Influence of the electromagnetic field pressure on the free bending of the straight side

N V Kurlaev¹ and M E Ahmed Soliman
Novosibirsk State Technical University, Department of Aircraft and Helicopter Construction, 20, Karl Marx Avenue, Novosibirsk, 630073, Russia

¹E-mail: kurlaev@corp.nstu.ru

Abstract. Bending is the operation of forming or changing the angles between the parts of the workpiece or giving it a curved shape and in the mean time is the most difficult and time-consuming operation of the technological process of manufacturing parts from profiles. Aircraft bending parts of the following nomenclature are obtained as profiles: frames, ribs, stringers, linings and brackets. Profile parts are responsible for their intended purpose; therefore, high requirements are placed on the accuracy of their dimensions and the preservation of the cross-section shape. The process of bending profiles has its own characteristics, which are due to the shape of the profile section; the first feature is the presence of vertical shelves, significantly loaded and deformed due to large distances from the neutral axis of the bent section, the second is the mismatch of the bending plane with the main axes of inertia of the section, which causes oblique bending and twisting of the part. When analyzing the bending process of extruded profiles, it should be borne in mind that the neutral layer of the workpiece coincides with the line that passes through the centers of gravity of the sections. When using the hypothesis of planar sections of the plot of deformations and stresses in the stretched and compressed zones do not have a mutually reflected form. It is very important how the profile is oriented in the bending plane. Different orientation of the profile, even the simplest cross-section (for example, angular), gives a qualitatively different picture of the deformed state.

1. Introduction
With an arbitrary load distribution, the straight-side of the part has a deviation from the shape of the specified profile, which is expressed in non-lying. Therefore, it is necessary to search for the optimal distribution of the pressure of the pulsed-magnetic field (PMF), at which the forming side will be rectilinear during deformation that will allow us to get accurate details [1-3]. Authors recommend a new bending method by using a free straight bending without a die and different from bending traditional methods with determining the bending radius ≥ 5°. The equation of the dynamic equilibrium of the workpiece elements under large deformations has the form:
\[
\begin{align*}
\frac{\partial}{\partial s} \left[ N_\theta r \cos \theta \right] &- \frac{\partial}{\partial s} \left[ Q_\theta r \sin \theta \right] - N_\phi + r \left( p_t - F_{r,\text{frict}} \right) - rm \frac{\partial r}{\partial t} = 0, \\
\frac{\partial}{\partial s} \left[ N_\theta r \sin \theta \right] &- \frac{\partial}{\partial s} \left[ Q_\theta r \cos \theta \right] + r \left( p_z - F_{z,\text{frict}} \right) - rm \frac{\partial z}{\partial t} = 0, \\
\frac{\partial}{\partial s} \left[ M_\theta r \right] &- M_\phi \cos \theta = r Q_\phi,
\end{align*}
\]

Where

\[ F_{r,\text{frict}} = k_{r,\text{frict}} \frac{\partial r}{\partial t}, F_{z,\text{frict}} = k_{z,\text{frict}} \frac{\partial z}{\partial t}. \]

In the flat case, in equations (1), the variable \( r = 1 \) and the value \( M_\phi = 0 \). The solution of the system (1) is implemented by the finite difference method (FDM) according to an explicit scheme of the "cross" type. The straight-side of the flat blank along the generatrix is divided into segments \( \Delta s = s_{i+1} - s_i; i = 1, \ldots, N_t \), (figure 1). The mass of the segment is \( m_i = m \Delta s_i \) and remains constant. According to the thickness, the board of the flat blank is divided into discrete layers that can perceive normal stresses [2-4]. It is assumed that these layers are separated by layers of material of infinitely small thickness, in which there are no normal stresses, which have infinite shear stiffness [5, 6]. The time process is also divided into intervals \( t_0, t_1, \ldots, t_j \) in increments \( \tau \) [6, 7].

![Figure 1](image-url)  
**Figure 1.** Scheme of loading without a die and dividing the straight-side of the flat blank into elements for numerical calculation using FDM.

