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SHAPE PREDICTION DURING THE FREE FORMING PROCESS OF SEMI-FINISHED PRODUCTS ELECTRODYNAMICALLY WORKED

SUMMARY

Possibility of free forming for semi-finished products and giving them demanded shapes without presence of forming dies distinguish the electrodynamic method in relation to standard technologies of metal plastic working, because there are no difficulties of using punch – die instrumentations. The article presents considerations referred to prediction possibilities of final shape of pipe and flat semi-finished products electrodynamically formed without using forming dies.

Keywords: *shape prediction, electrodynamic forming, Finite Element Method (FEM), numerical analysis*

PREDYKCJA KSZTAŁTU PODCZAS SWOBODNEGO FORMOWANIA PÓŁWYROBÓW OBRABIANYCH ELEKTRODYNAMICZNIE

Możliwość swobodnego formowania półwyrobów i nadawania im wymaganych kształtów bez udziału matryc wyróżnia metodę elektrodynamiczną (ED) w stosunku do klasycznych technologii plastycznej obróbki metali, gdyż nie stosuje się przy jej realizacji kłopotliwego oprzyrządowania typu stempel-matryca, a kształt półwyrobu po obróbce zależy od rozkładu sił Lorentza wywołanych polem magnetycznym wzbudzonym w obszarze induktor-półwyrób. W artykule przedstawiono rozważania dotyczące możliwości przewidywania końcowych kształtów półwyrobów rurowych oraz płaskich formowanych plastycznie metodą ED bez użycia matrycy.

Słowa kluczowe: *predykcja kształtu, formowanie elektrodynamiczne, metoda elementów skończonych (MES), analiza numeryczna*

1. INTRODUCTION

Electrodynamic forming belongs to a group of high rate technologies, which includes both explosive and electrohydrodynamic methods. Common characteristics of those methods is a conversion in seconds fraction order short time of large amounts of electric or blowing charge energy into worked semi-finished product elements movement energy and its work of deformation [1].

In the electrodynamic method volumetric Lorentz forces are used, exerts an influence on metal elements placed in a pulse magnetic field induced by an electric coil called inductor. Its turns conduct shock electric current obtained in the way of oscillating high energy condenser discharge. In a metal part placed close to the induction coil eddy current is induced whereas the consequence of the Lorentz forces acting is that both current circuits repel each other [2]. In the electrodynamic technology, possessing accordingly strength coils made as mechanically strengthen tool head in the right shape (e.g. cylindrical or flat coils) different metal parts plastic working operations are realized, e.g. pipes and sheets in use of compressing, bulging or stamping effects (Figs 1, 2).

Generated in coil – semi-finished product system pulse magnetic field, dynamically acting on located in it metal element, relocate it at high speed in order of tens and hundreds of meters per second. Movement energy is converted into work of deformation for semi-finished product which can be formed in use of forming die or without it presence.

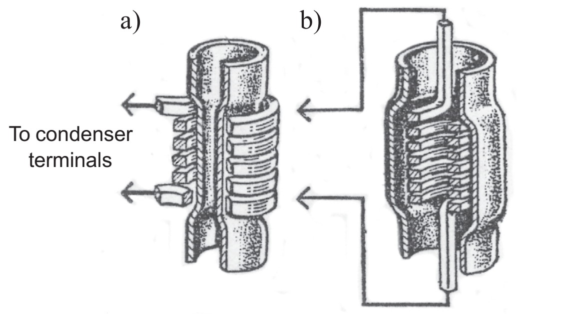

Fig. 1. Compressing and bulging of pipe elements

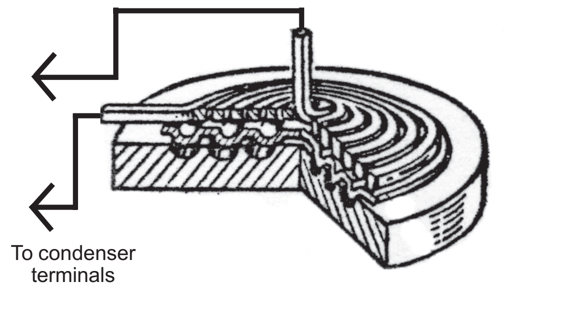

Fig. 2. Stamping of flat elements

Possibility of free forming for semi-finished products and giving them demanded shapes without presence of forming dies distinguish the electrodynamic method in relation to standard technologies of metal plastic working, because there are no difficulties of using punch – die instru-

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mentations. The final shape of elements after the working process depends on Lorentz forces distribution exerted by magnetic field induced in coil – semi-finished product system area. Character of this distribution is connected to coil construction and additionally can be modified by concentrator focus inductors placed in space between coil and semi-finished product, which concentrates magnetic field in working space over forming element, which results in the increase in value of force used for working operation. The article presents considerations referred to prediction possibilities of final shape of pipe and flat semi-finished products electrodynamically formed without using forming dies.

