Proposal for a Test Bench for Electromagnetic Forming of Thin Metal Sheets*

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Abstract

This paper presents a proposal to build a test bench for electromagnetic forming processes. The project considers the analysis of the electrical circuit and forces involved in the system for selection of low voltage capacitors, resistors, buses, main discharge switch and material choice for actuator's insulation and rigidity, considering also the manufacturing process of actuators and dies. Among the aspects considered for the design, energy efficiency has been prioritized by the use of non-conducting material to the dies. Main switches by mechanical contact and spark gap types were used and its wear and functionality was assessed. Free bulging experiments were performed with aluminium AA1100 plates for a system configured with a flat coil actuator. Test measurements of electric currents in the coil actuator with and without the workpiece as the secondary circuit were performed, as well as an evaluation of wear and functionality of the system. It is observed that the main switch discharge is one of the most critical items of the system.

Keywords

High speed forming, Flat coil, Spark-gap

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* *This work is based partially on the results of the Master of Science Dissertation of Evandro Paese. The authors would like to thank the following persons: Eng. Michael S. Ertle from TDK-EPCOS for donating the capacitors;* Eng. *Augusto Nienow from Ensinger Engineering Plastics for donating of* polyoxymethylene *block; Eng. Eliseu Silveira Brito for milling the actuator coil and dies, and to Eng. Marcio Migliavacca from Rexfort for milling the spark-gap parts.*

1 Introduction

In recent years, the electromagnetic forming (EMF) technique has been widely studied, especially with regard to the behaviour of materials under high strain rate, the potential for applications and numerical modelling of the process, with several works dedicated to these topics [1-12]. However, few studies have been presented for the design of EMF machines, whether for industrial or laboratorial applications [13].

Commercial solutions for EMF machines are very expensive and the user´s flexibility facing the choice of components with specific electrical properties is subjected to manufacturer´s availability. In laboratorial experiments, the electrical data are very important, as they help the understanding and identification of relevant parameters to the process while also allowing the development of numerical models to design actuators and dies, as well process analysis.

Given the importance of the machine, this paper presents an alternative proposal for a test bench for electromagnetic forming of thin metal sheets, prioritizing laboratorial application. The project considers the analysis of electrical components, development of a main switch like spark gap, choice of material and manufacturing process for insulation and rigidity of the actuator and dies, emphasizing the efficiency of the system. Free bulged tests results are presented with aluminium alloy AA1100 plates for an EMF system configured with a flat spiral coil as actuator, including discharge currents, wear analysis and systems functionality, providing more information for the design of EMF machines and the process itself.

2 The Electromagnetic Forming Process

In a simplified way, an electromagnetic forming system consists of a capacitor bank, an actuator coil, a main switch and the metallic workpiece to be deformed. The capacitor bank is connected to the actuator coil which is very close to the workpiece. When the main switch is closed, the energy previously stored in the capacitors is rapidly discharged through the coil as a high electric current pulse producing a transient magnetic field that induces opposite currents on the nearby conductive workpiece (Lenz's law). The electromagnetic repulsion between the currents flowing in opposite directions and in close proximity provides the deformation force (Lorenz law) to the workpiece [11].

2.1 Simplified Analysis of EMF Processes

The analysis of the EMF process is very complex because it responds to interaction of electric, magnetic, thermal and mechanical fields. This section presents a simplified way of examining the case to illustrate the basic principles of the process and its main parameters. Advanced information about the interaction of deformation and electromagnetic fields can be found in [14-18].

