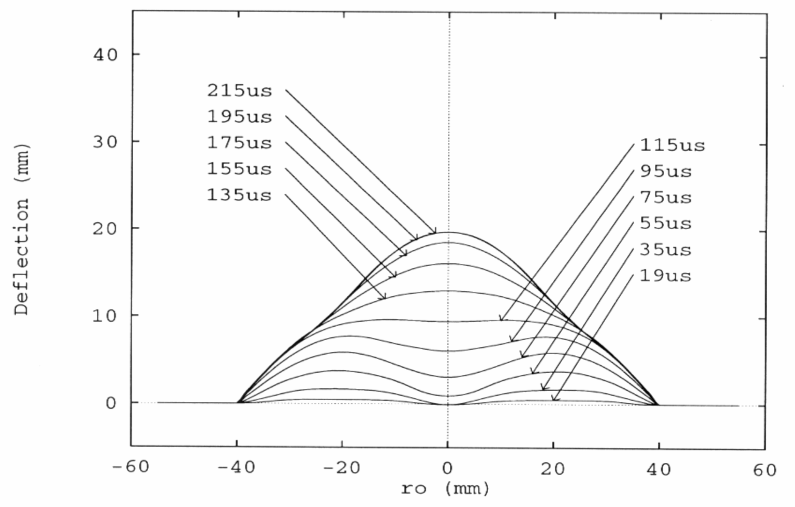

***Figure 1**: CALE calculated displacement profiles of Takatsu disk [7] during deformation with a flat spiral actuator [8]. The sheet is secured at its circumference.*

The early literature (from the first wave of electromagnetic forming research) seems to have only one reference to a non-axisymmetric actuator [6]. It consists of an elongated actuator and that work also discusses the non-uniform pressure distribution developed. Work on actuators for flat forming of sheet has been limited and it appears that an actuator that gives a uniform pressure distribution has not been available until now.

Uniform pressures can be developed if the current in the actuator and sheet are both uniform and the gap between them is roughly constant. It can be achieved in two ways: (i) a section along one perimeter of a flat spiral actuator (which might be elongated). Although the pressure varies along the radius of the coil, if one takes a small section, the pressure distribution at that section is close to uniform. An appropriate eddy current distribution must be considered if this approach is to have useful efficiency. (ii) By using a linear actuator, like taking a section in a three bar coil. Along any particular bar the pressure is close to being uniform so long as the sheet to coil gap is small relative to the bar width. The efficiency of this single-turn approach may be poor, however.

Process efficiency is of paramount importance. The cost of electrical energy in EMF is rather trivial, but if one is to use especially large energies or charging voltages, these cause problems with electrical interconnects and insulation, this puts large mechanical forces on the actuators that can damage the electromagnetic actuators. The approaches mentioned above can create a uniform pressure distribution, but the efficiency of such systems is poor.

This paper presents a new approach, which offers a uniform pressure distribution as well as high efficiency for flat sheet forming.

2 Experimental procedure

Figure 2 shows a schematic of a section through the uniform pressure actuator. When the capacitor bank is discharged the primary current flows through the primary coil. The primary coil is well insulated from the outer conductive channel. The outer channel and the sheet metal form a closed circuit and the induced current flows through it. Repulsive Lorentz forces develop between the opposed primary and induced currents, causing sheet metal to be thrown at the die with potentially high velocity. Since the induced current path completely encircles the actuator there is little loss of the magnetic flux energy and hence better efficiency. Also, since the primary coil repels from both the sheet and channel it is forced onto a mandrel and this can provide a robust actuator design.