2. PHENOMENA PROCEEDING DURING ELECTRODYNAMIC METAL FORMING

During discharging of condensers pulse electric current flows through coil turns, this current induces around inductor changing magnetic field, which partly penetrates metal semi-finished product inducing eddy currents in it. Resultant magnetic field induced by currents flowing in coil turns and generated in metal element causes its mutual repelling [2]. The knowledge of character and values of mechanical forces arisen in pulse magnetic field generated by mentioned currents is the basis to semi-finished product electrodynamic forming final effect prediction. Force $d\bar{F}$ acting on placed in magnetic field with magnetic flux $\bar{B}$ length element $d\bar{l}$ conducted current i can be described by an Ampere law as cross product

$$d\bar{F} = i\left(d\bar{l} \times \bar{B}\right) \tag{1}$$

Field of forces acting on semi-finished product parts description demands knowledge of generated in it electromagnetic field which results from relationship (1).

Electromagnetic field distribution in coil and worked semi-finished product surroundings depends mostly on: worked element magnetic properties, coil – semi-finished product system geometry and obtained from generator oscillating current pulsations.

Making use of first and second Maxwell laws relations between vector quantities of electric and magnetic field for well conducting medium shifted in space, we can describe by relations:

$$\mathrm{rot}\bar{H} = \bar{J}_C \tag{2}$$

$$\mathrm{rot}\bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{3}$$

$$\bar{B} = \mu \bar{H} \tag{4}$$

where:

- $\bar{B}$, $\bar{H}$ – accordingly of magnetic flux and magnetic intensity vectors,
- $\bar{E}$ – electric field intensity vector,
- $\bar{J}_C$ – worked semi-finished product total density current vector,
- γ, μ – accordingly conductivity and permeability of material.

Total current is induced in semi-finished metal product as result of two effects:

1) transformation, created by change of magnetic flux in time t;
2) movement, aroused in case of semi-finished product shifting in magnetic field.

Taking described effects into consideration total current density can be presented as sum

$$\bar{J}_C = \gamma\left(\bar{E} + \bar{v} \times \bar{B}\right) \tag{5}$$

where $\bar{v}$ – worked semi-finished product movement velocity vector.

After inserting formulas (4) and (5) into (2) and (3) equations we can obtain relations:

$$\mathrm{rot}\bar{H} = \gamma\left(\bar{E} + \mu \bar{v} \times \bar{H}\right) \tag{6}$$

$$\mathrm{rot}\bar{E} = -\mu \frac{\partial \bar{H}}{\partial t} \tag{7}$$

In further considerations cylindrical coordinate system were used, supposing that coil axis is directed along axis z and turns are wind in plane (φ, r). In the article magnetic field distributions generated by spiral stamping and cylindrical compressing or bulging coils. In view of axially symmetrical construction of those coils and worked by them elements in considerate coil – semi-finished product system physical models many simplified assumptions were taken, which allows to decrease the number of describing it equations followed from curl and cross vector product expansion showed in equatons (6) and (7).

One of the assumption is that in cylindrical coils in view of small winded turns spiral lead situated planes parallel to plane (φ, r) at cylindrical coordinate system. Eddy current density induced in thickness of compressed or bulged pipe have only circumferential component, so in generated magnetic field predominate axial component of magnetic field intensity H_z parallel to axis z of the coil. In case of spiral coil where turns are winded in (φ, r) plane current density, like in cylindrical coil has only circumferential component, but in magnetic field intensity distribution predominate H_r component parallel to mentioned above (φ, r) plane.

According to supposed assumptions, in case of electrodynamic compressing and bulging (Fig. 1) of axisymmetric semi-finished pipes in electromagnetic field distribution included in coil – semi-finished product space predominate axial component of magnetic field intensity H_z which does not depend on angle φ and circumferential component of current density γE_φ in formed element and coil. Current density does not change along axis z. In view of relatively small values of other components, we can omit them, so final form resulted from relations (6) and (7) field diffusion equation into pipe wall for compressing and bulging have the form

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\left(1 - \mu\gamma r v_r\right)\frac{\partial H_z}{\partial r} + \left(\mu\gamma \frac{\partial v_z}{\partial z}\right) H_z = \mu\gamma \frac{\partial H_z}{\partial t} \tag{8}$$

In case of flat elements, electrodynamic stamping in coil and sheet arises, like during pipe elements compressing and bulging, only current density circumferential components. On the other hand, in coil – semi-finished product working region there is a magnetic field in which predominate magnetic field vectors H_r, B_r radial components. Other components of these vectors we can omit for further considerations as it has negligible small values. After taking equations into account we can state that current density does not change its value along radius r and in view of system symmetry radial component does not depend on angle φ therefore we obtain final diffusion equation of field penetrates formed sheet material which has the form

$$\frac{\partial^2 H_r}{\partial z^2} - \mu v_z \frac{\partial H_r}{\partial z} + \mu\left(\frac{v_r}{r} + \frac{\partial v_r}{\partial r}\right) H_r = \mu\gamma \frac{\partial H_r}{\partial t} \quad (9)$$

After converting the equation (1) by inserting into it $\bar{J}_C dV$ product describing current element with volume dV by which current with density $\bar{J}_C$ flow we obtain a relation

$$d\bar{F} = \left(\bar{J}_C \times \bar{B}\right) dV = \bar{f} dV \quad (10)$$

in which $\bar{f}$ vector is mentioned volumetric force called Lorentz force density.