2.1.1 Analogy to Electrical Circuit

An electromagnetic forming system is a discharge circuit which consists of a primary RLC circuit coupled with a secondary RL circuit. Equations (1) and (2) describe the analogous electrical circuit of the system [19]:

$$\left(L_1\right)\frac{di_1}{dt}+\frac{d}{dt}\left(Mi_2\right)+\left(R_1\right)i_1+\frac{1}{C_0}\int i_1 dt=0 \quad (1)$$

$$\frac{d}{dt}\left(L_2 i_2\right)+\frac{d}{dt}\left(Mi_1\right)+R_2 i_2=0 \quad (2)$$

where, C_0 is the capacitor bank, L_1 and R_1 are respectively the total inductance and resistance of the primary circuit; M is the mutual inductance between the coil and workpiece, i_1 is the coil current, i_2 is the equivalent induced current in the workpiece, L_2 and R_2 are respectively the workpiece's equivalent inductance and resistance. The initial conditions for equations (1) and (2) are:

$$i_1=0,\quad \left(L_1\right)\frac{di_1}{dt}=V_0,\quad i_2=0 \quad (3)$$

with V_0 the initial voltage of the capacitor bank. The Mi_2 term is not constant, it varies significantly with the deformation of the workpiece (moves away from the actuator coil) and, to a lesser intensity with the penetration of the magnetic field in the workpiece.

2.1.2 Induced Magnetic Force and Magnetic Pressure Distribution

The resulting repulsive force between the magnetic field in the actuator coil and the induced magnetic field in the workpiece is typically referred to as the magnetic pressure. The induced magnetic force and pressure is given by equations (4) and (5) [9,11]:

$$\frac{F}{l}=\frac{\mu_0 I_1 I_2}{2\pi d} \quad (4)$$

$$P=\frac{\mu_0 H^2}{2} \quad (5)$$

Where F is force, P is pressure in Pascals, μ_0 is the permeability of free space, H is the electromagnetic intensity, d is the distance between the workpiece and the actuator.

The electromagnetic intensity H, which may be calculated by Biot-Savart law, is very dificult to determine because it depends on time, on the space location, on the applied current and geometry of the conductive media, in this case, the actuator coil and the deforming workpiece. Electromagnetic intensity distributions for idealized spiral coils have been analytically determined, but no general analytical solutions exist for sheet metal forming operations with flat coils [9,12].

2.2 Equipment

An electromagnetic forming machine may be treated as an RLC circuit, equation (1), and is basically composed of a high voltage DC power supply, capacitors, connecting lines, main discharge switch, actuator coil and other devices for operational safety and control. The most critical parts are the capacitors and the main discharge switch, which must be robust enough to withstand the high reverse voltage and current that may exceed 100 kA [13,20]. In addition to these characteristics, it is desirable that the resistance and inductance of the components are as low as possible in order to maximize the efficiency of the deformation process. Special attention should be given in the selection of connecting lines (buses), capacitors (capacity and internal resistance and inductance), the actuator coil design, and especially in respect to the main discharge switch.

3 Design Solution for an EMF Test Bench

The design for the test bench presented in this paper considered the above mentioned technical aspects and an economic alternative when compared to a commercial solution, as the total budget for purchasing and manufacturing the required components, excluding monitoring and data acquisition devices, amounts $2500.00 with all parts being made in Brazil. The following sections provide further detail on all the components used to build the machine. *Warning: readers interested in following the assembly and operation of the presented machine need to use individual protection equipment and take special care when handling with high voltage. Also, the reader should know that a high voltage (DC) power supply is needed to charge the capacitor bank and so make the machine operational. It is also recommended at least two persons to operate the machine, where one controls the charging procedure and the other the trigger circuit (main discharge switch).*

3.1 Capacitors

The energy stored (*U*) in a capacitor is determined by the following equation:

$$U = \frac{1}{2} C V^2 \tag{6}$$

Commercial EMF machines exploit this relation by using capacitors of low capacitance and high voltage (thousands of Volts). This is possible due to the highly insulating material (dielectric) which these capacitors are made from.

For this bench test, low voltage capacitors were selected on the basis of cost, market availability and operational safety. Based on these criteria, EPCOS electrolytic pulse capacitors of 450 V and 5600 μF (±20%) with screw terminals were chose. More detailed information about these capacitors may be found in the reference [21].