Three different actuators were used in this study. The first (Actuator 1) was based on winding 15 turns of copper magnet wire with a 9.0 mm^2 round cross section over a machined G-10 laminated phenolic composite block. The wound core was then placed inside an aluminum channel (7.5 x 2.5 x 9.375 cm and 0.3125 cm thick), which has Kapton® insulation on its interior. Urethane potting was then used to provide insulation and structural support. The actuator with the metal sheet is then clamped using an arrangement of eight nuts and bolts with a typical total clamping force of 80 kN. Actuator 2 was similar in construction, except it used 23 turns or rectangular copper wire (11.5 mm^2 cross section), presented a larger active area (15 x 15 cm), and used a machined, contoured aluminium return path. The third generation actuator (Actuator 3) featured an 11 turn primary coil machined from copper with a much larger cross section. It presents pressure over an area of (5 x 8 cm).

All actuators were driven using a commercial Maxwell-Magneform capacitor bank. The bank has a maximum stored energy of 16 kJ. The energy is stored in 8 capacitors, each with a capacitance of 53.25 µF. The system has a maximum working voltage of 8.66 kV. Both the number of capacitors and charging voltage are changed to control the discharged energy and voltage. Primary and induced currents are measured by active Rogowski flexible coils from Rocoil [8].

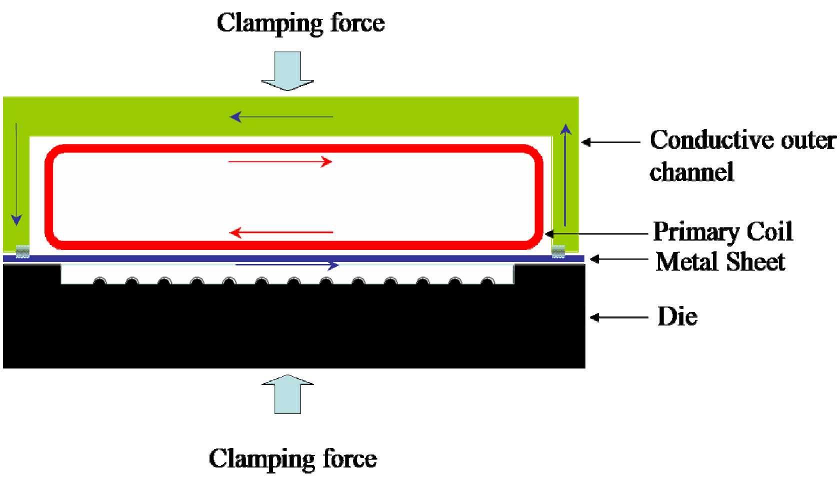

Figure 2: *Schematic of a uniform pressure coil. The primary coil has many turns going into the depth of the paper*

3 Key design concepts

In essence, the coil shown in Figure 2 acts as a simple LRC circuit. The variation in primary current with time is easily described in this manner. The most difficult part of a design calculation is determining the inductance of the actuator-workpiece system. Simple upper and lower bounds can be easily calculated based on assuming the inductance of an unshielded solenoid for the upper bound, and assuming the magnetic flux is completely contained in the volume between the outside of the coil and inside of the return channel and workpiece. These can be represented as:

$$L_s^{low} = \frac{\mu_0 A_s n^2}{l_s} \qquad \text{(Low frequency upper bound)} \qquad (1)$$

$$L_s^{high} = \frac{\mu_0 A_{gap} n^2}{l_s} \qquad \text{(High frequency lower bound)} \qquad (2)$$

Here, L represents inductance, n is number of coil turns, l is length A_s represents that area inside the solenoid and A_{gap} represents the area between the coil and return path. These equations are shown along with experimental data in Figure 3. Based on this, usual procedures can be used to estimate peak currents, rise times, and so forth. The pressure that acts on the workpiece can be calculated as:

$$P_m = \frac{\mu_o H_p H_i}{2} \qquad (3)$$

Here, P_m is magnetic pressure, and H_p and H_i respectively represent the current densities expressed in current per length (width) in the primary and induced circuits respectively. Relative to metal yield strengths, the generated pressures generated in electromagnetic forming are generally small. It is the impact with the die that generally generates the high pressure that can produce deep embosses and other phenomena that require high pressure.