Using relationships (2) and (4) in expression (10) we get the formula describing Lorentz force as cross product

$$\bar{f} = \mu \cdot \mathrm{rot}\bar{H} \times \bar{H} \quad (11)$$

If we assume that for compressing and bulging operations magnetic field intensity vector has only axial H_z component, whereas for stamping only radial H_r component, that volumetric densities of electromagnetic force acting at worked semi-finished product volume element will be accordingly equal:

– for compressing and bulging

$$f_r = \frac{dF_r}{dV} = -\frac{\mu}{r} H_z \frac{\partial H_z}{\partial r} \quad (12)$$

– for stamping

$$f_z = \frac{dF_z}{dV} = -\frac{\mu}{r} H_r \frac{\partial H_r}{\partial z} \quad (13)$$

Above forces acting direction is perpendicular to surface of forming element in moment of working process start and their senses directions is from tool to worked material.

To define electrodynamically worked element dynamics system, inner equilibrium state was investigated and its movement equations were defined. Considering three-dimensional stress state at worked element and taking into account the fact that there is axial symmetry in coil – semi-finished product system, element inner equilibrium state could be described from three scalar system of equations written for cylindrical coordination system.

In view of axisymmetric shape of worked semi-finished products it would not occur partial derivatives for variable φ in equations. Worked element rotation dangle axis z does not occur during forming in case of that we can assume that velocity $v\varphi = 0$.

$$\begin{cases} \frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\varphi}{r} + f_r = \rho\left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z}\right) \\ \frac{\partial \tau_{r\varphi}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_\varphi}{\partial \varphi} + \frac{\partial \tau_{z\varphi}}{\partial z} + \frac{2\tau_{r\varphi}}{r} = 0 \\ \frac{\partial \tau_{rz}}{\partial r} + \frac{\partial \sigma_z}{\partial z} + \frac{\tau_{rz}}{r} + f_z = \rho\left(\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z}\right) \end{cases} \quad (14)$$

where:

$\sigma_r, \sigma_\varphi, \sigma_z$ – 3-D stress state normal stress components,
$\tau_{rz}, \tau_{zr}, \tau_{r\varphi}, \tau_{\varphi r}, \tau_{\varphi z}, \tau_{z\varphi}$ – 3-D stress state tangent stress components,
v_r, v_φ, v_z – formed material displacement velocity vector components,
ρ – formed material density.

System of equations (14) describes equilibrium state for three-dimensional stress state written for cylindrical coordinates during axisymmetric semi-finished products electrodynamic forming in use of compressing, bulging and stamping effects. The above equations system is composed of relationships which describe three-dimensional stress state in formed element for elastic – plastic materials with acting at forming element massless Lorentz forces and connected to it movement inertia forces. On the basis of shown relationships, which describes physical phenomena character during electrodynamic forming process complete mathematical model was made, which were used as system of equations determining basis in carried out shape prediction calculations.

From equations (14) in first turn relations describing electromagnetic field distribution in forming semi-finished product surrounding were isolated. Based on received distributions values of volumetric Lorentz forces were determined, which made one of the boundary conditions at finite element analysis used as a calculation tool [3].

3. NUMERICAL ANALYSIS OF ELECTRODYNAMIC METAL FORMING PROCESS

In equations constituting mathematical model electrodynamic processes of pipes compressing or bulging and sheet shallow stamping two kinds of relationships can be distinguished:

1) concerning electromagnetic phenomena,
2) describing forming elements deformations at plastic range.

First of them, were used to magnetic field intensity at coil – semi-finished product system and forces acting on metal elements placed in this field determining. Obtained results were used for determination of pressures distributions acting on forming semi-finished products surfaces, what in turn allow for pointing out interesting their parts displacement distributions with making use of other equations.

3.1. Distributions of magnetic field intensity in coil – bulged pipe system

In Figure 3 geometry of coil – bulged pipe system is presented, for which magnetic field distributions were determined.

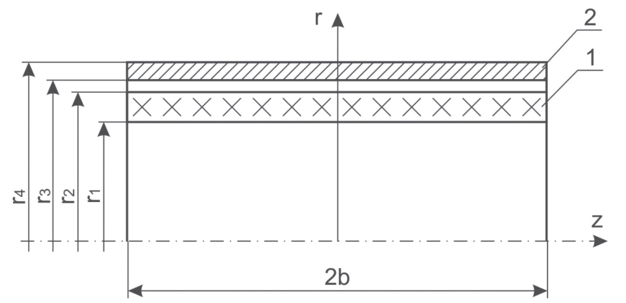

Fig. 3. Coil – bulged pipe system scheme: 1 – coil, 2 – pipe

Calculations were carried out for coil with following parameters: r_1 = 19.5 mm; r_2 = 23.5 mm; 2b = 60 mm, number of copper turns z = 9, pipe wall thickness $g = r_4 - r_3$, turn thickness $g_z = r_2 - r_1$.

Calculations were determined for cases of aluminum pipes bulging with inner diameter 48 mm and different wall thickness g: 1 mm; 1.5 mm; 2 mm.

