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ON THE POSSIBILITY OF AGILE MANUFACTURING OF RELIGIOUS OBJECTS BY ELECTROMAGNETIC FORMING METHOD

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Abstract

The objective of this paper is to discuss the possibility of using electromagnetic tools to manufacture of religious objects from metal by plastic deformation. The paper analyzes a very agile manufacturing method based on only one tool (a die) that gives shape to the desired part and on the action of electromagnetic force that can be applied to manufactured metal objects such as open boxes, frames, religious objects, etc. that may have surfaces with embossed details. Electromagnetic forming is a method that allows a pressure impulse to be directed to a part of metal sheet in a highly controlled and reproducible manner. The electromagnetic tool (a coil) configuration controls the spatial distribution of the deforming pressure and the energy stored in a capacitor bank controls the impulse size transmitted to the material that will be deformed.

Keywords: electromagnetic forming, manufacturing, religious objects

1. What is electromagnetic forming?

The electromagnetic forming (EMF) is a method, relatively new and of great perspective at the same time, which is used for processing metallic materials in the form of sheets and tubes. The method is based on a physical phenomenon, according to which a time variable magnetic field acts with a force on a metal workpiece which is found in that field. Plastic deformation occurs when stresses created in the material part exceeds its flow limit. Variable magnetic field is created by discharging electrical energy accumulated in a capacitor bank on a coil, placed in the vicinity of the workpiece.

The coil is therefore the working tool with which is created the impulsively magnetic field which is used for plastic deformation. The equipment used in practice enable magnetic fields of high intensity (H_{max} = 200-600 kOe). These values are reached by the passage of pulsed current of the magnitude 50-

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300 kA through the coil turns. In order to be able to get a front quick enough, the current through the coil, at the point of discharging, is usually using an operating voltage of approximately 1-20 kV, and in some cases up to 50 and even 100 kV. The coil will have flat spiral form for plastic deformation of metal sheets and solenoid form for the plastic deformation of metal tubes.

The principle of the plastic deformation by electromagnetic forming is based on the electromagnetic induction law and is illustrated in Figure 1.

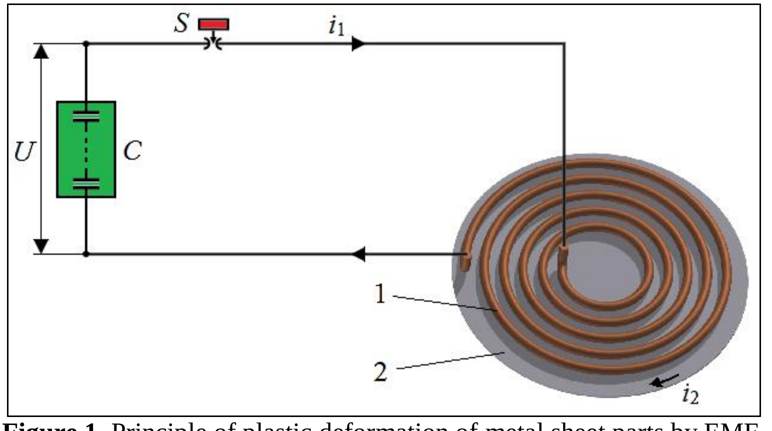

Figure 1. Principle of plastic deformation of metal sheet parts by EMF.

Thus, within the electrically conducting sheet (workpiece) located in variable magnetic field a current is induced. The variable magnetic field is obtained by discharging the energy of the capacitors bank, which has the capacity *C* and was charged at the high voltage *U* by means of the coil 1. When actuating the switch *I*, through the connecting lines of the coil, which has the inductance L_c and the resistance R_c, the inductor current i_1 will pass while through the workpiece 2 an induced current i_2 will circulate in the opposite sense. Owing to the repulsion of the two currents with opposite senses, a magnetic pressure is created that plastically deforms workpiece 2 according to the shape of the die, providing the value of the generated pressure overcomes the flow limit of workpiece material.