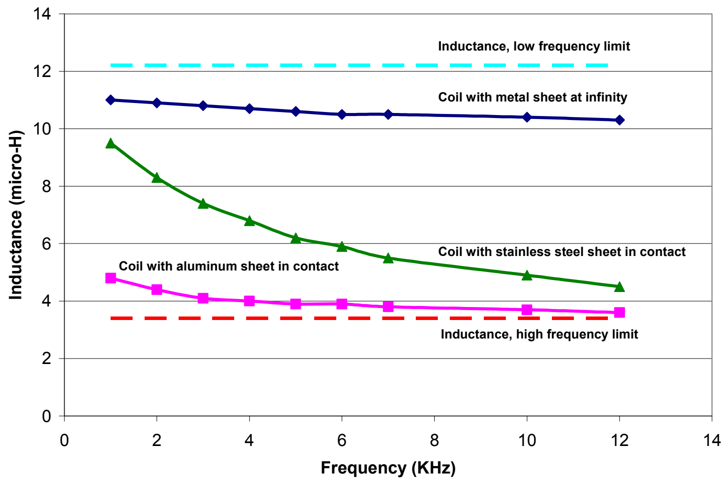

Figure 3: *Variation of actuator inductance with frequency, measured with LCR Bridge (Actuator 2)*

The pressure can accelerate a thin metal sheet towards a die in accord with Newton's first law. Because the pressures are substantial and the sheets are thin, over the space of just a few milimeters, the workpiece can be accelerated to significant velocities. This is demonstrated in Figure 4, which shows the predicted velocities of two aluminum sheets (both roughly 1mm in thickness) accelerated by two different coils. Very significant velocities can be reached using less than 2mm space for acceleration and only modest stored electrical energies are needed for launch.

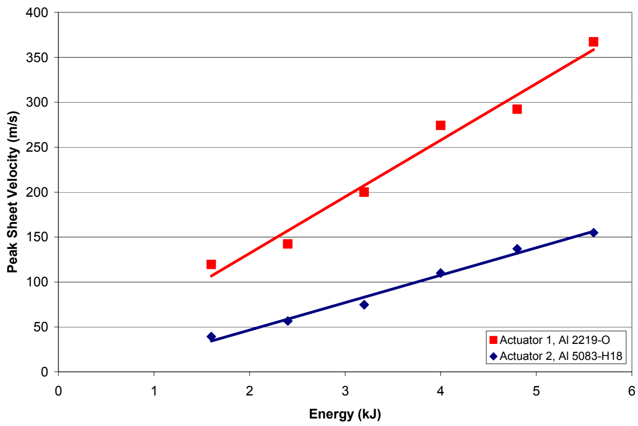

Figure 4: *Predicted variation of peak sheet velocity with energy with actuators 1 and 2. Key assumptions are that plastic work is not done on acceleration and the sheet is only accelerated over the first quarter*-cycle*. The 2219 and 5083 sheets have thicknesses of 0.8 and 1.1 mm, respectively*

4 Example operations with the UP actuator

The Uniform Pressure (UP) actuator provides capabilities that have not been available in a manufacturing tool. In short, it allows one to accelerate sheet metal to high velocities very uniformly and robustly and in a manner that is extremely repeatable. The closest competitor to this is the flat spiral coil that has been used in electromagnetic forming. This coil has a well-known spatial distribution of pressure that is problematic in that the pressure vanishes in the center. Also, these coils can not survive long life service at high pressures. Plum quotes as this coil being able to only sustain 35 MPa [9], which is much less than more traditional tube compression coils can sustain (up to 340 MPa [9]). The UP actuator has repeatedly robustly produced pressures exceeding 100 MPa. In addition, the pressure distribution is uniform over the area of the sheet and the UP actuator uses the electrical energy from the capacitor bank in a more efficient way.