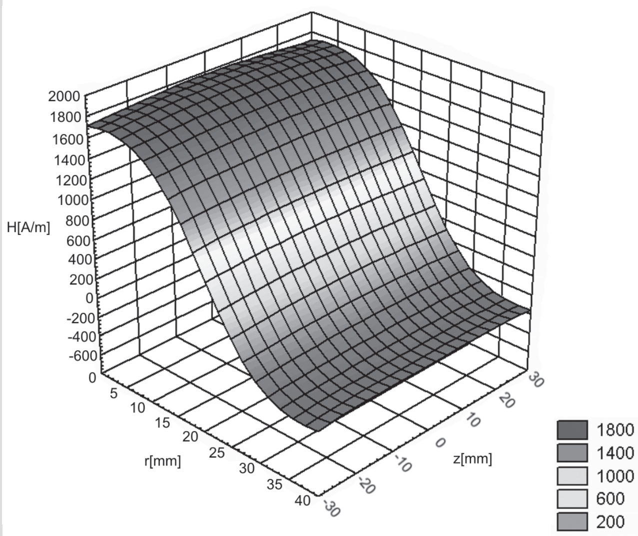

Fig. 4. Magnetic field intensity averaging values distribution character in space which surrounds coil and worked semi-finished product

Three-dimensional Figure 4 presents distribution of magnetic field changes in space which surrounds coil inserted into bulged pipe. Its illustrate trends of field changes along pipe generating line and wall thickness.

3.2. Distributions of magnetic field intensity in flat coil – stamped sheet system

In Figure 5 geometry of coil – stamped sheet system is presented, for which calculations were carried out.

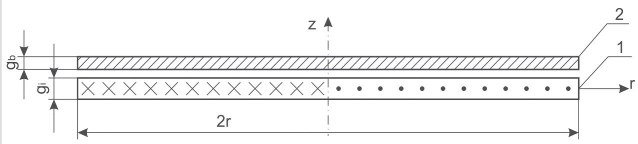

Fig. 5. Coil – stamped sheet system scheme: 1 – coil, 2 – sheet

Calculations were carried out for coil with following parameters: g_i = 16 mm; 2r = 200 mm, number of copper turns z = 22.

Calculations were determined for cases of aluminum sheets stamping with different thicknesses g_b: 1 mm; 1.5 mm; 2 mm.

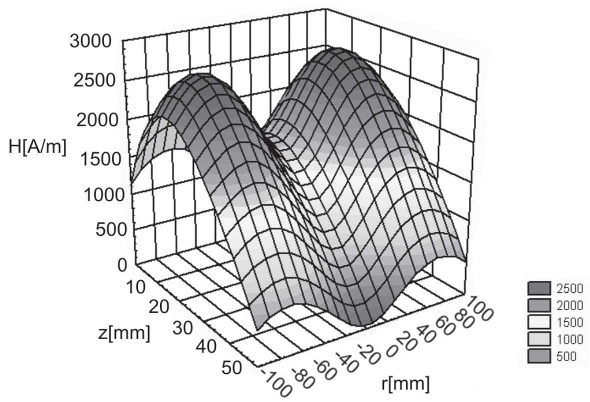

Fig. 6. Magnetic field intensity averaging values distribution character in space which surrounds coil and worked semi-finished product

In Figure 6 magnetic field intensity averaging value distribution in space which surrounds flat coil and formed sheet is presented. Those values were determined along coil generating line and in dependence of its radius.

3.3. Distributions of pressures acting on walls of bulging pipes and stamping sheets

Pressures acting during electrodynamic forming were calculated by knowing earlier pointed out magnetic field intensity H values which occur at surfaces of forming semi-finished products [4, 5]. Calculations were made following the rule that unitary magnetic field energy is equal pressure p exerted on forming semi-finished product

$$p_n = \mu \frac{H^2}{2} \tag{15}$$

where:

- p_n – pressure repelling parts of semi-finished product against coil,
- H – magnetic field intensity tangent component at surface of semi-finished product from the side of a coil.

If magnetic field excited by coil permeate forming metal value of pressure acting on semi-finished product was calculated from the formula

$$p_n = \mu \frac{H_1^2 - H_2^2}{2} \tag{16}$$

where: H_1, H_2 – magnetic field intensity tangent components at surfaces of semi-finished product: faced to coil and on the other side of a coil.

In Figure 7 values of pressure acting on inner surface of bulged pipe distributions are presented. Distributions were determined along coil – bulged pipe generating line z (Fig. 3) for different wall thickness g: 1 mm; 1.5 mm; 2 mm.

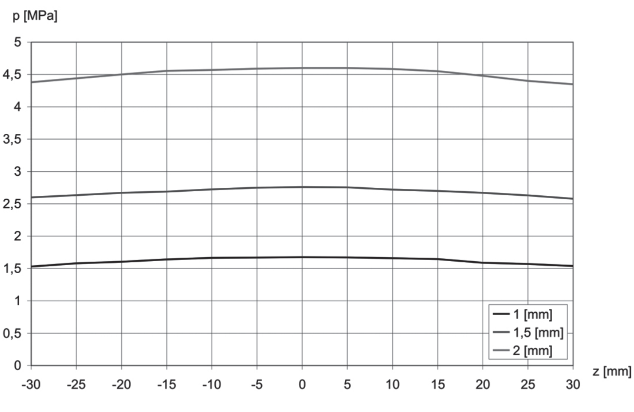

Fig. 7. Pressure acting on bulged pipe distributions along generating line z for different wall thickness, energy from capacitor E_g = 5.8 kJ

Figure 8 presents pressure acting on stamped sheet distributions. Distributions were determined along coil – stamped sheet system radius r (Fig. 5) for different sheet thickness g_b: 1 mm; 1.5 mm; 2 mm.

