Formation of deep-drawing in an open-die by pulsed-magnetic field pressure

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Abstract. The deep-drawing process is considered one of the most important metal processing processes, which is used to form sheet metal of bowl-shaped structures in the field of mechanical engineering, aviation and rocket engineering under tension and compression without changing the sheet thickness. The present work is to evaluate the formability of an aluminum alloy sheet using an open-die in deep drawing process, an attractive manufacturing technique using electromagnetic force (Lorentz) to form metal parts. This work investigates the history of deformation (displacement, deformation, strain rate) in the process of electromagnetic deep drawing in an open-die using a numerical model. The research methods are the finite element method (FEM) associated with the boundary element method (BEM) using LS-DYNA software for the analysis of electromagnetic, mechanical and thermal solvers. Results analysis of the deformable solid thickness in the process of deformation showed that the thickness increased in the marginal zone and reached 1.77 mm. Further, the thickness in the middle zone decreased by 0.23 mm and decreased by 0.35 mm in the central zone. The plastic deformation of the workpiece gradually increased from zero to 26% for the middle zone, 31% for the marginal zone and 46% for the central zone.

1. Introduction
This paper describes the numerical simulations, which carried out to determine the effect of various process parameters, such as discharge voltage and effect of EMF process, on the height of the dome, the diameter of the open die, the maximum major / minor deformations, the distribution of deformation and the distribution of the thickness of the D16AM sheet during free electromagnetic forming. Investigation of the behavior of the D16AM aluminum alloy in the conditional finite element simulation of magnetic pulse deformation is due to stretching process [1–4]. The results show that the height of the dome and the maximum deformation of the samples have a positive relationship with the discharge voltage. The maximum basic deformations of the order of 35–47% appear in the upper part of the dome peak, which is also the main area of thickness reduction, which indicates that the effect of inertia plays a key role in the EM process. In addition, an example of numerical simulation of electromagnetic formation was presented in the electromagnetic analysis module with the resulting mesh of the workpiece shape using a rigid plate under the workpiece to avoid corrugation defect or metal shrinkage [3, 4].
2. Materials and Methods

2.1. Experiment setup
The die 1 and plate (holder) 4 were modeled as a rigid body using shell elements. The blank 2 was positioned over a flat spiral coil 3 to evenly distribute the pressure and Lorentz force [5–8]. A solid hex mesh was built for the coil and blank. Shell elements were used for the die and plate. The grid model consisted of 2248 elements for the coil, 1848 for the aluminum sheet, 480 shells for the die, and 962 for the plate. A flat helical coil comprising 7 turns was made of 4 mm × 4 mm square copper wire. Figure 1 (a) shows the grid model at the initial time [9–12].

![Figure 1](image1.png)

(a) (b)

Figure 1. Longitudinal section finite element modeling with seven-turn coil: 1 – die; 2 – blank; 3 – coil; 4 – plate / holder (a) and its scheme of the electromagnetic forming (b).

2.2. Analysis of the results
At the end of the simulation, a graph of plastic deformation with values of 26% for the middle zone, 31% for the marginal zone, 46% for the central zone are displayed in figure 2 (b). Plastic deformation during the drawing process showed that the greatest amount of deformation is concentrated in the central zone of the workpiece, where the material flows over (figure 3).
Figure 3. Plastic deformations at different stages of forming from time to time: a – 0 sec., b – 5e-5 sec., c – 1e-4 sec., d – 1.5e-4 sec., e – 2e-4 sec., f – 2.5e-4 sec.
Figure 4 shows a graph of the hardening curve (stress versus strain) for the D16AM aluminium alloy with yield strength $\sigma_{0.2} = 80 MPa$ and ultimate strength $\sigma_B = 280 MPa$.

A comparison of the $z$-displacements history for three points on a deformable solid is shown in figure 5 (a). The good correlation of the results indicates that the numerical model is able to predict the displacement history quite well at different locations of the solid. This phenomenon was associated with the distribution of electromagnetic forces generated by the spiral coil, as shown in figure 5 (b). The initial delay in the displacement curve of the central region (zone of element # 585168) is due to the fact that there is no electromagnetic force in the central area (dead point) [3, 4]. Then the displacement increases rapidly, initially due to the movement of the middle area (zone of element # 583473) and continues due to the effect of inertia and concentration. In the peripheral areas (elements # 583473 and # 583182), the displacement begins earlier than the central area due to the initial direct impact of electromagnetic forces.

The thickness calculation, according to the control points, showed that the greatest thinning occurred in the central zone of deformable solid (thickness 1.15 mm), along the marginal zone, the thickness was 1.77 mm and along the middle zone of the workpiece was approximately 1.27 mm (figure 6).
The results of numerical simulation of the forming-drawing process with optimization of the parameters of pulsed loading on the workpiece to obtain parts of the required shape were summarized in the form of a nomogram [1–4]. The nomogram for determining the optimal pulsed-magnetic pressure (P) of (PMF) depending on the geometric parameters: the height of the part $h_p$, thickness $\delta_0$ and the die diameter $D_d$ and the dynamic yield stress of the workpiece $Y_{0w}$ for the deep-drawing process are shown in figure 7.

**Figure 6.** Change in the material thickness in the control zones during the deformation process.

**Figure 7.** Nomogram for determining the optimal pressure amplitude (P) of the PMF for forming a deep-drawing at various parameters $h_p$, $\delta_0$, $D_d$, $Y_{0w}$.

3. Results

Thus, the above studies allow us to draw the following conclusions:

- A model of the process using an open-die was developed and deep-drawing with a height of 72 mm was obtained in the process of magnetic-pulse deformation using the LS-DYNA program, which made it possible to solve the assigned tasks with high accuracy. During the calculation, mechanical, thermal and electromagnetic modules were used together.
The calculation of the deformable solid thickness, according to the control points, showed that the greatest thinning occurred in the central zone of the part by 0.12 mm, less than in the middle zone and by 0.62 mm, less than in the marginal zone.

Calculation of plastic deformations based on control points showed that the greatest deformation occurs in the central zone and estimated at 46%. In the central area of the deformable solid was generated (dead point) which has no electromagnetic force.

The EM calculation pressure value was estimated at 33 MPa at the deformation time 2.5e-4 sec.

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