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A Method to Study Thickness Reduction in Electro-hydraulic Forming of Cones

In this paper are presented some of the authors experimental researches connected to the electrohydroimpulses drawing of the thin conical parts made from aluminium, and also to the quality of these parts. Experimental conditions are specified and comparatively presented some results obtained for the same kind of parts, but in the case of magnetic impulses drawing (magneto – dynamic deformation). As a criterion for the quality of the parts obtained by electrohydroimpulses drawing in monoimpulse regime, the distribution of material's thickness reduction lengthways with the cone element is adopted, for different geometries of the cone. The study is achieved for various intermediate deformation stages and discharge energies.

Keywords: *cone, electrohydraulic forming, thickness, quality, drawing*

1. Introduction

Due to the technical difficulties which occurs in the case of classic drawing of the conical parts with thin walls, it has been tried to obtained this parts by alternative cold forming methods, non-conventional, such as the methods based upon the so-called technique of high energies-bearing impulses. Some of the more known proceedings from this category are explosive forming, magnetic impulses and electrohydroimpulses (electrohydraulic forming).

Some of the speciality papers [1,6,7,8] indicates the fact that in the case of explosive forming using high explosives of conical parts without flange, having vacuum in die cavity and using a small curvature of the shock wave front (meaning conical shape blasting charge located at a relative high distance to the semi-manufactured plate), it has been obtained parts with vertex angle between 30° and 130°, but of low quality. The unsuitable quality was given by the apparition of stability loss and unbalanced strain phenomenons, at their turn these phenomenons being a result of semi-manufactured plate's offsetting in the die's space. So, parts with variable length of the element of cone are obtained.

2. Experimental research

In some of the author's previous papers [2,3] has been presented the construction parameters of the own designed universal discharge chamber used in the experiments and also, of the electric system whereon the chamber was coupled (russian origin, model GIT 50 – 5x1/4C, modified).

The condensers battery capacitance was of C = 4...8μF and the discharge circuit inductance of 3,2 μH. The semi-manufactured plates was greased both on the die-block side and on the retaining ring one, only on the contact area, with 5-degree consistence grease (hard), of the type U 75 Ca 2, STAS 562-86. It was proved that, due to the high consistence, one can thus also ensure the sealing of the system retaining ring - plate - die-block. The tightening force on the screw at the retaining ring, measured with a dynamometric wrench was of 20 daN. The discharge electrodes was made by copper, having a conical shape, 8 mm in diameter and a non-isolated surface of 2,56 cm^2.

The condensers battery of just one generator (from those two of the group, with parallel connection) is made by a four condensers group, also of russian origin, IKG 50 UHL 4 type, each of them having 1 μF nominal capacity and 800 nH maximum inductance, nominal voltage being of U = 50kV.

The experiments was made on parts with flange (in order to avoid the danger of semi-manufactured plate offsetting), from aluminum sheet AlMg3 annealed, romanian standard STAS 7608-80 (Mg 2,7...3,5%; Mn 0,1...0,4%), with the thickness g = 1 mm and diameters ϕ_s = 140 and 210 mm. The die-block had a cone base diameter of ϕ_c = 120 mm and vertex angles α = 60°, 90°, 120°, with a die entrance radius of 6 mm. After the semi-manufactured plate flange was tightened with the retaining ring, the conical cavity of the die was evacuated. The experiments proved that an air pressure under 7 Pa ensures a better moulding of the semi-manufactured plate on the die surface and leads to drosses avoiding on the part face from the die-block (drosses occurs as a result of air heating during it's fast compression at manufacturing).

3. Magnetic impulses drawing

The experiments made using a spiral plane inductor shown that for parts with narrow flange, specific defects like in drawing occurs, meaning wrinkles on the flange zone and on the section neighbouring to conica part base. So, the semi-manufactured plate setting becomes unstable and the offsetting occurs again, followed by obtaining a flange with unequal width. For plates with ϕ = 210 mm, that is for a ratio $\phi_s / \phi_c > 1,7$, the flange strains was small and by copying of die cavity shape it was obtained an almost correct shape of the part.