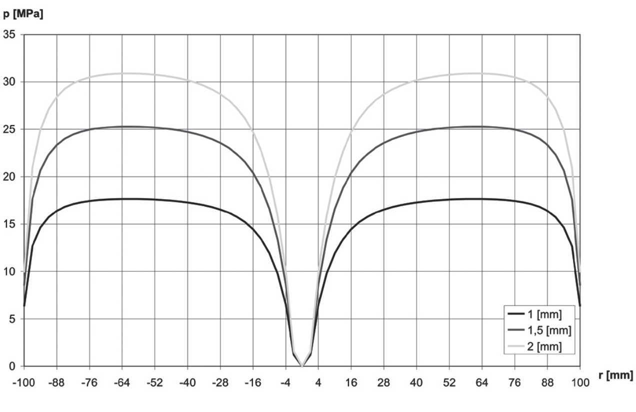

Fig. 8. Pressure acting on stamped sheet distributions for different thicknesses, energy from condensers E_g = 4.0 kJ

3.4. Electrodynamically formed element parts displacement

In carried out analysis connected to possibilities of electrodynamic deforming of semi-finished products finite element method was used in the form of MSC.Marc/Mentat software. In view of axial symmetry of forming elements during creation of models 4-noded axisymmetric elements were used, where as one of the boundary conditions shown in Figures 7 and 8 pressure was taken. Within strengthen analysis framework standard Newton-Raphson iteration procedures were used. In presented below diagrams displacement at wall cross sections of bulged pipe and stamped sheet values distributions are shown. Mutual positions of working tool (coil) and worked semi-finished products are shown in Figures 3 and 5. Worked elements displacement distributions were determined for pipes made from PA 38 alloy and for sheets made from Al 99.9% aluminum (Figs 9–12).

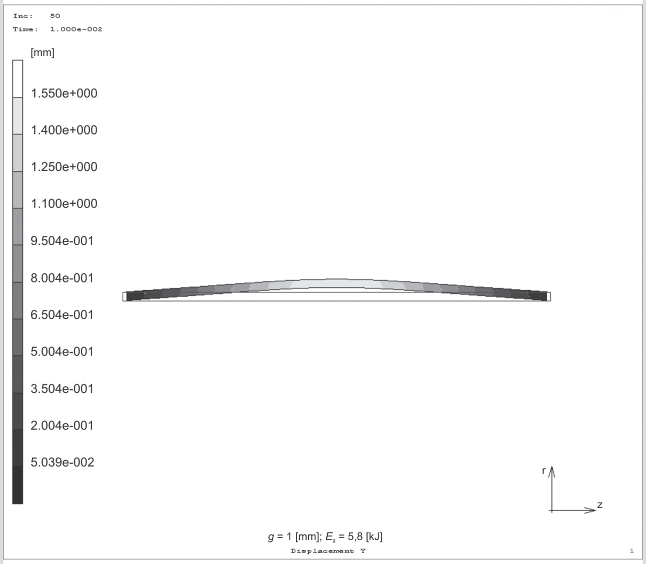

Fig. 9. Pipe wall final displacement, material PA38 aluminum alloy in as-rolled conditions

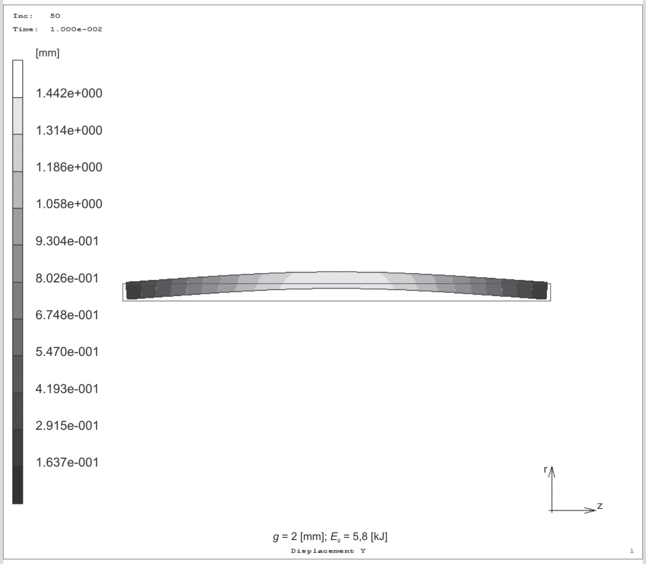

Fig. 10. Pipe wall final displacement, material PA38 aluminum alloy in softening conditions

