Impact of the electromagnetic field pressure on the bending of high convex-side

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Abstract. A large number of aircraft parts made of sheet materials are used as flanges, common to such parts is the presence of walls, sides, and various elements that increase rigidity and reduce mass. These sheet parts are complex, mostly closed forms, which by plastic deformation methods require a rather complex stamping tools. Technological methods of manufacturing have certain disadvantages associated with the need to refine the shaping. In addition, the frequent updating of product designs and their constant improvement with a significant amount of experimental and small-scale production required the creation of technological methods that provide a significant reduction in terms of preparation. When punching sheet metal parts, in particular, by the pressure of magnetic-pulse field, the accuracy of shaping is mainly influenced by the shape of the flange in the process of deformation. At the final stage of shaping, an impact contact occurs between the flange of the part with the die or form-block. On impact, elastic unloading of the flange occurs due to the removal of inertial tensile stresses along the generatrix. After the impact contact, dynamic springing or rebound of the flange occurs.

1. Introduction
To optimize the modes of magnetic pulse stamping of sheet parts with flanging along the contour, from the point of accuracy view, it is necessary to know the dependence of the rebound magnitude on the impact speed on the tooling. In addition, it was necessary to determine the effect of the form-block material on the rebound. Authors believe that there are no volumetric forces and external heat sources. The stress-strain behavior of the workpiece and tooling materials in the interaction regions is described by an elastic-plastic model of the Prandtl-Reis type [1, 2]. The Mises criterion is used as a plasticity criterion.

The equations of material particles’ trajectory and the medium continuity:

\[ \dot{x}_i = v_i; \dot{V}_j \rho_0 = v \rho. \] (1)

Changes in the momentum of the material particle:

\[ \rho \dot{v}_i = \sigma_{ij,j}. \] (2)

Change in internal energy and strain rate tensor:

\[ \rho \dot{e} = \sigma_{ij} \cdot \dot{e}_{ij}; \dot{e}_{ij} = 0.5 v_{i,j} + v_{j,i}. \] (3)
The components of the stress tensor are represented as follows:

$$\sigma_{ij} = -p \delta_{ij} + s_{ij}. \quad (4)$$

Where $s_{ij}$ is the component of the stress tensor deviator, responsible for the resistance to the shape changes of a material particle and $\delta_{ij}$ represents the symbol Kronecker.

2. Numerical implementation of pulsed deformation

2.1. Mathematical calculation in the contour flanging processes

A material particle moving along its trajectory can rotate as a rigid whole, which is taken into account by the Yauman derivative:

$$\frac{Ds_{ij}}{Dt} = s_{ij} + s_{ik} \omega_{kj} + \alpha \omega_{ij}; \omega_{ij} = 0.5(v_{i,j} - v_{j,i}). \quad (5)$$

Investigating the problem of hitting the flange side of the workpiece on the rigging and writing down the equations of motion in Lagrange variables in the Cartesian coordinate system:

$$\begin{align*}
\frac{\partial r}{\partial t} &= v; \quad \frac{\partial z}{\partial t} = w; \quad \frac{1}{\rho} \frac{\partial \rho}{\partial t} = -\frac{\partial v}{\partial r} - \frac{\partial w}{\partial z} - \alpha \frac{\partial v}{r}; \\
\rho \frac{\partial v}{\partial t} &= \frac{s_{rr}}{\rho} + \frac{s_{zz}}{\rho} + \alpha \frac{s_{00}}{r} - \frac{\partial p}{\partial r}; \quad \rho \frac{\partial w}{\partial t} = \frac{s_{rz}}{\rho} + \frac{s_{zz}}{\rho} + \alpha \frac{s_{00}}{r} - \frac{\partial p}{\partial z}; \\
\rho \frac{\partial E}{\partial t} &= \frac{\partial \rho}{\partial t} + s_{rr} \frac{\partial v}{\partial r} + s_{zz} \frac{\partial w}{\partial z} + \alpha s_{00} \frac{\partial v}{r} + s_{rz} \left( \frac{\partial v}{\partial r} + \frac{\partial w}{\partial z} \right). \\
\frac{\partial s_{rr}}{\partial t} &= 2\mu \left( \frac{\partial v}{r} + \frac{1}{3} \cdot \frac{\partial \rho}{\partial t} \right); \quad \frac{\partial s_{zz}}{\partial t} = 2\mu \left( \frac{\partial w}{r} + \frac{1}{3} \cdot \frac{\partial \rho}{\partial t} \right); \\
\frac{\partial s_{00}}{\partial t} &= 2\mu \left( \frac{v}{r} + \frac{1}{3} \cdot \frac{\partial \rho}{\partial t} \right); \quad \frac{\partial s_{rz}}{\partial t} = \mu \left( \frac{\partial v}{r} + \frac{\partial w}{r} \right). \quad (6)
\end{align*}$$

Where $r, z$ are the coordinates of the material particles; $v, w$ are the components of the velocity vector on the corresponding coordinate axes; $\rho$ represents the current density of the material; $\sigma_{ij}, s_{ij}$ are the components of the stress tensors, the stress tensor deviator and the strain velocity tensor $[1, 3]$. The value $\alpha = 0$ corresponds to a plane deformed state, and $\alpha = 1$ corresponds to an axisymmetric one.