Also, the complete forming of parts with vertex angles 90° and 120° was achieved. The parts with vertex angle 60° was unsuitable, as a result of part crack,

crack which occurs on the cone base, at the filleted corner between flange and element of cone (for high discharge energies) or at cone apex (for low discharge energies). It is to be noticed that the change in discharge energy influences both shape precision of the part's conical surface and the material thickness variation lengthways to element of the cone (fig.1).

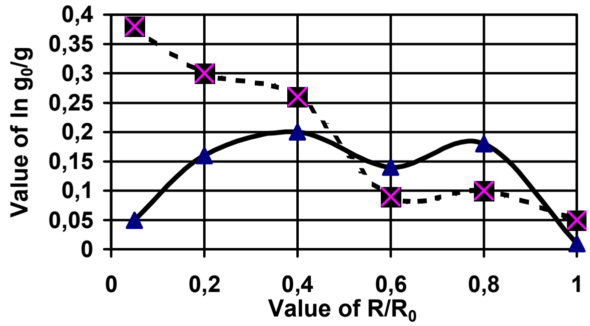

Figure 1. The dependence of thickness lengthways to element of the cone, for different discharge energies (apex angle 120°, plate diameter 210 mm)
■ – 4,3 kJ, C = 6 μF, U = 38 kV; ▲ – 6,1 kJ, C = 6 μF, U = 45 kV
R_0 – initial plate radius; R – momentary radius; g_0 – initial thickness; g – momentary thickness

As it is shown, when discharge energy increases, the material's thickness reduction near the flange increases and the material's thickness reduction near the cone apex decreases. This can be explained by the fact that, for a higher discharge energy, the speed of axial movement of the semi-manufactured plate is higher, obviously resulting a larger stretch strain on the longitudinal wave front which starts from the retaining ring zone. In the same time, a bigger reduction in thickness of the peripheric zone leads to a smaller value of thickness reduction for the central zone of the plate, under the condition that the die limits the crushing tendency of the central section.

It was experimentally proved that for a conical part with satisfactory quality it is necessary the discharge energy to be approximate 6...8 times bigger that in the case of a spherical part with same height, material and thickness, having the diameter equal to cone base.

Other experiments related to the forming capability of the conical parts are presented in paper [9], where the wrinkling phenomenon was studied. A schematic of the experimental setup used to test the effects of sheet velocity on wrinkling is shown in fig. 2. A vacuum chamber houses a flat electromagnetic coil. A sheet metal blank is placed over the coil. The die into which the metal is to be formed is positioned directly above the sheet metal. Discharge of the capacitor bank propels the aluminum sheet at the die.

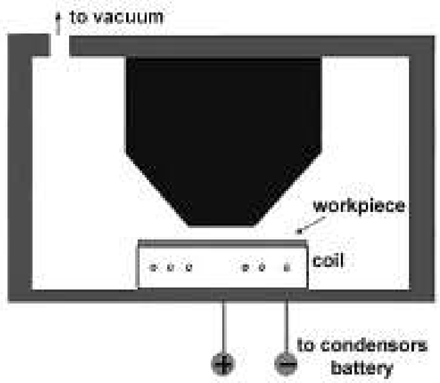

Figure 2. Experimental set for obtaining conical parts

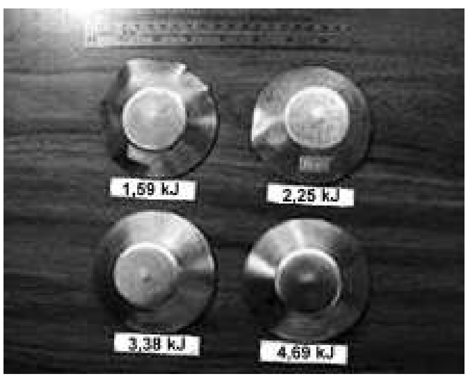

Figure 3. Samples obtained by electromagnetic impulses

For the wrinkling studies, a male die in the shape of a cone section of semi-apex angle 45° was used. Sheets of 1100-O Al were formed over the die. At low capacitor discharge energies (approximately 1,69 kJ), significant wrinkling occurred. When the energy level was increased to 2,25 kJ, the extent of wrinkling declined and was completely absent at 3,38 kJ and 4,69 kJ. A photograph of samples formed at different energy levels is shown in fig. 3. Similar trends in wrinkling were observed in 6061 T-6 Al. No blank holders were used in this experiment.