### 2. Numerical implementation of pulsed deformation

#### 2.1. Mathematical calculation for free bending of the straight-side

System (2) is supplemented by equations for the relationship between displacements and deformations, stresses with forces and moments, as well as equations for the initial and boundary conditions. For the time step increments \( j + 1 \) we do have the next equations [8, 9]:

\[
\Delta r_{i+1} = \tau^2 \frac{1}{m r_i} \left\{ \frac{N_{\theta,i} r_i \cos \bar{\theta}_{i+1} - N_{\theta,i-1} r_i \cos \bar{\theta}_i}{\Delta s_i} - \frac{Q_{\theta,i+1} r_i \sin \bar{\theta}_{i+1} - Q_{\theta,i} r_i \sin \bar{\theta}_i}{\Delta s_{i+1}} - N_{\phi,i} \right\} + \Delta r_i. \tag{3}
\]

\[
\Delta z_{i+1} = \tau^2 \frac{1}{m r_i} \left\{ \frac{N_{\theta,i} r_i \sin \bar{\theta}_{i+1} - N_{\theta,i-1} r_i \sin \bar{\theta}_i}{\Delta s_i} + \frac{Q_{\theta,i+1} r_i \cos \bar{\theta}_{i+1} - Q_{\theta,i} r_i \cos \bar{\theta}_i}{\Delta s_{i+1}} \right\} + \Delta r_i, \tag{4}
\]

For the next time step, the results of the calculations on the previous time step are taken as initial conditions.
Based on the known values at the moment of time \( t_j \) (starting from the initial moment \( t_0 \)), the values \( r_{j+1} \) and \( z_{j+1} \) at the moment of time \( t_{j+1} \) are found.

2.2. Finite Element Analysis (FEA) - model geometry
The dimensions of the aluminum sheet metal before forming: the thickness \( \delta_0 \) is 1.5 mm; height of its side \( H_f \) is 13 mm and it’s a suitable height to get straight flange without a springback. The dimensions of the workpiece after forming: the height of the flange side \( h_f \) is 14.5 mm. The load of pressure \( P \) was assumed to be uniformly distributed on a straight shape with amplitude of 25 MPa on it with a free bending radius \( r_b \) is 5 mm (figure 2) [6, 10-12].

![Schematic diagram of the process and designations for free bending and forming of straight-side by the pressure of magnetic-pulsed field (PMF).](image)

2.3. Impact contact of a stamped sheet metal part with a free shaping
The production of sheet metal parts requires the development of efficient technological processes that can significantly improve both operational performance and efficiency in production. In many ways, modern requirements are met by processes using high-speed loading when forming parts. One of these methods is magnetic-pulsed pressure, which allows high-energy of PMF to be applied to parts made of electrically conductive materials. The duration of a stamped side edge contact with a free shaping is significantly affected by dynamic yield strength \( Y_{0w} \) of the workpiece material, upon impact at constant velocity [6]. If \( Y_{0w} \) is increased indefinitely, then for a constant impact speed can achieve such a value of \( Y_{0w} \) at which a plastic compression wave does not arise in the workpiece. With a decrease of \( Y_{0w} \), the acoustic wave appears and if its intensity becomes higher, the dynamic yield strength of the workpiece material is getting lower. The electromagnetic coil is decisive for electromagnetic forming and must be designed to be positioned under the metal sheet as shown in figure 3 to generate electromagnetic forces equally.
Figure 3. Grid scheme of the straight side free bend on a sheet metal by electromagnetic field pressure. 1 – single turn coil; 2 – blank; 3 – hard boundary plate.

2.4. Results of the numerical simulation analysis
Plastic strain during the free straight-side bending process showed that the greatest deformation is concentrated in the bending zone, where also a significant thinning of the part wall occurs (figure 4).
Figure 4. Plastic strain of the straight-side free bend with a discharge voltage of 1.1 kV at different time stages: \((0 - 6.7e^{-5} \text{ sec.})\)

The plastic strain graph of the straight-side free bend showed the maximum value of 0.26 for the bending zone, 0.05 for the straight zone and 0.01 for the flanging zone (figure 5).

Figure 5. Plastic strain of the straight-side free bends in different zones: A – central zone; B – bending zone; C – flanging zone.

Figure 6 shows a graph of the circumferential deformation with a value of \((-0.006)\) for the bending zone, \((-0.03)\) for the flanging zone and \((-0.2)\) for the straight zone.