3.2 Main Discharge Switch

The main discharge switch needs to be efficient in the transmission of the high currents and provide operational availability, i.e., it needs to resist to the wear. Discharge switches based on terminal contacts are not efficient in the transmission of high current, much less wear resistant and in some times, resulting in the undesired welding of the terminals [11-13]. Two possible switches without contact are the spark-gap and the thyratron valve, both are electronic controlled high voltage switches (hundreds of kV) and support high peak currents (kA). The solution was the development of a non automated spark-gap (SG) of easy construction and implementation (Figure 1). In this system a secondary circuit is used to form plasma between the electrodes and thus driving the main switch without mechanical contact. The secondary circuit consists of a small wire diameter, which is evaporated by short circuit from its own, forming plasma between the electrodes and thus conducting the high current pulse [12].

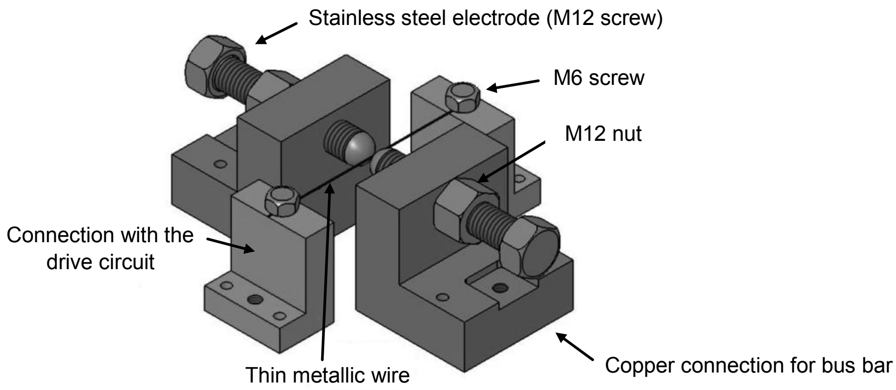

Figure 1: *Main discharge switch without mechanical contact (Spark-gap) [12].*

3.3 Actuator Coil and Dies

For this project, a flat spiral coil actuator was selected (Figure 2). The coil was modelled on CAD and then machined on a CNC machine from a 150 x 150 x 15 mm copper plate. A cavity in the shape of the coil was machined with a 0.1 mm gap in a polyacetal block providing rigidity and insulation. The upper die has a circular cavity. The coil and the upper die were fixed by screw connections (M6). Table 1 presents more detailed information.

Coil	Material	Electrolytic copper
	No. of windings	6
	Radius of outer ring	60 mm
	Pitch	10 mm
	Cross-section area	16 mm^2
	Electrical resistivity	1.2396 mΩ (ohmmeter-D05 Cropico)
	Self inductance	1.2 μH (LCR meter Minipa MX-1001)
Die mould	Material [22]	Tecaform AH (Polyoxymethylene)
	Ultimate yield strength	60.7 MPa
	Hardness	86 HRM
	Dielectric strength	19.7 kV/mm
	Cavity diameter	Ø=120 mm
	Cavity depth	30 mm
	Blank diameter	Ø=180 mm

Table 1: Coil and die parameters

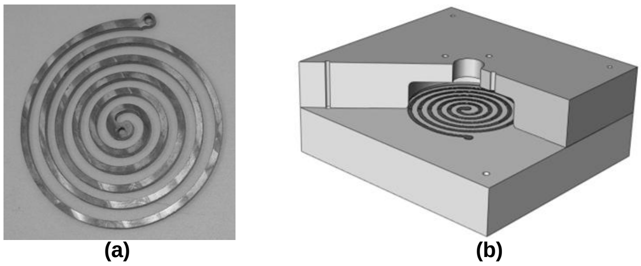

Figure 2: *Machined flat spiral coil of electrolytic copper (a) and a sectioned view of the dies (b).*

3.4 Connecting Lines

Usually, a coaxial configuration for the connecting lines is used, as this will minimize the inductance. As this type of solution is expensive, simple copper bus bars were used. The bars should have a lower electrical resistivity, in other words, it must have no more than the same electrical resistivity than the actuator coil installed on the machine. Commercial copper profiles of 15.87 x 3.17 mm meets the desirable requirements with a cross section area of 48.8 mm^2 and sufficient width to maximize the contact area with the terminals of the previously selected capacitors. Copper flexible connectors, with an equivalent cross section area of 36.4 mm^2 were also used.