Electromagnetic forming is considered by many researchers as a method of manufacturing agile as it can respond quickly to customer needs to produce a wide variety of shapes and sizes of parts, with surface quality and precision dimensional raised. Kamal and co-workers [1] consider that the electromagnetic forming is a very agile method for the manufacture open boxes such as carcasses, with surfaces which may include details as they come out in relief very pronounced. They applied the method to make a cellular phone housing of aluminium sheet, which could not be easily achieved by conventional operation. Electromagnetic method is considered very agile because working tools can be manufactured in a very short time (few hours), not require tight tolerances and special mounting conditions on electromagnetic forming equipment (installation). In another paper [2] are introduced the principles of agile sheet metal forming, in which electromagnetic forming occupies a central role. As an additional demonstration that the electromagnetic deformation is an agile manufacturing method is presented by the results of the method application at the manufacture of some components for aircraft [3].

The main advantage of electromagnetic forming method is its high working speed, the change of the workpiece shape is so fast that their material properties can change, becoming much more ductile. This change in material properties is known as ‚hyperplasticity' and has been clearly observed in electromagnetic forming of aluminium [4]. Deformation speeds of this processing method reach values of up to 200 m/s. Other advantages of the electromagnetic forming are: the forming device is devoid of moving parts, no wear; the decreasing the number of required operations; improved strain distribution; less wrinkling; springback is almost eliminated; does not require lubricants.

2. Main parameters of electromagnetic forming process

2.1. Calculation of the discharge current intensity and frequency

In all the cases, calculation is developed based on the adoption of an equivalent electric scheme for the *equipment-tool-part* (ETP) system. The equivalent scheme of the discharge circuit of an electromagnetic forming equipment is shown in Figure 2.

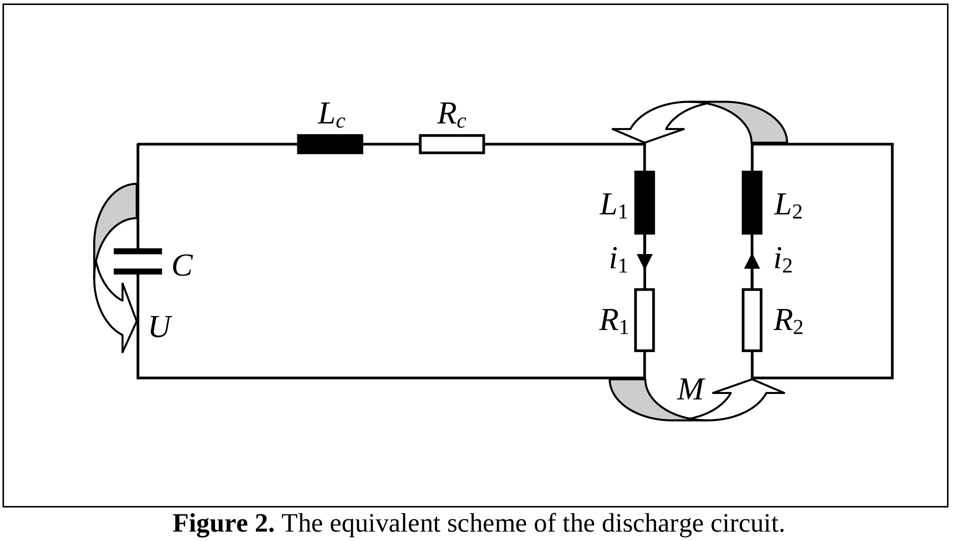

Figure 2. The equivalent scheme of the discharge circuit.

