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DETERMINATION OF PRESSURES ACTING ON SHEET METAL IN THE PROCESS OF ELECTRODYNAMIC FORMING BY MEANS OF SPIRAL INDUCTORS

The paper presents methods of analytical and measurement-based determination of pressures acting on sheet metal in the process of electrodynamic forming by means of flat inductors generating pulse magnetic field. Pressures are determined for sheet metal of different thicknesses processed by means of circular and elliptical spiral inductors. The paper describes also examples of copper and aluminium sheet metal forming conducted by means of the analysed inductors and shaped forming dies.

1. Introduction

Electrodynamic forming consists in the processing of metallic components situated in pulse magnetic field by means of Lorentz forces. These forces are generated without any intermediate masses, as an effect of a dynamic interaction between an induction coil (an inductor) and a metallic object situated close to the coil, [1]. An alternating magnetic field is created around inductor coils conducting oscillating current generated by capacitor discharge. The field penetrates the semi-finished product and induces eddy currents along circular lines parallel to the inductor coils, [2].

Inductors, performing the function of tools in the electrodynamic method, are usually shaped as cylindrical or flat coils. In the following description of inductor and semi-finished product geometry, a cylindrical coordinate system will be used with z, r, φ axes aligned with inductor longitudinal axis, inductor radius, and coil axis respectively. In cylindrical inductors, coils wound along a helix with a small pitch, and create a cylindrical surface, and the length l of the coil is bigger than its radius r ($l > r$). In spiral inductors, coils wound

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in one plane, and create an arrangement in the form of a flat spiral fulfilling the condition $l < r$.

The density j of the current flowing in a circular circuit has only one circumferential component j_φ. The components of the magnetic field intensity vector $\boldsymbol{H}$ around such circuit can be calculated from the first Maxwell's field equation:

$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{j} \tag{1}$$

With the assumption that $j_r = 0$ and $j_z = 0$, the circumferential component of current density determined from formula (1) can be described as:

$$j_\varphi = \frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} \tag{2}$$

This means that the component j_φ of the density of current flowing in a circular circuit is accompanied by a magnetic field containing two components of magnetic field intensity: an axial component H_z and a radial component H_r.

Electrodynamic forming method uses the effect of Lorentz forces repelling the semi-finished product from the inductor. Final processing by means of inertia forces is performed with the use of a forming die situated along the route of the semi-finished product or without any die.

Electrodynamic forming method is used mainly for forming tubes and sheet metal. During the processing of tubular products, a cylindrical inductor interacts dynamically with the tube, displacing its wall in radial direction. In such case, the axial component of the magnetic field intensity is important. Cylindrical coils are used to perform the following operations, [4]:
- to compress tubes inserted into the coils,
- to expand tubes slid over the coils.

The paper describes opportunities arising from the application of flat inductors to the process of forming sheet metal situated above the inductor, parallel to the plane containing coils that create a spiral inductor. In such an arrangement, sheet metal is displaced relative to the plane of the spiral inductor, in the direction of its axis, under the influence of the radial component B_r of the magnetic field intensity. The volumetric density of the Lorentz force $\boldsymbol{f}$ is described by the following vector product:

$$\boldsymbol{f} = \boldsymbol{j} \times \boldsymbol{B} \tag{3}$$

where: $\boldsymbol{j}$ is the density of the eddy current in the metallic semi-finished product, and $\boldsymbol{B}$ is the magnetic flux density in the semi-finished product.

The axial component of the Lorentz force acting on the semi-finished product, calculated from formula (3) and taking into account only components j_φ and B_r, is given by:

$$f_z = -j_\varphi B_r \tag{4}$$

By substituting relationship (2) into formula (4), and by taking into account the value of the component H_r of the magnetic field intensity the following expression can be obtained:

$$f_z = -\frac{\partial H_r}{\partial z} B_r \tag{5}$$

As it has been mentioned at the beginning, in the electrodynamic forming method the tool does not come into direct contact with the material being formed. Therefore, in order to determine the effects of the forming process it is necessary to know the distribution of pressures caused by Lorentz forces generated over the whole surface of the product being formed.

