Investigation of the free expansion of thin-walled tubular parts by pulsed-magnetic field

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Abstract. Magnetic-pulse processing is the process of converting the preliminarily accumulated electrical energy of the capacitor into the plastic deformation work of the workpiece. The technological processes of magnetic-pulse processing have complex electromechanical nature and also associated with high strain rates. These process parameters are difficult to determine experimentally, so it is proposed to perform and analyze them through numerical modeling. This article presents a study of the expansion rate of a tubular workpiece and its effective plastic deformation by pulsed-magnetic field. The influence of process parameters on free tube expansion is discussed in detail. The results were obtained through 3D finite element modeling, using the ANSYS software. The development of such a finite element modeling model makes it possible to exclude the conduct of experimental studies to detect the magnetic-field and the velocities, which are involved in the process. Numerical research makes it possible to determine the optimal value of the pulsed-magnetic field pressure for free expansion of tubular parts.

1. Introduction

Expansion of thin-walled tubular parts in a free state is accompanied by the formation of cracks or strain. Under dynamic loading until noticeable cracks appear, significant circumferential plastic deformations of tubes can be achieved [1–3]. Due to the numerical modeling, which allows predicting the behavior of a tube during expansion by a pulsed-magnetic field (PMF), it is possible to determine the limiting degrees of expansion of thin-walled tubular parts, select optimal deformation modes and design multi-transition processes [1, 4].

Theoretical and experimental analyzes of the expansion of thin-walled tubular parts, which are close in their geometric shape and material properties to ideal ones, have shown that such tubes, when loaded with a uniformly distributed load of the PMF, lose stability under parametric excitation of elastic bending vibrations of the tube wall at the initial moment of loading [5].

The choice of optimal deformation modes made it possible to obtain circumferential plastic deformations of 30-40% before the formation of cracks. To determine the parameters of the elastoplastic deformation of the tube during the expansion of the PMF, the entire deformation process was considered, including the elastic state of the tube material, the transition process from the elastic state to the plastic state, and plastic flow. For this purpose, the problem was solved by the finite element method in the ANSYS software. The Explicit Dynamics (ED) module allows solving problems of high-speed and highly nonlinear processes by Euler-Lagrange equation [6, 12]. The Maxwell module was used to perform electromagnetic simulations. The main part of the module is
called eddy current solver. This module allows us to inject the source of electric currents into solid conductors and calculate the corresponding magnetic fields, electric fields, induced currents, Lorentz forces, heating, etc. [7, 10].

Figure 1. Equivalent electrical circuit of the magnetic-pulse tube expansion.

2. Operating Principles
Magnetic-pulse processing (MPP) is based on the conversion of electrical energy accumulated in a capacitor bank, when discharged to inductor or directly to the workpiece, into the energy of a pulsed-magnetic field that performs the work of deforming an electrically conductive workpiece. Magnetic-pulse processing of metals is characterized by the fact that the pressure on the deformable metal workpiece is created directly by the action of a pulsed-magnetic field without the participation of intermediate solid, liquid or gaseous media. The related electromagnetic phenomenon is considered using Maxwell’s equations [2, 3, 8]:

\[ \nabla \times \vec{H} = J \]  
\[ \nabla \cdot \vec{B} = 0 \]  
\[ \nabla \times \vec{E} = -\frac{\partial}{\partial t} \vec{B} \]  
\[ \vec{B} = \mu \vec{H} \]  
\[ \vec{J} = \gamma \vec{E} \]

Where \( H \) represents the magnetic field strength, \( B \) represents the magnetic field density, \( E \) represents the electric field, \( \mu \) represents the magnetic permeability and \( J \) represents the current density.

The Lorentz forces \( F \) can be calculated by the following equation:

\[ \vec{F} = \vec{J} \times \vec{B} \]  

The accumulated energy \( E \) in the capacitor bank is defined by the equation:

\[ E(t) = \frac{1}{2} CV^2 \]
The equivalent electrical circuit of the magnetic-pulse tube expansion has the form of an exponentially decaying sinusoid as shown in figure 1. The circuit discharge current $I(t)$ of the magnetic-pulse installation is defined by the following equation:

$$I(t) = \frac{U_0}{\omega L} \exp\left(-\frac{R}{2L} t\right) \sin(\omega t),$$

(8)

Where $U_0$ represents the capacitor charge voltage, $C$ represents the capacitor bank capacity, $R$ represents the total active busbars resistance of the installation, arrester, inductor and workpiece, $L$ represents the circuit inductance, $\omega$ represents the circular oscillations frequency of the discharge current. The PMF pressure on a stationary workpiece is approximated by a decaying quadratic sinusoid [4]:

$$P = P_0 \exp(-\beta t) \sin^2(\omega t)$$

(9)

Figure 2 shows a block diagram of communications in ANSYS. The mechanical solver (ANSYS Mechanical) deals with the mechanics of the movement of material masses. The Electromagnetic Module (Maxwell) deals with the dynamics of electromagnetic fields. Internal energy, heat generation and heat flux are calculated by a thermal solver (ANSYS CFD).

The input values in RLC circuit parameters for the simulation in the Maxwell module carried out as following [4]: Capacitor energy with a total capacitance of 420 $\mu$F; maximum charging voltage of 9 kV; $R = 9 \, m\Omega$; $L = 440 \, m\Omega$; $E = 1.2 \, kJ$. The maximum value of the magnetic field was 10 T for the element located in the center of the coil due to the combined action of the magnetic fields of all turns.