3.5 Electrical Circuit Configuration

With all major components defined, it is now important to sketch the electrical circuit configuration to assist the assembly process. Figure 3 shows a schematic electric circuit for the EMF system.

The capacitor bank C_0 shown on figure 3 consists of six capacitors, arranged as a series-parallel circuit (Figure 8). In this configuration it is possible to apply up to 1000 V and the maximum energy storage, which is calculated by applying the equation (6), gives 4.3 kJ. The circuit presented on Figure 4 has 10 kΩ resistors between the capacitors terminals. These resistors equalize the applied voltage and also serve to discharge the capacitors when the power is not used for electromagnetic forming.

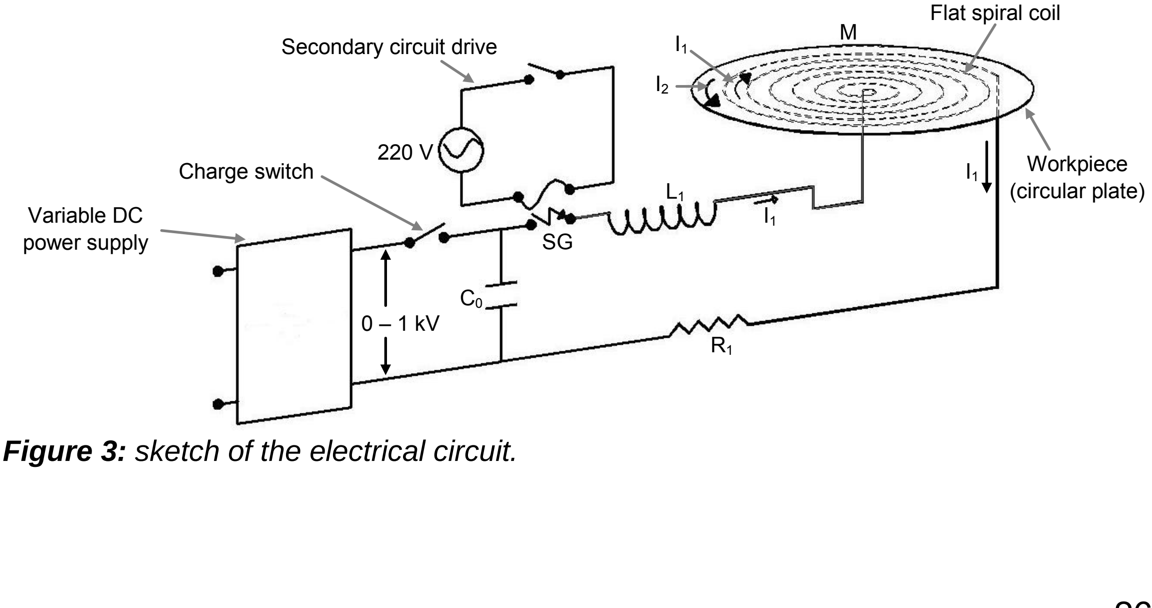

Figure 3: *sketch of the electrical circuit.*

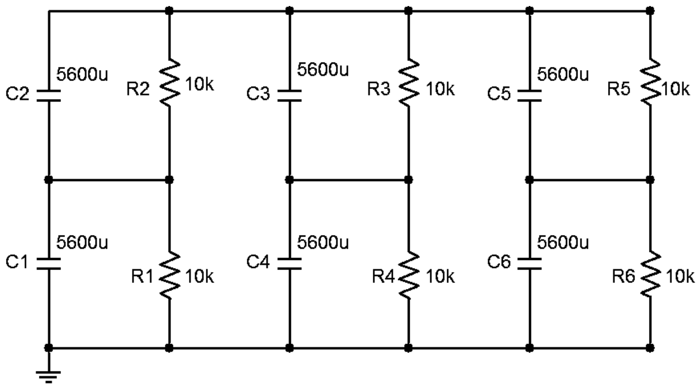

Figure 4: *circuit of the capacitor bank with 5600 µF capacitors and the 10 kΩ resistors.*

3.6 Test Bench frame

All components were mounted over medium-density fibreboard, fixed with screws and nuts. Figure 5 shows the completed EMF machine with all monitoring and data acquisition devices.