The pressure acting at a specific point of the semi-finished product can be determined from formula (5) in the following manner:

$$p = \int_0^g f_z(z)\mathrm{d}z = -\int_0^g \frac{\partial H_r}{\partial z} B_r \mathrm{d}z \tag{6}$$

where g is the thickness of the semi-finished product in the direction of the processing force.
By substituting $\boldsymbol{H} = \boldsymbol{B}/\mu$, ($\mu$ – magnetic permeability) into formula (6), the following relationship can be obtained:

$$p = -\frac{1}{\mu} \int_0^g \frac{\partial B_r}{\partial z} B_r \mathrm{d}z \tag{7}$$

By calculating integral (7) without taking into account any variability of the magnetic flux density B along the thickness of the semi-finished product, the following relationship can be obtained:

$$p = \frac{B_{r1}^2 - B_{r2}^2}{2\mu} \tag{8}$$

From formula (8) it is possible to calculate the pressure acting on the semi-finished product repelled by the inductor, if the radial components of the magnetic flux density on the semi-finished product surface, $B_{r1}(0)$ (facing the inductor) and $B_{r2}(g)$ (on the opposite side) are known.

In the most extreme case, the pressure exerted on the surface of the semi-finished product being repelled by the inductor reaches its maximum value if the magnetic field does not penetrate the semi-finished product but it is concentrated only in the area between the circuits ($B_{r2} = 0$). Such a state is theoretically possible in a situation when the current flowing in the inductor coils and the eddy current excited in the semi-finished product have identical instantaneous values but their phases differ by π.

Pressure distributions can be determined from formula (8), if only the values of the resultant magnetic flux density at the points of interest, situated on the opposite sides of the semi-finished product relative to the inductor, are known. In such a case, however, no changes in the magnetic flux density in the material processed are considered. More precise picture of dynamic interactions between the inductor and the semi-finished product during the electrodynamic forming process can be obtained by determining the distributions of volumetric density of Lorentz forces acting on the semi-finished product particles. If the assumption of constant densities of the current flowing through the inductor coils and the eddy current generated in the semi-finished product is practically fulfilled, the density of the Lorentz force is proportional to the density of magnetic flux generated in a unit volume of the semi-finished product. The distribution of pressures acting on the semi-finished product particles is identical with the distribution of the radial component of the density of the resultant magnetic flux generated in the semi-finished product, [3].

The chapters below describe the methodology of experimental and analytical determination of the distribution of pressures acting on sheet metal subjected to electrodynamic forming with the use of flat inductors. The experiments were conducted in the laboratories of the Department of Process Control at the AGH-University of Science and Technology in Cracow.

2. Experimental determination of pressure distributions

The experiments included the determination of pressures acting on sheet metal during the forming process accomplished by means of flat inductors containing spirally wound coils, shaped in the first case as an Archimedes' spiral (circular inductor, Fig. 1), and in the second case as an elliptical spiral (elliptical inductor, Fig. 2).

Pressures were calculated from formula (8) using known values of radial components of the magnetic flux densities taken from measurements. The measurements were made with miniature probes in the form of induction coils stuck to the semi-finished product at the points of interest, to both surfaces: the one directed towards the inductor, and to the opposite one, [6].

In the experiments, the probes were stuck to the semi-finished product made of sheet metal along the inductor radius.