Figure 5 shows some examples of the kinds of operations that can be performed with the UP actuator. In addition, the actuator is well suited for complex punchless shearing operations. This shows that the coil can be used for large-scale forming operations, such as cell phone cases. Lastly, areas that require modest forming over large areas, like fuel cell bipolar plates, can be formed. There are two very important practical implications to this. First, because pressure is spatially uniform the same energy will appropriately shear or form ridges on the workpiece, regardless of location. Second, all these operations are done where only one side of the workpiece makes contact with any tool and the only moving part is the sheet itself. This has obvious advantages if one would like to shear or blank complicated shapes. Further, it means that coated or decorated materials can be formed without any contact on one side of the sheet.

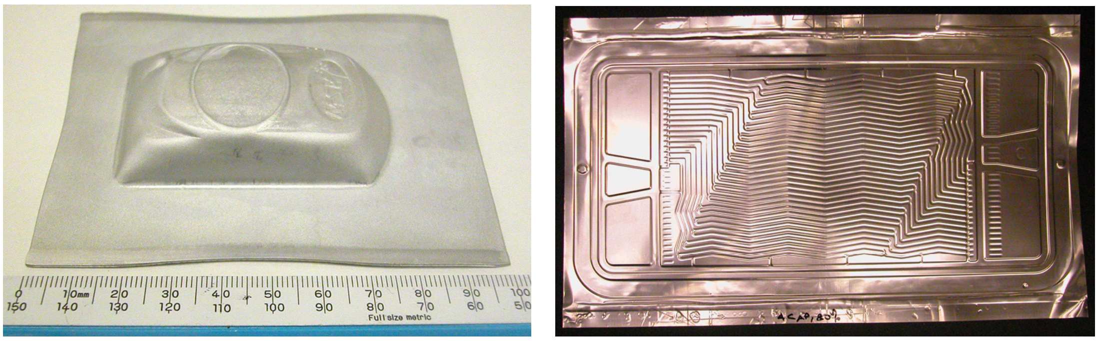

Figure 5: *Examples of operations formed with the UP actuator at Ohio State. From left: an example of forming into an aggressive cellphone die. This example used 0.8mm thick 2219-0 and two shots were used to aid shape forming. Right shows a prototype fuel cell bipolar plate (22.5 cm x 35 cm) that was formed from 0.13mm thick 301 stainless steel. This plate was formed in three vertical sections using a 0.13mm thick copper driver and 19 kJ per forming operation*

There is voluminous literature on the impact of solids and the effects of this in terms of both wave propagation and microstructure changes. Much of this literature is concerned with ballistic events that have velocities of 750 m/s and beyond. At or beyond these impact velocities materials suffer severe plastic deformation, spalling, and/or other forms of damage upon impact and this work is often concerned with penetration mechanics. At lower velocities the impact may be fully elastic, using linear elasticity; The impact pressure, P_i, that is developed when two semi-infinite elastic bodies labeled 1 and 2 collide at an impact velocity V_i is given as:

$$P_i = \frac{\rho_1 \rho_2 C_1 C_2}{\rho_1 C_1 + \rho_2 C_2} V_i \qquad (4)$$

Here, for each material, 1 and 2, ρ represents density and C is the longitudinal wave speed. Longitudinal wave speeds are on the order of 7,000 m/s for most structural metals. For aluminum-steel and steel-steel impact pressures of about 2 GPa and 5.6 GPa are generated for a 200 m/s impact. Higher pressures are available by modifying the strike material or by increasing the impact velocity. Also, at these pressures there are significant deviations from linear elastic behavior. The required equations of state are well known (Example, these are included in the libraries for impact codes such as AUTODYN) and these deviations cause higher pressures than estimated from the elastic equation and for planar impact events the shock wave is not dissipated terribly rapidly by plastic deformation.

