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Electromagnetic flat sheet forming by spiral type actuator coil

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Abstract. Focus of present work is to develop a setup for high strain rate electromagnetic forming of thin aluminum sheets (0.5, 1.0, 1.5 and 2.0 mm) and optimization of forming parameters. Flat spiral coil of 99.9% pure Cu strip (2.5x8.0 mm) with self-inductance 11 μH, 13 no. of turns and resultant outer diameter of 130mm has been fabricated and was coupled to a capacitor bank of energy, voltage and capacitance of 9 kJ, 900 V and 22.8 mF, respectively. To optimize the coil design, a commercially available software FEMM-4.2 was used to simulate the electromagnetic field profile generated by the coils of different pitch but same number of turns. Results of electromagnetic field intensity proposed by simulation agree in close proximity with those of theoretical as well as experimental data. The calculation of electromagnetic force and magnetic couplings between the coil and metal sheet are made. Forming parameters were optimized for different sheet thicknesses. Electromagnetic field intensity's profile plays a principal role in forming of typical shapes and patterns in sheets.

1. Introduction

The commercial application of this process has existed since the 1960s. A recent interest in understanding the electromagnetic forming (EMF) of metals has been stimulated by the desire to use more aluminum in automobiles. The large majority of applications have involved either the expansion or compression of cylinders (tubes). Sheet materials with particular geometry are difficult to form as compared to flat sheets.

Electromagnetic forming (EMF) systems are based on the principle of mutual induction between actuator coil and a conductive workpiece [1]. In the EMF process, a transient electric pulse of high magnitude is sent through a specially designed forming coil using a low-inductance electric circuit. During the current pulse, the coil is surrounded by a strong transient magnetic field. The transient nature of the magnetic field induces current in a nearby conductive workpiece that flows opposite to the current in the coil. The coil and the workpiece act as parallel currents through two conductors to repel each other. The force of repulsion can be very high, equivalent to surface pressures of the order of tens of thousands of pounds per square inch. Thin metal sheets can be accelerated to high velocity in fractions of a millisecond [2-3]. High forming speed facilitates the formability of metals. Also, the dynamics of contact with the forming die can help mitigate springback, an undesired effect that cannot be avoided in other forming techniques such as stamping [4]. These benefits would result in increased use of aluminum in fuel-efficient (light weight) vehicles. Several studies have started from this premise; most of them involve specific situations like deformation of tubular parts by solenoid coils, while few studies have analyzed sheet metal forming by planar coils [5-8].

The objective of this work is to develop a setup for high strain rate electromagnetic forming of thin aluminum sheets and optimization of forming parameters. For this purpose, an in house EMF facility was developed and aluminum sheets were formed successfully.

2. Work descriptions

A system of electromagnetic forming has been developed for forming of thin circular metal sheets by using a flat spiral coil. Electromagnetic forming (EMF) systems consist of two major parts: a capacitor bank couple to an electromagnetic coil termed as 'actuator'. Workpiece placed above the flat actuator coil as shown in Figure1.The capacitor bank provides stored energy in the form of high current transient electric pulse, while during discharge through a low inductive reactance actuator coil.Transient magnetic field thus generated in the coil induces a reverse field in the workpiece. Interaction of these fields provides a magnetic pressure, which in turn forms the work piece.

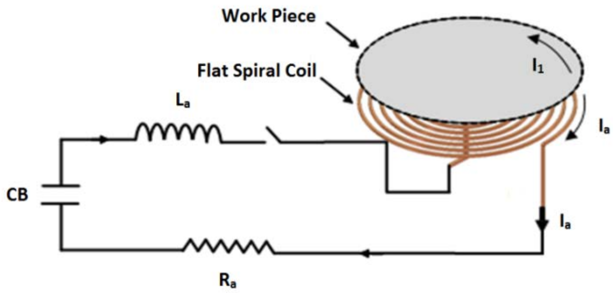

Figure 1. Schematic diagram of the electromagnetic forming system

An in-house developed capacitor bank of energy 9 kJ, voltage 900 V and capacitance 22.8 mF was used. The capacitor bank has provision to operate in the voltage range of 100 to 900 V and current limit exceeding 10 kA, for the mentioned coil. The cycle time of capacitor bank is 45 seconds.

The forming fixture is shown in Figure 2, while detailed characteristics of coil are given in Table 1. During EMF process, high-intensity electromagnetic force is applied to the coil. The coil, insulators and support structure must be capable of bearing this force, as well as thermal shock, within the elastic limit. Thus, actuator coil's design and material selection play vital role in system performance. Material selections are made by taking electrical resistance and mechanical properties into consideration. Moreover, for use in automotive industry, coil systems should be low-cost, modular, and have high durability (~100,000 cycles) [9]. Thus, the coil has been cycled several times at high current levels to confirm its durability.