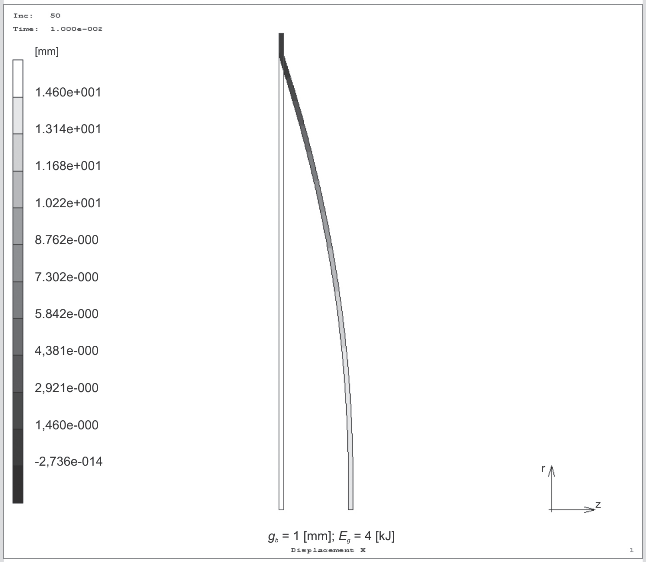

Fig. 11. Sheet final displacement

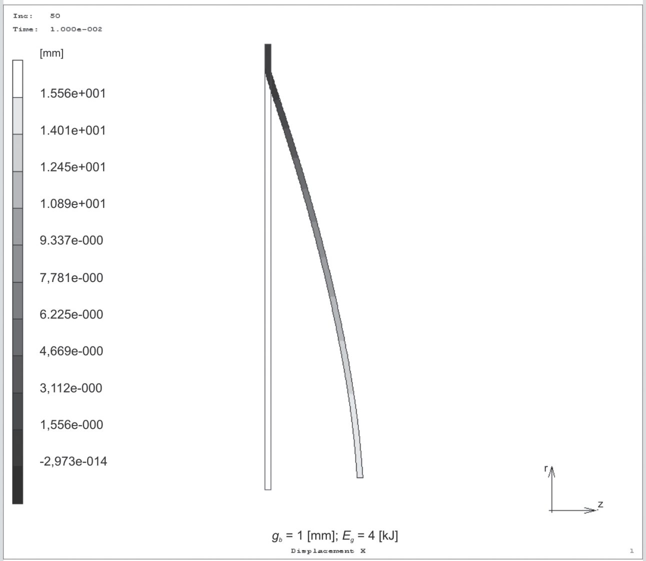

Fig. 12. Sheet with hole final displacement, g_b = 1 mm; E_g = 4 kJ

4. EXPERIMENTAL RESEARCH

In the previous chapter analytically determined distributions of pressures acting on semi-finished products and displacements of its elements during electrodynamic forming operations were presented. Obtained results are effect of the mathematical model solution, in which for description of complex electromechanical phenomena occurred during forming many simplified assumptions were taken. For analytically obtained results verification experimental research cycle were undertook, which aim was:

- determination of real pressure distributions acting on semi-finished products formed in pulse magnetic field with use of cylindrical and flat coils,
- making series of working operations consists in electrodynamic forming of pipes and sheets processed by determined pressures without using shape dies.

4.1. Pressure values determination

Value of resultant pressure acting on element electrodynamically formed results from relationship (16), for which magnetic field intensity tangent component correspond to magnetic field intensity axial component H_z in case of cylindrical coils and radial component H_r – in case of flat coils. Values of magnetic field intensity were determined by measurements. Metrology problem rely on magnetic field intensity tangent component measurement in choose points at semi-finished product surface from side of a coil and on opposite side. Measurement experiments were realized by using miniature sensors made as air induction coils, placed at semi-finished product surface in such a way, that coil cross section was perpendicular to magnetic field lines.

Figures 13 and 14 present pressure values distributions acting on inner surface of bulged pipe and on surface of stamped sheet obtained analytically and by measurements [6]. Pressure values expressed on diagrams in relative units were determined for identical generator energy values E_g.

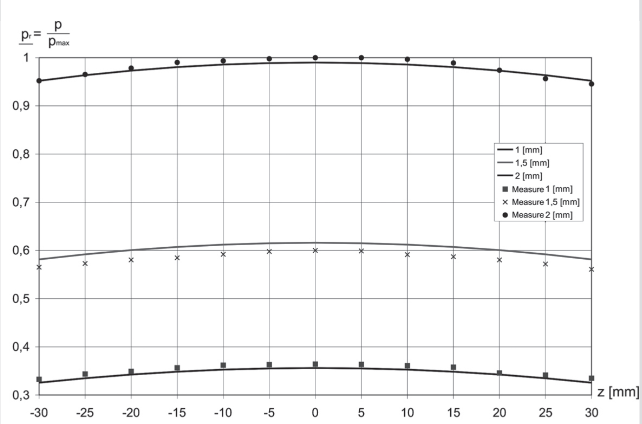

Fig. 13. Distributions of measured and calculated values of pressure acting on bulged pipe wall along generating line z for various wall thickness