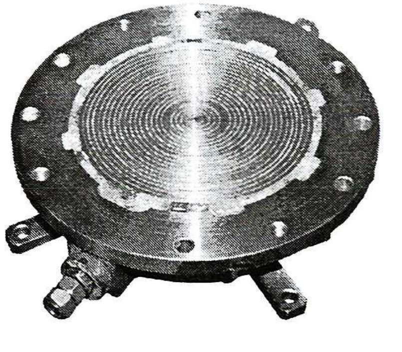

Fig. 1. Circular inductor, diameter 100mm

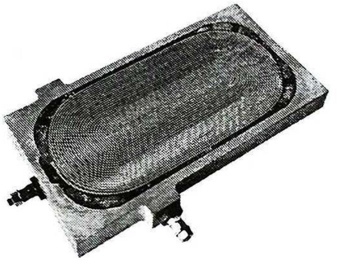

Fig. 2. Elliptical inductor

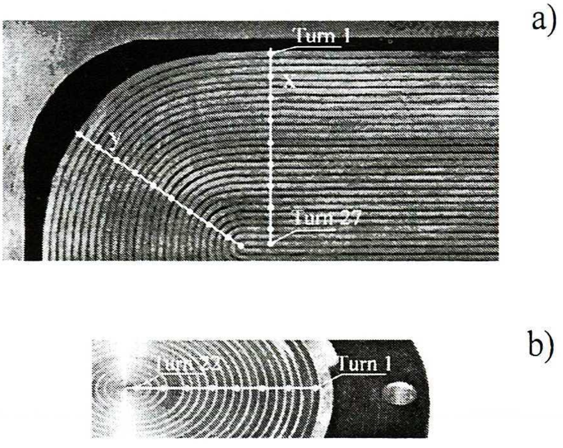

Fig. 3. Points on the inductor surface over which the values of magnetic flux density generated over the sheet metal surface were determined: a – elliptical inductor, b – circular inductor

In the case of elliptical inductor, the probes were stuck along the lines x and y shown in Figure 3a. In the case of circular inductor probes were stuck along the radius, Figure 3b. The value of the tangential component B_r of the magnetic flux density obtained from the measurements is described by the following formula:

$$B_r = \frac{1}{ws} \int e\mathrm{d}t \tag{9}$$

where w is the number of coils of the measuring coil (probe), s is the cross section of the coil in the direction perpendicular to the tangential component of the magnetic flux density, and e is the output voltage of the coil.
The voltage e read from probe terminals was integrated and subsequently recorded by a computer with a measuring card and an appropriate software package installed. Sample recordings (time profiles) of the magnetic flux density B_r and corresponding pressure p acting at a specified point of the semi-finished product surface are shown in Figures 4a and 4b. Pressure distributions shown later are based on the first registered maxima p ($t = \tau/4$), see Fig. 4b.

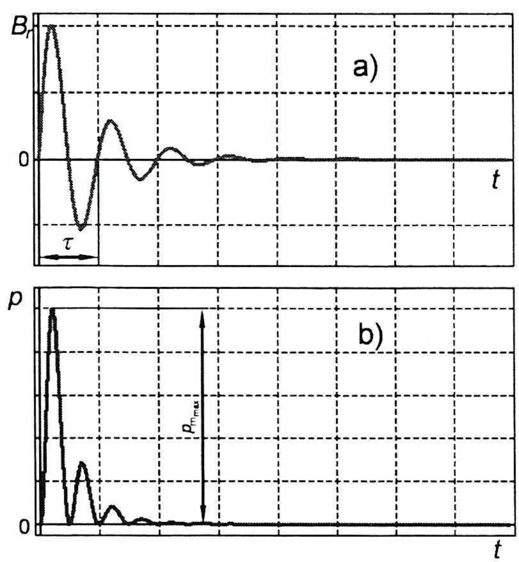

Fig. 4. Magnetic flux densities B on the sheet metal surface – a and corresponding pressures p – b

Figure 5 shows the distribution of pressures exerted on copper sheets 0,1 mm and 1 mm thick, caused by the repelling action of a circular inductor. Although the pressures were determined along the diameter D of the inductor, due to the symmetry of the values obtained with respect to centre of the inductor the plots show distributions along the inductor radius $R = D/2$.