2.2. Finite Element Analysis (FEA) - model geometry

The dimensions of the circular workpiece before forming: the thickness $\delta_y$ is 1.5 mm; height of its side $H_f$ is 30 mm with a radius $R_{\text{Conv}}^f$ of 60 mm. The dimensions of the workpiece after forming: the height of the flange side $h_f$ is 31.5 mm with a radius $R_{\text{Conv}}^f$ of 36.5 mm. The load of pressure $P$ was assumed to be uniformly distributed on a convex shape with amplitude of 32 MPa on the die with a convex bend radius $r_b$ is 5 mm, as shown in figure 1.
2.3. FEA - model material

When modeling the magnetic pulse deformation of a sheet metal in the processes of flanging along the contour, the following assumptions are made (figure 2 (a)):

- The billet is considered to be thin (shell) with finite dimensions, the material is isotropic;
- The stress-strain state of the workpiece is flat;
- The temperature along the thickness of the workpiece is constant;
- The deformation process is adiabatic.

During the quasi-static shaping of sheet parts, the board loses stability in the process of bending-forming with the formation of several corrugations along the perimeter under the influence of compressive stresses arising in it (figure 2 (b)) [1, 4-7]. The fit of the corrugation defect is considered as a problem of plastic deformation of a cylindrical shell, under the influence of an external uniform distributed load $P_{uni}$. The value of the pressure required for straightening the corrugation is determined, provided that there is no loss of stability:

$$p_{uni} = \frac{2h_0\tan\alpha \delta_0 \alpha_0}{(1 - \tan^2\alpha) R_i B_i} \left[ \frac{1}{2} \left( \tan^2\alpha + \sec^2\alpha \right) - \tan^4\alpha \right].$$

$$\frac{1}{2} \left( \tan^2\alpha + \sec^2\alpha \right) - \tan^4\alpha.$$
2.4. Results of the numerical simulation analysis

Plastic strain during the convex-side bending showed that the greatest deformation is concentrated in the bending and flanging zones, where also a significant thinning of the part wall occurs (figure 3) [8, 9].

![Plastic strain graphs](image)

**Figure 3.** Plastic strain of the convex-side with a discharge voltage of 2 kV at different time stages: \(0 \sim 2.4e^{-4}\) sec.

The plastic strain graph of the convex-side bending showed values of 0.1 for the central zone, 0.4 for the both other zones (figure 4).
Figure 4. Plastic strain of the convex-side bending in different zones: A – central zone; B – bending zone; C – flanging zone.

Figure 5 shows a graph of the circumferential deformation with a value of (-0.1) for the central zone, (-0.18) for the flanging zone and (-0.37) for the bending zone.

Figure 5. The change in the circumferential deformation for different zones.

The calculation of the thickness for the central zone estimated as 1.34 mm, for the flanging zone is 1.4 mm and the greatest thinning of the deformable solid estimated as 1 mm for the bending zone (figure 6).

Figure 6. The change in the thickness of the material for different zones during the deformation process: A – central zone; B – bending zone; C – flanging zone.
The results of numerical simulation of the convex-side bending process with optimization of the parameters of pulsed loading are summarized in the form of a nomogram to determine the optimal pressure \( P \) depending on the dynamic yield stress of the workpiece \( Y_{0w} \), bending radius \( r_b \), thickness \( \delta_0 \), its diameter \( D_w \) and flanging coefficient \( K_f^{\text{Conv}} \) (figure 7) [1, 10].

\[
100\delta_0 \quad D_w \quad 1.5 \quad 1 \quad 0.75 \quad 0.45 \quad 0.6 \quad 0.8 \quad 1 \quad 2 \quad \gamma_b = 2\delta_0 \quad \gamma_b = 3\delta_0 \quad P, \text{MPa} \quad Y_{0w}, \text{MPa} \quad K_f^{\text{Conv}}
\]

**Figure 7.** Nomogram for determining the required pressure \( P \) value of electromagnetic field from the material properties \( Y_{0w} \) at three different parameters: \( r_b, \left( \frac{\delta_0}{D_w} \right) \) and \( K_f^{\text{Conv}} \).

### 3. Results and Analysis

Thus, the conducted research allows us to draw the following conclusions:

- When the sheet metal hitting the rigging of the convex-side, the corrugations are dynamically seated due to the suitable required electromagnetic field pressure for straightening, which estimated by 32 MPa.
- Numerical simulation of the forming-convex bending processes (without loss of stability) with a discharge voltage of 2 kV terms of the sides of sheet parts is carried out. The influence of various factors as rigging bending radius and flanging coefficient on the accuracy of magnetic pulse shaping of parts is determined.
- The calculation of plastic strain in the bending and flanging zones showed the greatest deformation of the part, which estimated at 0.4.
- In the above output, it was observed that the highest circumferential deformation was (-0.1) and located in the central zone.
- The calculation of the thickness showed that the greatest thinning was 1 mm in the bending zone.
- Based on the results of magnetic pulse shaping parameters, nomogram is constructed that allows us finding the value of the optimal pressure amplitude of the magnetic pulse field for stamping the part with maximum accuracy.

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