Therefore, ETP system is a discharge circuit consisting in: (i) a capacitors bank, with capacity C and voltage U; (ii) the connecting lines, with inductance L_c and resistance R_c; (iii) the coil, with inductance L_1 and resistance R_1 and (iv) the workpiece, with inductance L_2 and resistance R_2, being magnetically connected with the coil. This model of equivalent scheme of the discharge circuit assimilates the coil and the workpiece to a transformer, with the mutual inductance M. Under these circumstances, the equivalent electric circuit is described by equations [5]:

$$(L_1 + L_c)\frac{\mathrm{d}i_1}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}t}(M\, i_2) + (R_1 + R_c)\, i_1 + \frac{1}{C}\int i_1\, \mathrm{d}t = 0 \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(L_2\, i_2) + \frac{\mathrm{d}}{\mathrm{d}t}(M\, i_1) + R_2\, i_2 = 0 \tag{2}$$

where i_1 is the current passing through the coil and i_2 represents the sum of the induced currents in the workpiece.

The initial conditions for equations (1) and (2) are:

$$i_1 = 0\,; \quad i_2 = 0\,; \quad (L_1 + L_c)\frac{\mathrm{d}i_1}{\mathrm{d}t} = U \tag{3}$$

where U is the initial voltage of the capacitors bank.

In order to simplify the calculation, some authors neglect the influence of mutual inductance M and only a total inductance L and resistance R are taken into consideration that cumulate the influences of the coil connection parameters and the coil and workpiece specific parameters, according to the relationships:

$$L = L_c + L_1 + L_2 \tag{4}$$

$$R = R_c + R_1 + R_2 \tag{5}$$

In this case, the oscillating circuit equation has the form:

$$L\frac{\mathrm{d}i_1}{\mathrm{d}t} + R\, i_1 + \frac{1}{C}\int i_1 \mathrm{d}t = 0 \tag{6}$$

which has the solution

$$i_1(t) = I_{max} \cdot \mathrm{e}^{-\alpha t} \sin\omega\, t \tag{7}$$

where I_{max} is the maximum value (amplitude) of the discharge current, α represents the *damping coefficient* and ω is the *current pulsation*.

The damping coefficient α and the current pulsation ω are determined with the relationships:

$$\alpha = \frac{R}{2L} \tag{8}$$

$$\omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} = \sqrt{\frac{1 - D_a^2}{LC}} \tag{9}$$

where D_a is called *damping factor* and has the expressing,

$$D_a = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{10}$$

For a given value of the damping coefficient D_a much lower than unit, the maximum value of the discharge current can be determined from the expression:

$$I_{max} = U\sqrt{\frac{C}{L}}\left(1 - \frac{\pi R}{4}\sqrt{\frac{C}{L}}\right) \tag{11}$$

Besides discharge current intensity, the decisive influence on the electromagnetic forming processing has the discharge current frequency, which is determined with the relationship:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{12}$$

where L represents the total inductance of the discharge current, R is the total resistance of the circuit and C the total capacity of the capacitors bank.

The discharge current frequency directly influences the deformation degree, an optimal frequency value existing for which the maximum deformation degree could be obtained.

2.2. Calculation of magnetic induction and pressure

Considering a solenoidal coil, its magnetic induction is determined with the relationship:

$$B(t) = B_{max} \cdot \mathrm{e}^{-\alpha t} \sin \omega t \tag{13}$$

where,

$$B_{max} = \frac{\mu_0 N I_{max}}{a} \tag{14}$$

where B_{max} is the maximum value of magnetic induction, μ_0 is the magnetic permeability of vacuum, N is the solenoid number of turns and a the solenoid length.

The total pressure acting on the part equals the pressure difference on its two faces:

$$p = \frac{1}{2}\mu \left(H_1^2 - H_2^2\right) \quad \text{[Pa]} \tag{15}$$

where H_1, in A/m, is the intensity of the magnetic field in the space between coil and workpiece and H_2, in A/m, is the intensity of the magnetic field on the opposite face of the workpiece.

For a clearly expressed pellicular effect, pressure calculation relationship is written as:

$$p(t) = \frac{1}{2\mu_0} B_{max}^2 \cdot \mathrm{e}^{-2\alpha t} \sin^2 \omega t \tag{16}$$

Pressure calculation can be also performed with other relationships having specific forms to each part type.

3. Electromagnetic forming tools and equipment

Electromagnetic forming tools are simple, are quickly produced and not expensive. The scheme of electromagnetic forming device is shown in Figure 3.