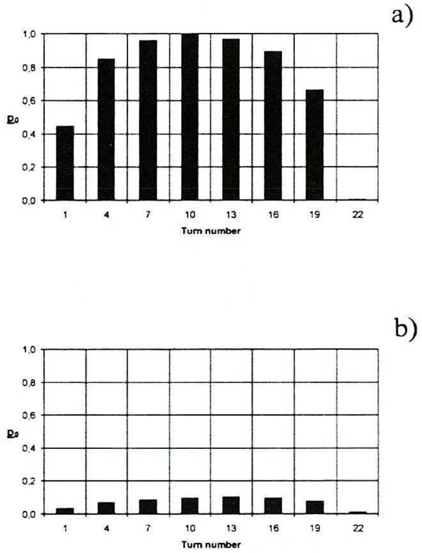

Fig. 5. Distributions of pressures acting on copper sheets 1 mm – a and 0,1 mm thick – b, caused by a circular inductor

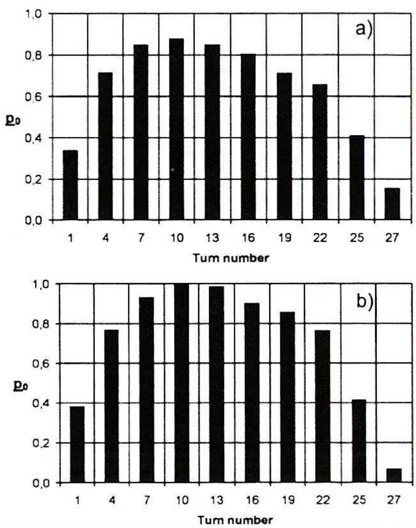

Fig. 6. Distributions of pressures generated by an elliptical inductor on copper sheet 1 mm along straight sections of coils x – a and along arc sections y – b

Fig. 6 shows the distribution of pressures generated in a sheet metal having uniform thickness along the x and y directions of an elliptical inductor. In order to eliminate the influence of the varying geometry of the inductor and the semi-finished product arrangement on the value of the measured component B_r of the magnetic flux density, any possibility of sheet metal displacement during the measurements was disabled. The pressures shown in the graphs are expressed in relative units of measure $\underline{p_o} = \frac{p_o}{p_{o\,max}}$, (where $p_{o\,max}$ is the maximum value of pressure for 1 mm sheet). An analysis of the graphs shows that both inductor types generate combined trapezoidal-parabolic distribution of pressure acting on the sheet metal along inductor winding width. The pressure acting on the sheet metal reaches its maximum p_{max} in the middle of the winding width and decreases at its ends. In inductors, it is possible to define an area covering about 75% of winding width over which the pressure exerted on the sheet metal does not decrease below $0{,}7p_{max}$. With flat, spiral inductors, the level of pressure acting on sheet metal directly above the central coil is significantly reduced. In circular inductors, a circular area around the z axis of the inductor is affected, in elliptical inductors a rectangular area along the longer axis of the ellipse is affected. Additionally, it was found that the pressures over the arc sections of coils in elliptical inductors were lower in comparison with the pressures over the straight sections of coils.

3. Analytical determination of pressure distributions

In a system consisting of an inductor and a semi-finished product, the axial component f_z of force described by formula (4), and acting on a unit volume of the semi-finished product conducting current of a certain density, is proportional to the axial component of the magnetic flux density of the resultant magnetic field generated by currents flowing in all inductor coils and in the product being processed. When non-ferromagnetic materials are processed, in order to determine the resultant magnetic field the principle of superposition can be used and applied to densities of magnetic flux excited at a certain point by individual current circuits (inductor coils, semi-finished product). To accomplish this task, a physical model of the system containing the inductor and the semi-finished product was created. The inductor was modelled as a set of elementary coils conducting currents of the same density. In the model of the semi-finished product, conducting layers were replaced with a set of elementary circular filaments conducting current of the same density. Using the theory of electric circuits, a relationship was derived describing the density of a magnetic flux generated at an arbitrary point of space by the current flowing through an infinitesimally thin, circular circuit,

[5]. Analytical relationships and the superposition principle mentioned above were incorporated in an algorithm for numerical determination of distributions of forces acting on semi-finished products. The algorithm was used to analyse the distributions of forces acting on semi-finished products made of various metals, processed by means of cylindrical and flat inductors of various sizes.