Figure 6. The change in the circumferential deformation for different zones.
The calculation of the thickness for the flanging zone estimated as 1.49 mm, for the straight zone is 1.45 mm and the greatest thinning of the deformable solid estimated as 1.39 mm for the bending zone as shown in figure 7.

![Figure 7.](image)

**Figure 7.** The change in the thickness of the material for different zones during the deformation process.

The results of numerical simulation of the straight-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 strength of the workpiece \( Y_{0w} \), bending radius \( r_b \), thickness \( \delta_0 \), its diameter \( D_w \) and height of the aluminum sheet metal side before forming \( H_f \) (figure 8) [2, 3].

![Figure 8.](image)

**Figure 8.** Nomogram for determining the required pressure \( P \) value of electromagnetic field from the material properties \( Y_{0w} \) at three different parameters: \( r_b \), \( \frac{\delta_0}{D_w} \) and \( H_f \).

### 3. Results and Analysis

Thus, the conducted research allows us to draw the following conclusions:
A new method is proposed for bending the straight-side of sheet metal without using a die, as in the traditional method, experimental results have shown the effectiveness of this method for bending a straight flange and coincided with modeling.

Numerical simulation of the straight-side bending process, without springing back with a discharge voltage of 1.1 kV terms of the side of sheet part is carried out.

The calculation of plastic strain for the bending zone showed the greatest deformation of the straight part, which estimated at 0.26.

In the above output, it was observed that the highest circumferential deformation was (-0.006) and located in the bending zone.

The calculation of the thickness showed that the greatest thinning was 1.39 mm in the bending zone.

Acknowledgments
The research was carried out on the equipment of the Centre for Collective Use "Structure, mechanical and physical properties of materials" in Novosibirsk State Technical University.

References
[1] Belyy I V, Fertik S M and Khimenko L T 1970 Electromagnetic Metal Forming Handbook (Kharkiv: Visha shkola) 190
[2] Ahmed Soliman M E 2021 Preparation of samples for investigating the durability of aluminum alloy D16AM after deformation and magnetic-pulse processing J. of Phys.: Conference Series 1889 022086 (Krasnoyarsk: ICMSIT II-2021) 6
[3] Kurlaev N V and Ahmed Soliman M E 2020 Simulation of rift element forming by magnetic-pulse deformation: IOP Conf. Ser.: Mater. Sci. Eng. 919 022011 (Krasnoyarsk: SibGU) 6
[4] Risch D, Brosius A and Kleiner M 2007 Influence of the Workpiece Stiffness on the Electromagnetic Sheet Metal Forming Process into Dies J. Mater. Eng. and Perf. (JMEP) 16 327-30
[5] Golovashchenko S 2005 Sharp flanging and flat hemming of aluminum exterior body panels: J. Mater. Eng. and Perf. (JMEP) 14 508-15
[6] Kurlaev N V and Gulidov A I 2005 Impact of pulse processing on technological defects of workpieces (Novosibirsk: SBRA Sciences) 168
[7] Golovlev V D 1974 Calculations of sheet metal stamping processes (Stability of sheet metal forming) (Moscow: Mechanical Engineering) 136
[8] Sachdev A K and Wagoner R H 1983 Uniaxial strain hardening at large strain in several sheet steels: J. of Appl. Metalwork. 3(1) 32-37
[9] Yudaev V B, Kurlaev N V and Favorin V M 1989 Numerical solution of problems of pulsed deformation of sheet blanks Proc. of the 11th All-Union Conf. On High Numerical methods for solving problems of the theory of elasticity and plasticity (Novosibirsk: ITAM) 23-6
[10] Mikkola M G, Tuomala M and Sinisaso H 1981 Comparison of numerical integration methods in the analysis of impulsively loaded elastoplastic and viscoplastic structures Int. J. Comput. Struct. 14(5-6) 469-76
[11] Mc Namara C F 1974 Solution Schemes for problems of nonlinear structural dynamics: Fran. ASCE. 96(2) 96-102
[12] Leu D K 1997 A simplified approach for evaluating bendability and springback in plastic bending of anisotropic sheet metals: J. Mater. Process. Technol. (JMPT) 66 9-17