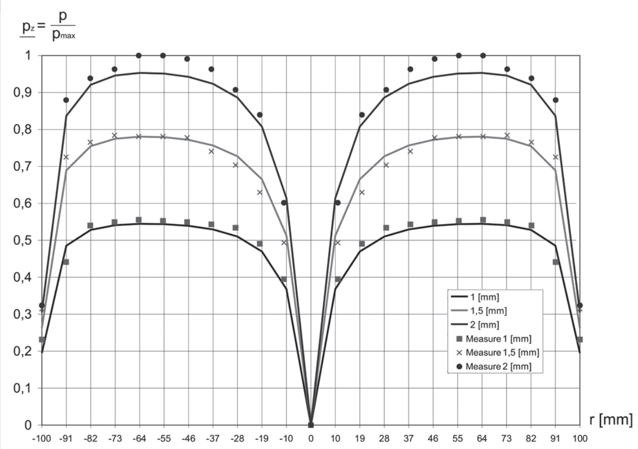

Fig. 14. Distributions of measured and calculated values of pressure acting on stamped sheet along radius r for various its thickness

4.2. Free forming of pipes and sheets

Experiments relies on electrodynamic pipe segment bulging (Fig. 15) and sheet disks stamping (Fig. 16), which dimensions are compiled in Tables 1 and 2. Full disks and disks with central hole with diameter D_0 were submitted to stamping.

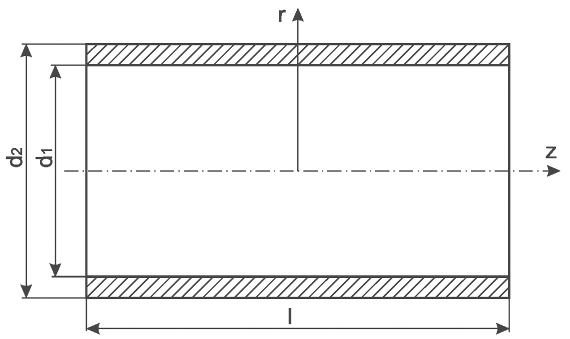

Fig. 15. Assigned for bulging pipe segment

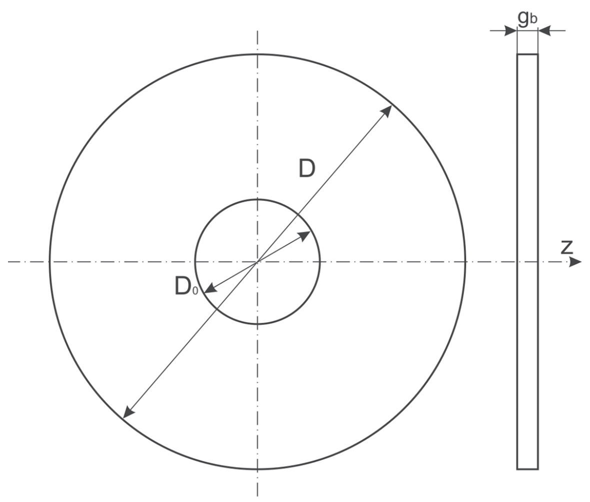

Fig. 16. Assigned for stamping sheet disk

Table 1

Dimensions of bulged pipes by energy $E_g = 5.8$ kJ

No.	Material	State	d_1 [mm]	$d_2 - d_1$ [mm]	l [mm]	Δr_{max} [mm]
1	PA 38	soften	48	1	60	4.6
2	PA 38	soften	48	1,5	60	2.45

Table 2

Dimensions of stamped disks by energy $E_g = 4.0$ kJ

No.	Material	State	D/D_0 [mm]	g_b [mm]	Δz_{max} [mm]
1	Al. 99.9%		200	1	19.2
2	M63	soften	200/60	1	14.7

In the last columns of the tables maximum values of pipe wall displacement Δr_{max} and sheet disk displacement Δz_{max} after working is presented. In Figures 17–20 diagrams of pipes wall displacement distribution along their generating line and sheet drawings along disks radius, obtained by calculations and determined by measurement of formed samples are compared. Measurement of diameters and drawings depth were made in marked places shown in figures of formed semi-finished products. It should be marked, that semi-finished products before forming were submit to softening heat treatment, which consists in its annealing in temperature 400 Celsius degrees for one hour and next free self-cooling at room temperature. All pipes were free shaped, but sheet disks before forming were mounted in grip to prevent displacement of disk border.