This impact pressure can be useful in several aspects of surface engineering. First, pressures high enough to produce significant microstructural changes, such as those produced by techniques as e.g. laser-shock-peening. Second, as shown by Prandtl's 1920 analysis of the hardness test, if a deformable material is pressed over a rigid surface with a pressure that is some factor (about 3 times) greater than the flow stress of the deformable material it will flow and conform to the surface of the rigid material. This is the basic theory behind hardness testing. The pressures generated by Equation 4, thus, can exceed he flow stress of common engineering metals by many times. So, if features are significantly thinner than material thickness simple impact can be used to reproduce them. Figure 6 shows an example of this. Here, aluminum sheets are impact embossed into a decorative optical diffraction grating made from electroless nickel (much harder than aluminium or copper). Optically, the grating pattern is transferred to the metal sheet and SEM shows that there is very good reproduction of the submicron features. This manner of surface reproduction may be suitable for many problems in micro manufacturing.

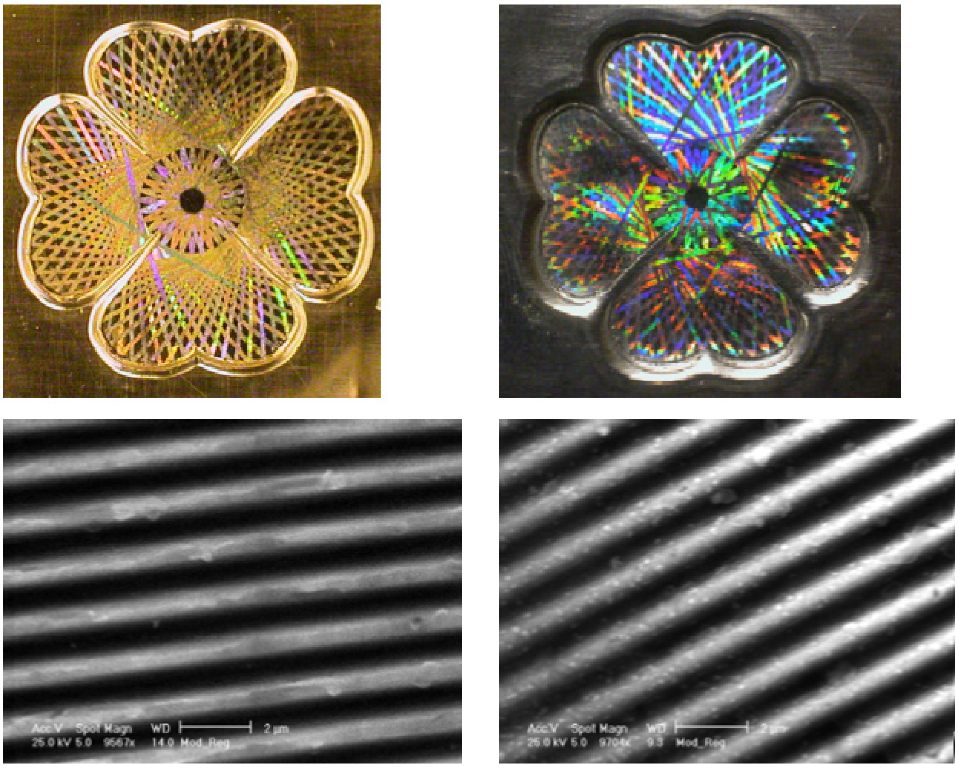

Figure 6: *Examples of embossing onto sheet from a coin with a holographic image (about 2.5 cm across) into 0.13 mm thick soft copper sheet (left) and 0.25mm thick 5052-H32 sheet. Both experiments had rough vacuum on both sides of the sheet and a standoff of 2.32 mm. The copper was formed at 2.4 kJ; the aluminum was formed at 4.0 kJ. SEM images compare the original holographic surface (electroformed nickel) and the pattern embossed in the copper (right). In both cases the entire area formed was about 100 x 75 mm*

5 Conclusions

A new type of electromagnetic actuator that can produce pressure relatively uniformly over sheet structures is presented. The actuator is mechanically robust and electrically efficient. It can develop sheet velocities in excess of 200 m/s over short acceleration distances. This can make it appropriate for many embossing and/or micro manufacturing applications.

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