After solving the electromagnetic field problem, the volumetric heat release was transferred from Maxwell to (ANSYS Fluent) to determine the temperature, subject to the condition of a forced convention. Further, the determined temperature from (ANSYS Fluent) and the electromagnetic force from Maxwell will be transferred to (ANSYS Mechanical) to assess the stress-strain state of the workpiece.

3. Modeling the tube-expansion process

Figure 3 shows the cross section of 3D model in its original position. The gap between the coil and the workpiece is 1 mm. The coil has 4 turns and a rectangular section of 7×3 mm with a step of 9 mm. The outer diameter of the coil is 56 mm. Copper from the ANSYS material library was chosen as a material for the coil [9–12]. A tube with an outer diameter of 60 mm, a length of 70 mm and a thickness of 1 mm was chosen as a workpiece. The material which used for the tube is aluminum alloy AMg6 and its Properties are shown in Table 1.

Table 1. Properties of the AMg6 material.

| Properties       | Value | Unit  |
|------------------|-------|-------|
| Density, $\rho$  | 2640  | $kg/m^3$ |
| Yield Strength, $\sigma_{0.2}$ | 145  | MPa   |
| Tensile Strength, $\sigma_u$     | 315   | MPa   |
| Elastic Modulus, E | 70 | GPa |
|-------------------|----|-----|
| Specific Heat Capacity of the Material, C | 1090 | $j \cdot kg^{-1} \cdot K^{-1}$ |

**Figure 3.** Cross section of the grid model: 1 – coil; 2 – tubular blank.

Figure 4 shows the deformation of the tube at $P=30$ MPa by the above equation (9). The maximum circumferential plastic deformation occurs during $t = 100 \mu s$ and estimated at 25%. The tubular wall thickness at the end of the operational time was 0.48 mm.

**Figure 4.** Plastic deformation of the tubular blank at different stages of time ($t$).

On the basis of numerical simulation, a nomogram was built to determine the relative deformation of the tube wall $\varepsilon_\phi$ depending on the pressure $P$ of the PMF (Fig. 5) [2].
Figure 5. Nomogram for determining the relative deformation of the tube wall \( \varepsilon_\varphi \) depending on the pressure \( P \) of the PMF, dynamic yield strength of the workpiece material \( Y_0 \) and the geometric parameters of the tube (\( D_0 \) is the tube outer diameter and \( \delta_0 \) is the tube wall thickness).

4. Results
Thus, the performed numerical simulation allows us to draw the following conclusions:

- The maximum displacement and maximum expansion rate are achieved in the middle of the tube because the maximum magnetic field is located in the middle of the coil.
- The described technique is applicable for predicting the free expansion of thin-walled tubes by a pulsed-magnetic field, as well as for calculating the process of expanding tubes with initial imperfections.
- The results of numerical simulation of the consolidated expansion process of tubular part were summarized in the form of a nomogram to determine the optimal value of the tube wall deformation.

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References
[1] Kurlaev N V, Ryngach N A, Tagoev F M and Ahmed Soliman M E 2020 Numerical simulation of pulsed calibration of welded tubular part: IOP Conf. Ser.: Mater. Sci. Eng. 843 012003
[2] 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
[3] Kurlaev N V, Ryngach N A and Ahmed Soliman M E 2020 Simulation of drawing-forming by magnetic-pulse deformation: IOP Conf. Ser.: Mater. Sci. Eng. 919 022004
[4] Shang J, Hatkevich S and Wilkerson L 2012 Comparison between experimental and numerical results of electromagnetic tube expansion, *12th International LS-DYNA Users Conf.* USA

[5] Areda G and Kore S D 2019 Numerical study and experimental investigation on electromagnetic crimping for tube-to-rod configuration: *Int. J. Prec. Eng. Mfg. (IJPEM)* **20** 181-91

[6] Thompson M and Thompson J 2017 *ANSYS Mechanical APDL for Finite Element Analysis* (Oxford: Butterworth-Heinemann) p 466

[7] Isachenkov V N, Samokhvalov V A, Glushchenkov V I and Pesotskiy V I 1989 Magnetic-pulse calibration of thin-walled hollow parts: *J. Forge. and Stamp. Prod. Mat. Working by Pressure (KShP)* **7** 5-7

[8] Psyk V, Risch D, Kinsey B L, Tekkaya A E and Kleiner M 2011 Electromagnetic forming – a review: *J. Mater. Process. Technol. (JMPT)* **211** (5) 787-29

[9] Song F M, Zhang X, Wang Z R and Yu L Z 2004 A study of tube electromagnetic forming: *J. Mater. Process. Technol. (JMPT)* **151** (1-3) 372-75

[10] Kislookiy V N 1966 Algorithm for numerical solution of problems of statics and dynamics of nonlinear systems: *Applied mechanics* **2** 87-91

[11] Li Qiu, Yantao Li, Yijie Yu, Yao Xiao, Pan Su, Qi Xiong, Jinbo Jiang and Liang Li 2019 Numerical and experimental investigation in electromagnetic tube expansion with axial compression: *The Int. J. of Adv. Manuf. Technol.* **104** 3045-51

[12] Zhang H, Murata M and Suzuki H 1995 Effects of Various Working Conditions on Tube Bulging by Electromagnetic Forming: *J. Mater. Process. Technol. (JMPT)* **48** 113-21