Figure 2. Assembly photograph of the actuator coil and forming fixture

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Table 1. Description of parameters system used in the current study

Equipment	Parameter	Value
Actuator Coil of 99.9% pure Copper	Numbers of turns	13
	Outer diameter	140mm
	Inner diameter	45mm
	Pitch	3.15mm
	Section of the wire	2.5 x 8mm
	Self inductance (La)	11μH
Capacitors Bank	Capacitance	22.8mF
	Maximum voltage	900V
	Maximum energy	8.9kJ
Metal Sheet	Material	Aluminum
	Thickness analyzed	0.5, 0.8, 1.0, 1.2, 1.5, 2.0 mm
	Diameter of metal sheet	135mm
	Gap between actuator and metal sheet	3mm

The schematic model of the system is shown in Figure 1, which shows a circularmetal sheet placed on flat spiral coil connected to a charged capacitor. Electromagnetic forming system represented by Figure 1 is governed by a set of coupled differential equations. The transient electromagnetic problem can be separated in an RLC primary circuit coupled with secondary RL circuit [10-11]. The discharge of the capacitor in the primary circuit as:

$$\frac{d}{dt}(L_a \, . \, I_a + M \, . \, I_1) + R_a \, . \, I_a + V_C = 0 \qquad (1)$$

Where L_a, R_a and V_c are the self-inductance, resistance of actuator coil and charging voltage of capacitor bank. M is the mutual inductance between the actuator coil and work piece. I_a and I_1 are discharge current in actuator coil and the induced current in work piece, respectively. For secondary RL circuit the differential equation is:

$$\frac{d}{dt}(L_1 \, . \, I_1 + M \, . \, I_a) + R_1 \, . \, I_1 = 0 \qquad (2)$$

Where L_1 and R_1 are the self inductance and resistance of work piece.

FEMM 4.2 software was used for modeling of actuator coil and the magnetic field generated while discharge through capacitor bank. It works on the principle of Biot-Savart law and Maxwell's equation. Magnetic field produced by the coil was thus simulated as shown in Figure 3 and the results have been verified experimentally using gauss meter with accuracy of more than 95 %.

3. Results and discussions

Flat spiral coil has been used for thin metals sheet forming. For this purpose, design of actuator coil was first optimized using FEMM-4.2 software. Coils with approximately same outer diameter, same no of turn but with different pitch, cross sectional area have been designed and magnetic field thus produced was modeled as shown in Figure 3a. Simulation results show that the coil with pitch 3.15 mm (bottom coil (d)) produced a uniform field (3.2 T $\pm$ 0.1) throughout the winding area as shown in Figure 3b. The other three coils i.e. a, b, c have different pitch and less Lorentz force value given in Table 2. Although the coil a has greater value of magnetic field than the coil d, but it has lesser

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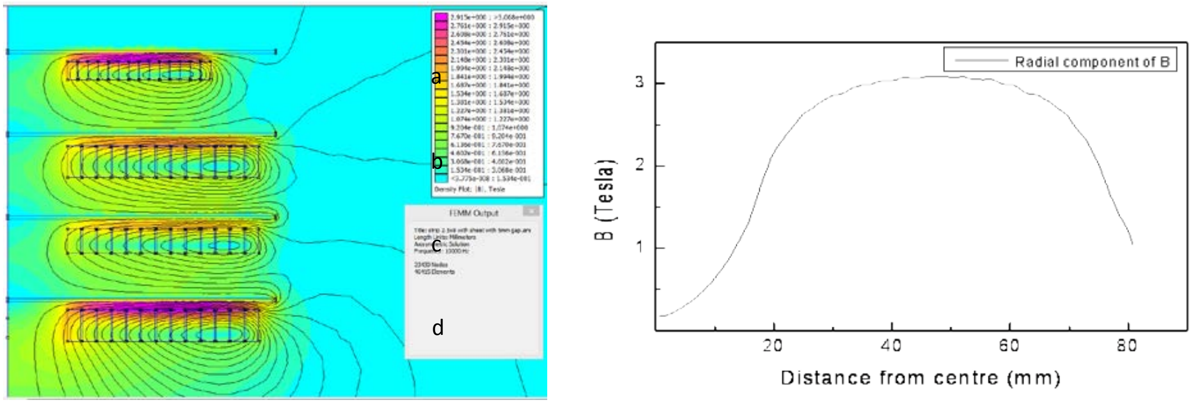
effective length. Hence, a coil with same specifications as the coil‘d’ was fabricated and used in the further experiments.