Inertial effects are thought to be responsible for reduced wrinkling. A brief, one-dimensional example can demonstrate how this might occur. Consider a slender bar (like an arrow), thrown at a wall. When pressed against the wall statically or when projected at low speeds, the bar buckles. However, when projected at high speeds, buckling does not occur.

In this way it could be conclusioned that the deformation of conical parts by electromagnetic impulses, in monoimpulse regime, is possible only for parts with relative big apex angles and only for carefully chosen discharge energies. The obtained shape is not too accurate, the plate recoil at the impact with the die and the central zone necking during setting on die phenomenons having a great influence on the precision and the quality of the parts.

4. Electrohydroimpulses drawing

The electrohydroimpulses drawing, both for working in monoimpulse and multiimpulse regime, is characterized by another map of the pressure distribution on the plate surface, reported to the hydraulic drawing or to the electromagnetic impulses. In a schematic way, the succession of part shape modification for different types of pressure loadings is given in fig.4.

If in the case of using spiral plane inductor the pressure decreases towards the semi-manufactured plate center, in the case of electrohydroimpulses drawing it's an inverse situation, that is the pressure increases in the plate center. Obviously, these types of loadings must leads to different successions of part shape in the intermediate stages of deformation.

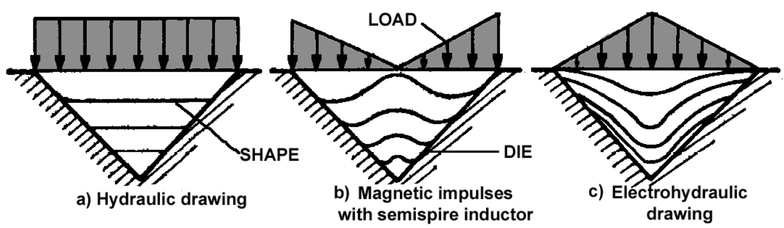

Figure 4. Changing in part shape for different pressure loadings

As it is shown, in the center of the part occurs a zone which has an inverse curvature reported to the final one [8,9]. As a result, the part center will be obtained in the deformation final stage, and the longitudinal plastic wave which starts from the retaining ring zone determines the appearance of some radial components of the material particles movement, components which are oriented starting from the plate axis. These will determine a high degree in thickness reduction near the part apex.

In the case of electrohydroimpulses drawing in mono or multiimpulse regime, due to the higher pressure in the part center, this zone will has a curvature with the same sign as the final one. Also, in this case, the longitudinal wave is spreading from the center towards the periphery and as a result, behind the wave front, occurs a deflection of material particles, deflection having a radial component directed to the part axis. This determines a filling of cone apex, without additional thickness reduction.

It is supposed that the semi-manufactured plate deformation will take place both under the action of direct shock waves and reflected from the dome or from the discharge chamber walls. Furthermore, the interaction between direct and reflected waves, as well as the interaction between incident on the plate and reflected from the plate waves can substantially change the pressure distribution map on the plate surface. Despite of these, the importance of these interactions reported to the effect on the total deformation degree is minor. On the other side, an important influence could has the second pressure impulse, due to gas bubble.

The diagrams obtained in the monoimpulse regime experiments [5] proved the existence on the plate surface of a various pressure distribution, depending on the symmetry zone of the shock wave front shape (cylindrical, transition cylindrical-spherical and spherical), on the measuring direction reported to the discharge axis and, obviously, on the distance to the plate center.

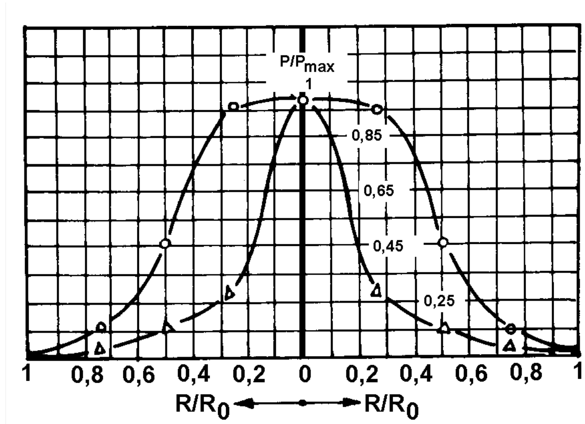

Figure 5. Pressure experimental distribution on the plate surface in the cylindrical symmetry zone

° longitudinal direction ; Δ cross direction on the discharge axis

In figure 5 is presented the pressure experimental distribution on the plate surface, in the cylindrical symmetry zone $h/l < 2,5$, where h – semi-manufactured plate–discharge axis distance; l – electrode gap.