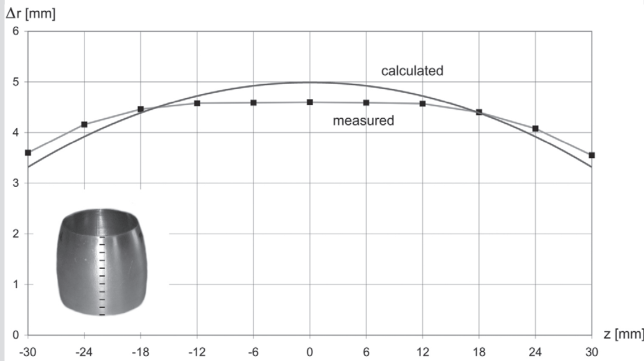

Fig. 17. Bulged pipe radius increment along generating line

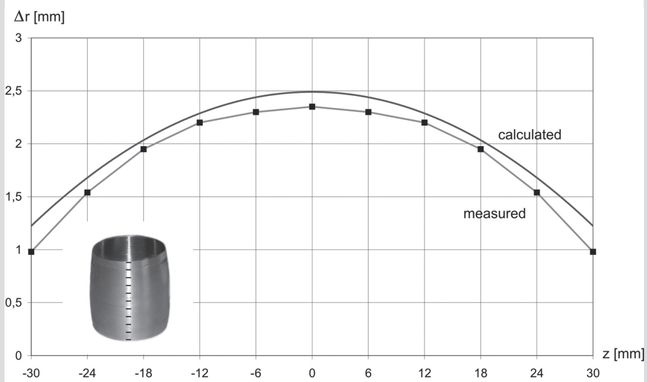

Fig. 18. Bulged pipe radius increment along generating line

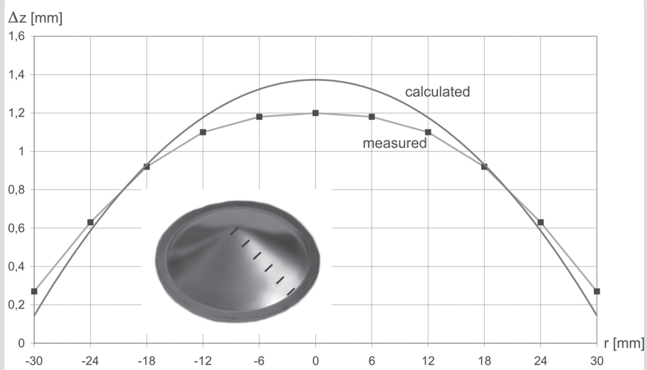

Fig. 19. Stamped sheet disk stamping depth increment along radius

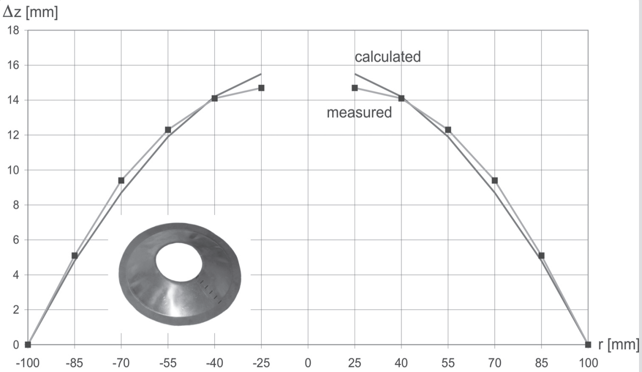

Fig. 20. Stamped sheet disk stamping depth increment along radius

In order to compare sample displacement grade obtained analytically and experimentally relative coefficients were introduced:

– for pipes

$$\chi_r = \frac{\Delta r_t - \Delta r_p}{r_2} 100\% \quad (17)$$

– for sheet disks

$$\chi_k = \frac{\Delta z_t - \Delta z_p}{R} 100\% \quad (18)$$

In equations (17) and (18) following denotations were taken: $\Delta r_t, \Delta r_p$ – pipe radius increments obtained analytically and experimentally; $\Delta z_t, \Delta z_p$ – sheet disks stamping depth increments obtained analytically and experimentally; $r_2 = \frac{d_2}{2}$, $R = \frac{D}{2}$ – pipe and sheet disk radius initial values (Figs. 15 and 16).

In Table 3 obtained for tested samples maximum values of relative coefficients are compiled. Ordinal numbers of tested samples are the same as those showed in Tables 1 and 2.

Table 3

Deformation relative coefficients value

Stamped sheet disks		Bulged pipe	
No.	$\chi_{k\,\max}$ [%]	No.	$\chi_{r\,\max}$ [%]
1	4.6	1	1.62
2	0.8	2	0.63

High divergence of obtained analytically and experimentally deformations is characteristic for sheet disk in area around its centre, which is dead zone results from flat coil construction. In that zone Lorentz forces values are equal zero, but obtained deformations are not effect of direct exerting of pressure acting on surface of disk [3].

5. SUMMARY

The main advantage of metal forming in pulse magnetic field generated by induction coil called inductor which conducts short oscillating current is the possibility of sheets and pipes plastic forming without using dies. In the article analytical method of solving this problem on the basis of electrodynamic phenomena, which happens during forming is proposed. At first stage of the analysis on the basis of electromagnetic field theory equations, three-dimensional Lorentz forces distributions acting on forming elements for cases of pipes bulging and sheet shallow stamping were determined. In second stage of the analysis, mathematical model describing pipes shaping process dynamics was proposed. This model allows for formed semi-finished products final shapes determination. Making mentioned model equations from theories describing stress and strain states at forming element were used. Into that model determined in the first stage, Lorentz forces and inertia forces from movement during forming were taken. Analytical considerations were limited to cases in which shapes of semi-finished products has axial symmetry and for which elastic – plastic material have isotropic physical properties. Formed semi-finished products elements displacements were obtained by solving presented models in numerical manner with use of FEM software in version MSC.Marc/Mentat. Elaborated model was verified by series of experiments in which pipes and sheet rollers with thickness up to 2 mm and generator energy up to 6 kJ were formed. For presented conditions maximum difference between deformations obtained analytically and experimentally does not exceed about 1.5%. This shows that elaborated model is useful for semi-finished product final shape prediction for materials with early known dimensions, as well as material characteristics which are electrodynamically formed by set energy.

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