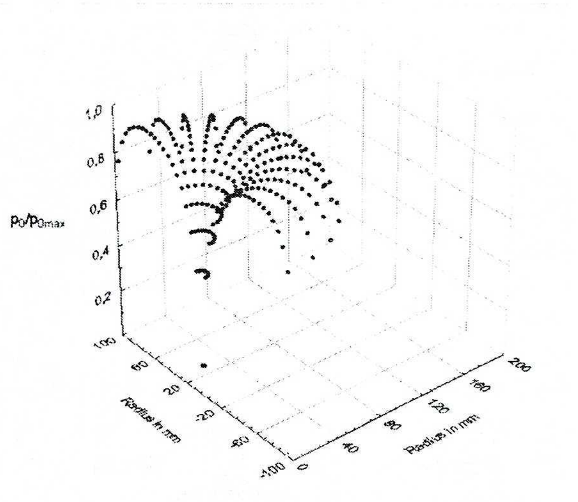

Fig. 7. Distributions of pressures determined analytically for thick metal sheet and a circular inductor

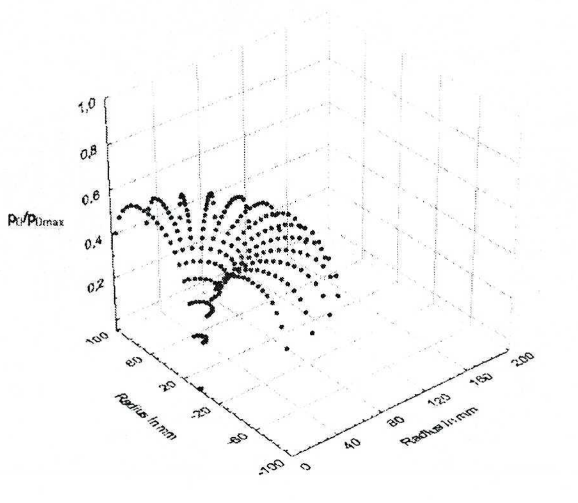

Fig. 8. Distributions of pressures determined analytically for thin metal sheet and a circular inductor

Figures 7 and 8 show in half-section sample distributions of pressures generated by circular inductors, calculated analytically for non-ferrous thick (Fig. 7) and thin (Fig. 8) metal sheets. The patterns of pressure distributions determined analytically and experimentally are similar. Pressures are expressed in relative units of measure defined as in Figure 5. The distributions shown contain low-pressure zones situated around the geometrical centres of the inductors, accounting for few percent of the inductor active surface. The existence of these zones limits the application of flat spiral inductors designed as described in the paper.

4. Selected electrodynamic sheet metal forming operations

Flat, spiral inductors described above were used in various operations of plastic sheet metal forming presented in Figures 9 through 12. The operations of simultaneous cutting of a central hole and making indentations (Fig. 9a); forming a cap out of a flat disc (Fig. 9b); and forming a collar around a ring (Fig. 9c) were accomplished with the use of forming dies. For those operations, the existence of a low-pressure zone in a flat inductor was not so important. Figure 10 shows photographs of sheet metal after forming with visible areas where the surface was not completely formed due to the existence of low-pressure areas mentioned above. This is especially demonstrated when reproducing more complex shapes. For example, on a sheet metal surface, apart from the underpressed area in the centre, the shape of the forming die was reproduced very precisely, including inscriptions and traces of the turning tool left on purpose (Fig. 11). Figure 12b shows a copy of a miniature engraving measuring 60×50 mm^2 (Fig. 12a) made in aluminium sheet placed over the inductor in an area of high effectiveness of its coils.