The composing elements are: 1- component port-coil; 2 - flat spiral coil; 3 - housing; 4 - plate; 5 - die; 6 - blank holder; 7 – workpiece; 8 - deformed part; 9 - screws. The spiral coil 2 is made from electrotechnical copper with the section circular or rectangular shape. Coil turns are reinforced by casting an epoxy resin, and its setting is made inside of the polyamide housing 3. Work piece 7 is fixed between die 5 and blank holder 6. All the elements are secured by two plates 4 and tightened with screws 9.

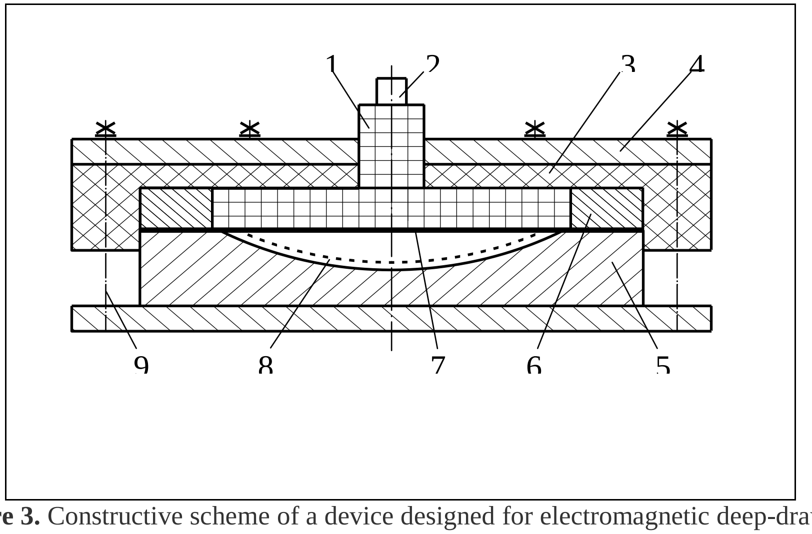

Figure 3. Constructive scheme of a device designed for electromagnetic deep-drawing operations.

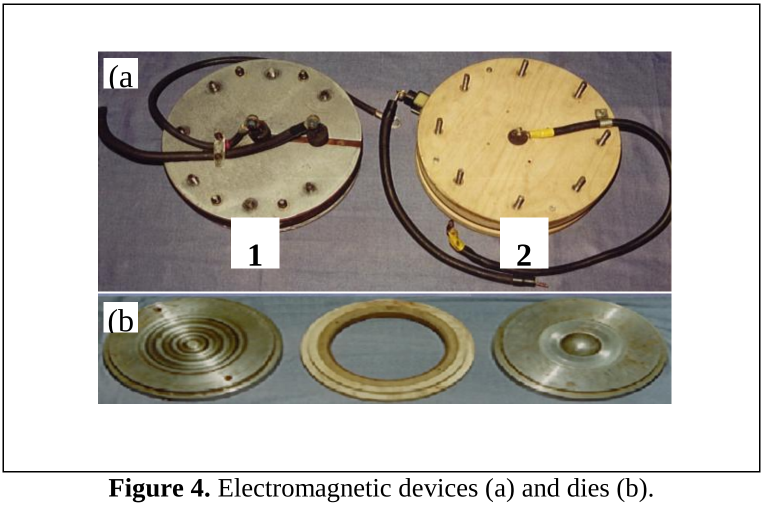

Figure 4. Electromagnetic devices (a) and dies (b).

The overview of two devices used for electromagnetic deep-drawing is shown in Figure 4, together with some of the dies used.

Operation of the electromagnetic forming equipments is based on the phenomenon of electromagnetic induction, by which they obtained currents induced in a conductor located in variable magnetic field of high intensity.

Scheme of an equipment of electromagnetic forming is shown in Figure 5.