Experiments made on semi-manufactured plates [2] shown that, for each combination of the electrical parameters of the discharge circuit, the maximal effects on drawing depth is obtained for ratio values $1 \leq h / l \leq 2$.

Also, in this values range of the ratio h / l, the value of the ratio P_{max} / P_g remains approximate stable (where P_{max} – maximal pressure of shock wave, experimentally determined on plate center and P_g – bubble gas pressure), which means that the quantitative study of the maximum drawing depth can be made taking into account just one of the components.

On the experimental results basis obtained in [2], it can be said that, for multiimpulse manufacturing in automatic regime, doesn't exist important differences of pressure maximal values and of theirs distribution on plate surface (for each impulse separately considered) in comparison with monoimpulse manufacturing, except the case of very short time between two successive shots.

Also, the experiments made on real plates [2,4] proved that this various pressure distribution doesn't lead to significant modifications of drawing depth measured on those two directions (longitudinal and cross on discharge axis). As a result, from the real physical effect point of view, this various distribution can be replaced with a distribution having a constant variation law on the entire surface of the semi-manufactured plate, equal to the average of pressure maximal values, for each R radius of the plate measured in those two directions [5], as can be seen in fig. 6 (P_L – pressure in longitudinal direction on discharge axis, P_T – pressure in cross direction, P_{rez} – resultant pressure).

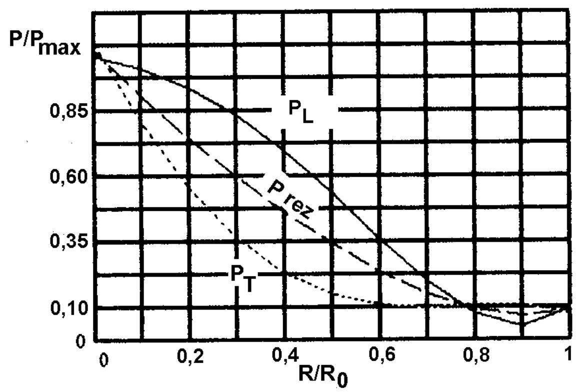

Figure 6. Theoretical pressure approximation on plate surface

During the experiments made to clarify how the conical parts are deformed, has been used intermediate conical parts of different heights, introduced in the working die, these compeling the semi-manufactured plate to stop in different strain intermediate stages (drawing of some frustum of cone with different heights). The distribution of thickness modifications lengthways to the element of the cone, for different heights of the frustum of cone with an apex angle equal to 60°, to the same discharge energy (10 kJ; U = 50 kV; C = 8μF) is given in fig.7. Semnifications: ♦ - ratio $h/h_0 = 0,2$; ■ – ratio $h/h_0 = 0,3$; ▲ - ratio $h/h_0 = 0,4$; – - ratio $h/h_0 = 0,7$; marker ▬ and dash line (------) - ratio $h/h_0 = 1$ (finished part).

From the diagrams results that at small height ($h/h_0 = 0,2$ and $h/h_0 = 0,3$), the biggest thickness reduction occurs near the flange. This can be explained by the fact that, when passing from the conical surface to plane zone, the longitudinal wave is spreading towards the retightening zone, determining a relative high thckness reduction. When the height increases ($h/h_0 = 0,4$ and $h/h_0 = 0,7$) and the cone formation is more and more complete, the sections with big thickness reduction are moving towards the part axis. With all these, even when the part formation is complete ($h/h_0 = 1$), the zone with the highest thickness reduction is not on the part axis, but moved on the zone where the maximal variation gradient of the resultant pressure lengthways to the plate radius occurs (fig.6).

Under these conditions, the study was based on the average of the maximal pressure distributions, even these, for different components, are reached in different moments in time [2,4]. This way to solve the problem is dictated by the necessity to consider the global effect of the pressure impulses on the plate.