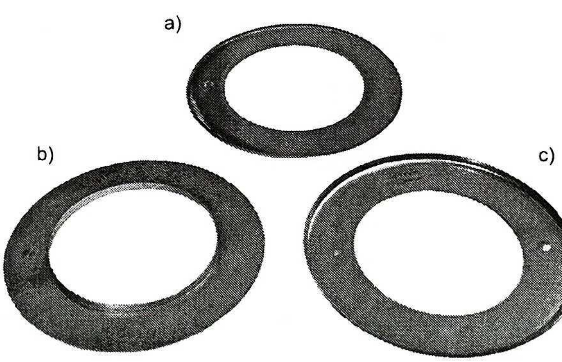

Fig. 9. Sheet metal forming without a zone of decreased pressure over a circular inductor

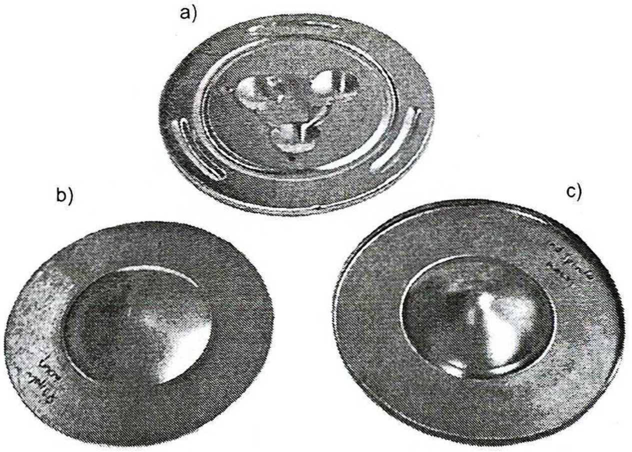

Fig. 10. Sheet metal forming with a zone of decreased pressure over a circular inductor

Fig. 11. Reproduction of a forming die with the use of a circular inductor

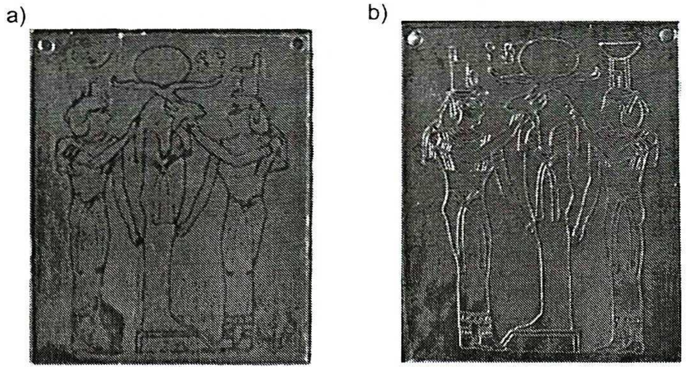

Fig. 12. Copy of an engraving made in a sheet metal; a – forming die, b – stamped reproduction

5. Summary

The paper describes the properties of flat, spirally wound inductors used for electrodynamic forming of sheet metal. The methodology of experimental and analytical determination of force and pressure distribution inside a system composed of an inductor and sheet metal can be used to verify the effectiveness of Lorentz forces in various forming operations.

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Wyznaczanie ciśnień działających na blachy kształtowane elektrodynamicznie z wykorzystaniem spiralnych induktorów

S t r e s z c z e n i e

W artykule przedstawiono sposoby: analitycznego i pomiarowego wyznaczania ciśnień działających na blachy formowane elektrodynamicznie przy pomocy płaskich induktorów wytwarzających impulsowe pole magnetyczne. Ciśnienia wyznaczano dla blach różniących się grubością przy zastosowaniu do ich obróbki induktorów spiralnych okrągłych i eliptycznych. W artykule przedstawiono również przykłady formowania blach miedzianych i aluminiowych za pomocą badanych induktorów z wykorzystaniem matryc kształtowych.