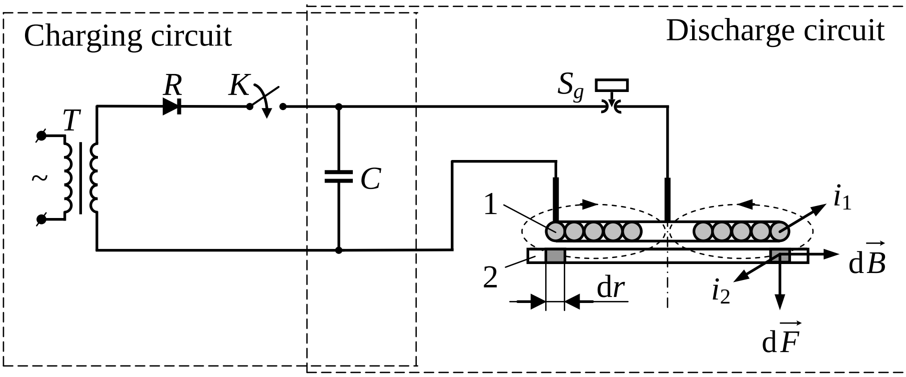

Figure 5. Scheme of an equipment of electromagnetic forming with flat coil.

If it is considered a flat spiral coil 1, having the terminals connected to a circuit containing a current source, a high voltage transformer *T*, a rectifier *R*, a capacitors bank *CB* and a spark gap *Sg*, at the close of the circuit the coil will be conducted by a variable current i_1, damped sinusoidal form, and around of the coil will take birth a variable magnetic field.

Considering a ring of elementary thickness d*r* into workpiece 2, the magnetic field variable of the coil induces current i_2 in the ring, parallel and opposite direction with current i_1 which passes through the coil. As a result, between the two conductors (the coil and workpiece) by circulating currents of opposite directions rejection forces arise, therefore causing the plastic deformation of the workpiece in a hollow part with shape and size desired.

In general, the force of interaction with which a magnetic field of induction $\vec{B}$ acts on an element of conductor $\mathrm{d}\vec{l_2}$ run of electric current i_2 is:

$$\mathrm{d}\vec{F} = i_2 \cdot \mathrm{d}\vec{l_2} \times \mathrm{d}\vec{B} \tag{17}$$

The equipment of electromagnetic forming from our Laboratory of Unconventional Technologies of Plastic Deformation (Figure 6) has the following characteristics: the charging voltage of the capacitors bank: 0...10 kV; the capacity of the capacitors bank: 4×50 μF.

4. Examples of electromagnetically formed parts and possible applications in the manufacture of religious objects

Objects made of materials with low specific weight (aluminium, copper) and tubes with thin walls are best suited to be processed through electromagnetic forming. In Figure 7 are presented examples of objects with different shapes and sizes produced by EMF from metal sheet [6].

Figure 6. Vue of electromagnetic forming equipment.

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Figure 7. Examples of deep-drawn parts by electromagnetic forming.

The field of cleaning and restoration of religious objects seems to be well represented in the literature. Some researchers deal with: the creation of databases for the restoration of religious objects [7], the application of statistical methods of analysis [8], the corrosion of religious artefacts [9], the analysis by electronic microscopy [10] and spectrometry [11] of ceramic and stone monuments, cold plasma cleaning method of heritage objects [12]. Other concerns refer to obtaining and characterization some new materials used for the restoration and protection of religious objects and monuments [13-15].

However, scientific papers dealing with the problematic of religious objects manufacture are almost non-existent. Here, our paper brings the discussion of a new manufacturing technology that can be easily applied to obtain religious objects.

5. Conclusions

This work demonstrates the potential of electromagnetic forming method for manufacturing a wide variety parts from metal sheet or tubes. The paper presents the agile electromagnetic forming as one that uses a minimal set of tools easily modified to achieve objects in accordance with dimensional requirements and specifications of properties. Examples of parts carried out shows that the electromagnetic forming with common coils has remarkable results and can be extended to the production of religious objects from metal tubes and sheet.

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