Regarding the pressure distribution measured lengthways to the discharge axis, it is to be noticed that on a zone with a length approximate equal to the electrode gap, the pressure decreasing gradient on the radius is relatively low. But, when the plate – discharge-axis distance increases, the pressure decreasing gradient increases, that zone having a higher and higher curvature.

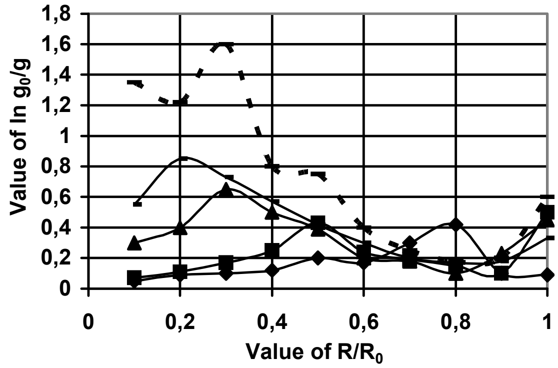

Figure 7. The distribution of material thickness variation lengthways to the element of the cone, for different strain degrees

In fig. 8 are presented the diagrames of material thickness variation lengthways to the element of cone with apex angle equal to 90°, for different discharge energies. Semnifications: ♦ - 6,4 kJ (8 μF, 40 kV); ■ – 9,2 kJ (8 μF, 48 kV); ▲ – 10 kJ (8 μF, 50 kV).

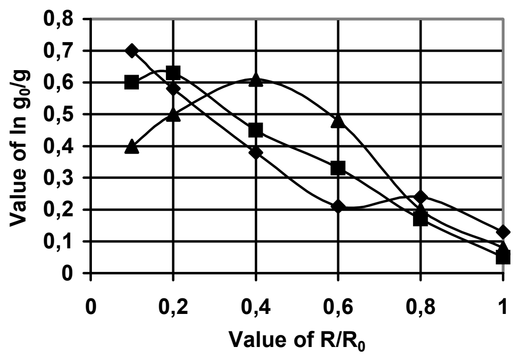

Figure 8. Dependence of thickness modifications by different discharge energies

From the diagrams results that for the discharge energy 6,4 kJ, the biggest thickness reduction occurs at the top, central zone being in danger to crack. For high discharge energies, at the cone apex can occur an increase in material thickness. This increase in thickness can be explained by the radial movement towards the axis of the material particles, on the longitudinal plastic wave front, in the apex final forming stage, movement which leads to volume growing of the central section of the part and to the increase in thickness. The diagrames in fig. 6 and 7 confirms the results presented in paper [8].

5. Conclusions

The practical "forming window" in a metalforming operation is usually limited by necking or tearing problems on one hand and wrinkling on the other. In conventional metalforming processes, this "forming window" for aluminum is very narrow as tearing is severe and wrinkling and springback are pronounced. High-rate forming techniques make aluminum more formable by widening the forming window on both sides.

An increase in ductility can be explained, at least partially, on the basis of inertial stabilization of neck growth during high-rate forming. Note that since there is a significant increase in ductility with velocity for many materials, forming limits of those materials become a function of the metalforming velocity. Therefore, efforts to predict forming capabilities of methods operating in the range of high forming velocities must include this effect.

The conical parts forming by electromagnetic impulses, in monoimpulse regime, is possible only for parts with relative big apex angles and only for carefully chosen discharge energies. The obtained shape is not too accurate, the plate recoil at the impact with the die and the central zone necking during setting on die phenomenons having a great influence on the precision and the quality of the parts.

Obtaining by electrohydroimpulses in monoimpulse regime of the conical parts is more propitius from the part quality and accurate point of view, but it is advisable to be limited to the conical parts with flange, with apex angles over 60° and with small apex filleted radius. In the case of the parts with high drawing depths, manufacturing using just one impulse is obviously insufficient. In this case it is to be used multiimpulse drawing, shot by shot regime or automatic regime (impulse sequence or spike train). It is expected that, due to wrinkling tendency and material hardening, as well as due to the increasing of plate – discharge axis distance, the deformation of the plate to be more harder that on primary impulse. The technological implications of multiimpulse manufacturing can be the subject of subsequent researches in the field.

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