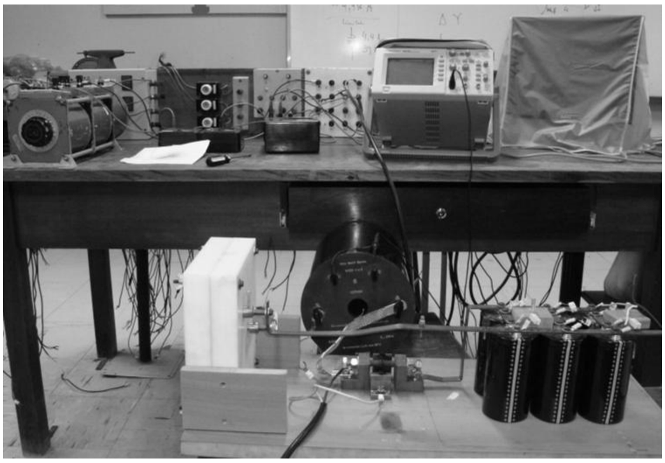

Figure 5: *Test bench for electromagnetic forming of thin metal sheets at LMEAE/UFRGS.*

3.7 Procedures for operation of the test bench

The steps to prepare the machine for an EMF operation consist of: checking if the system is energized and then disconnect and/or discharge it if necessary, positioning the sheet on the die/closure and fixation of the dies with butterfly nuts and place the thin metallic wire on the trigger circuit (secondary circuit). Setup of the monitoring and data acquisition devices and start charging the capacitor bank with the desirable energy. Once the charge is complete, the DC power supply must be disconnected from the capacitor bank and then the trigger circuit may be fired. Again, users are warned to beware of the risk of electric shock and fire by short circuit. The authors recommend installing voltmeters on the charging and trigger circuits to ensure that it is not energized. If necessary, wait a moment for the 10 kΩ resistors to dissipate the previously stored energy. Always use individual protection equipment and a voltmeter to check the voltage of the circuit before touching it.

4 EMF Analysis procedure

The experimental procedures consisted of free bulging tests of aluminium alloy AA1100 sheets. A voltmeter, a 1 mΩ shunt resistor and an oscilloscope were used for data acquisition and monitoring (Figure 5). Table 2 presents system parameters and working conditions.

Circuit conditions	Capacity of condenser bank	8400 μF
	Energy (maximum)	4.3 kJ @ 1 kV
Workpiece	Material	AA 1100
	Electrical resistivity [23]	$3{\cdot}10^{-8}\ \Omega{\cdot}m$
	Thickness	0.8 and 3 mm
	Diameter	180 mm
	Gap distance	1 mm

Table 2: System parameters and working conditions

5 Results and Discussion

The machine showed satisfactory results with the electromagnetic forming deformation imposed to the workpiece. On Figure 6 it is possible to see the final deformed sheets of 0.8 mm and 3 mm thick.

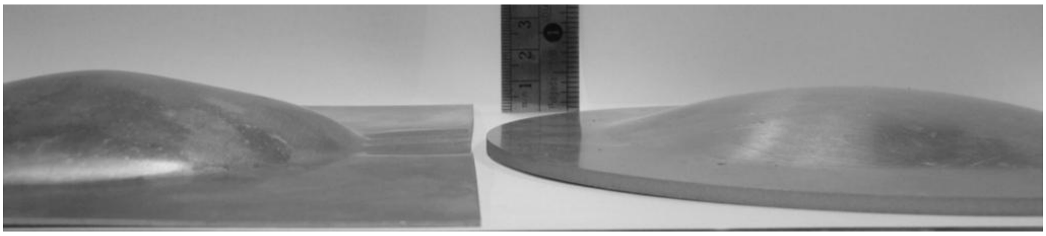

Figure 6: *Electromagnetic forming results for AA1100 sheets with 0.8 (0,9 kV) and 0.3 mm (1 kv).*

Discharge current and voltage tests showed that the spark-gap switch has great efficiency (Figure 7) where it is also possible to note that the spark-gap switch allows current and voltage reversion. Workpiece thickness has influence on current peaks: a thin sheet has a small area relative to the induced currents flow, thus a higher electrical resistivity.