For efficient operation, the fitting of the work piece to the coil also plays an important role. It has been found that minimum gap between the works piece and actuator is favorable for efficient forming. However, sufficient clearance must be provided to allow space for insulating materials and to facilitate the loading and unloading operation.

Table 2: Description of parameters of simulated actuator coils.

Coil	Lorentz Force (kN)	H_{radial} (T)
a	15.7	3.5
b	12.5	2.9
C	7.9	2.8
d	26.3	3.1



(a) (b)

Figure 3. (a) Magnetic field profile taken by software is shown for four different actuators with circular geometry carrying current “I” under the same discharge voltage **(b)** quantitative radial component of field of bottom coil.

Limited work is available on the role of pitch in the design of flat spiral coil. Kamalet al [7] worked on a new type of flat coil to generate uniform pressure on the work piece. He argued that the spatial distribution of forming pressure in electromagnetic forming was controlled by the configuration of the coil. Golovashchenkoet al [11] also proposed a new generation coil design along with coil failure modes and its remedies. Field shaper is another tool that is used to modify the electromagnetic field to have desired distribution of the magnetic field and magnetic pressure. Yu et al [12] studied the effect of field shaper on magnetic pressure on tubular work piece and found that a greater radial magnetic pressure can be achieved with field shaper than the case without it. In the present study, the coil have been designed by optimizing the pitch as well as the cross sectional area to achieve a thoroughly uniform magnetic field.

Forming is accomplished with no physical contact on the work piece. The pressure on the work piece is applied by magnetic field and translation of force requires no medium**.** As the magnetic field can pass through non-conductive materials, it is possible to form a coated work piece without damaging the coating.

Sheet forming experiments were conducted for different sheet thicknesses and at two different energy levels (4kJ and 8.9kJ) of capacitor bank are shown in Figure 4. At low energy level the sheets with thickness 0.5 & 0.8 mm showed poor forming, however sheets with thicknesses 1.0 to 2.0 mm did not form. At the energy level of 8.9 kJ all of sheets having thicknesses 0.5, 0.8, 1.0, 1.2, 1.5 and

2.0 mm have been formed well. It is attributed to the fact that thicker sheets need more force than the thinner ones which is provided through the force generated by coupling of applied and induced fields and it is always higher in thicker sheets than that of relatively thinner sheets. Outer diameter of all sheets is 135 mm while the height of formed doom is 25-28 mm. The forming profile at high energy (9 kJ**)** is not symmetric in the thin sheets (0.5 and 0.8 mm), however, in sheets with thickness 1 to 2 mm, forming profile have been found symmetrical. Ali M et al [14] and Takatsu N et al [1] calculate the magnetic pressure produce by the actuator coil between the work piece. They use the coil having turns five in case of Ali M et al and six in case of Takatsu N, but we use the coil having 13 turns. Design of the coil was modified with batter understanding so that approximately same magnitude value of the force got using 900V instead of 6kV.The results are also in modest agreement with the previously reported results [1,13,14].

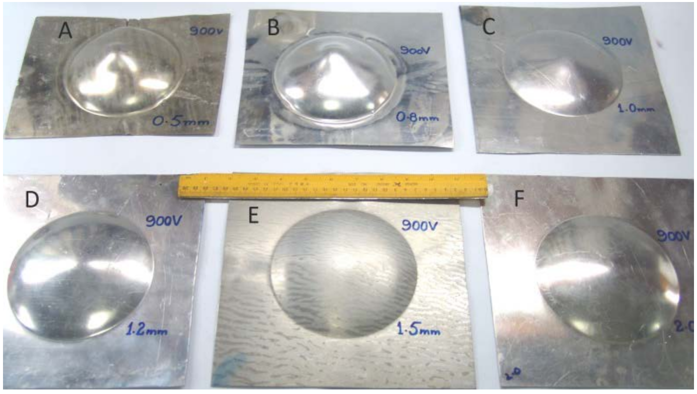


Figure 4. Different formed sheets at 900v, 9 kJ; top row from left to right 0.5, 0.8 and 1.0mm thickness, top row from left to right 1.2, 1.5 and 2.0 mm thickness.

4. Conclusion
A system for electromagnetic forming was constructed by coupling an in-house developed capacitor bank to an indigenously designed and developed actuator coil. To obtain uniform magnetic field, actuator coil was modeled in FEMM-4.2 to optimize the design parameters like pitch and cross sectional area. Results were then used to develop the coil for further use in forming experiments. Forming experiments were performed with aluminum sheets of varying thickness at different forming energies. Forming was conducted successfully and it has been thus established that the forming of thicker sheets require high forming energies.

5. Acknowledgement
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