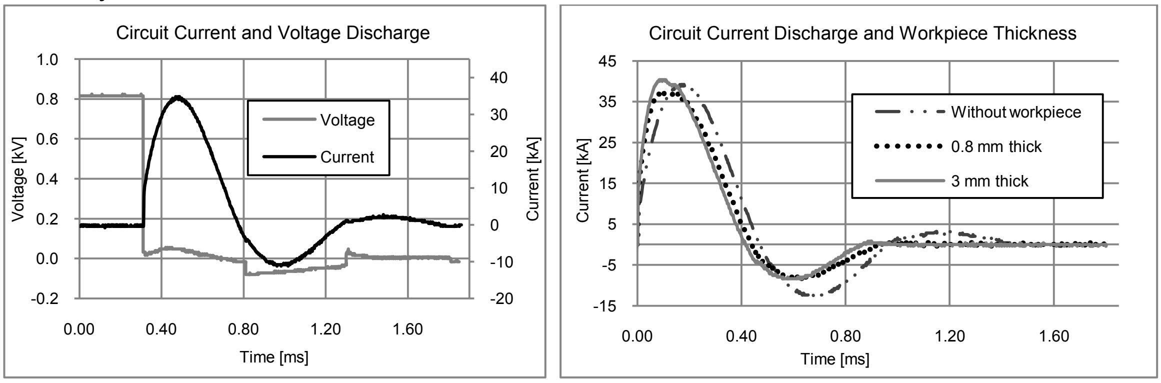

Figure 7: *Acquired voltage and current curves for the spark-gap and circuit current discharge curves situations with and without the aluminium sheet plate charge.*

Data from the experimental results confirmed the high current and reverse voltage that the machine components are subjected. Upon completion of over 50 experiments, the machine is still operational. However, wear its noticeable in the spark-gap, in the flexible copper connections and in the actuator coil, Figure 8, due to the high current discharges.

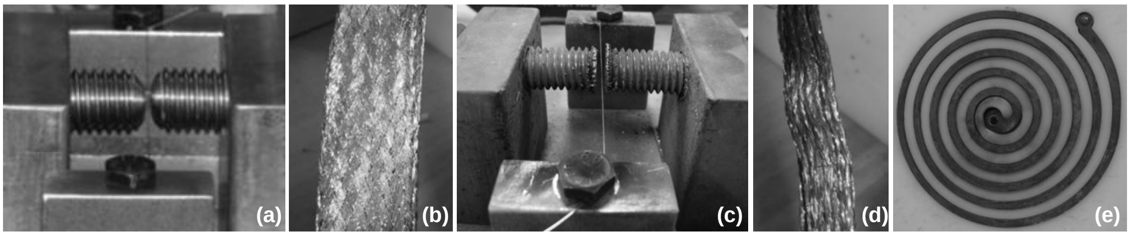

Figure 8: *initial state of the spark-gap (a) and copper flexible connector (b). Noticeable wear after over 50 highly energized pulses: spark-gap (c), copper flexible connector (d) and actuator coil (e).*

6 Conclusions

The paper presents a proposal of a test bench for electromagnetic forming of thin metal sheets for laboratorial experiments. The presented design solutions are simple, functional and feasible. Aluminium sheet plates of up to 3 mm thick (Table 1) were successfully deformed by the presented EMF machine confirming that this concept serves as test bench and also as a reference for the construction of more powerful and robust machines and with higher degree of automation. Acquired data for discharge current and voltage helped to identify process parameters and its influences, assisting in the development of other areas such as numerical modelling, die design and materials, and finally to the dissemination of this technique.

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