Numerical simulation of pulsed calibration of welded tubular part

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Abstract. The article presents the analysis of electrodynamic processes during magnetic-pulse "expansion" of thin-walled tubular parts. The authors consider the cases where tubular parts are made by welding. As a result of welding, a deviation from the round shape occurs which requires calibration. Particular attention is paid to the case when the welding zone of a metal thin-walled tube touches the die. For the dynamic analysis of large deformations, the finite element method (FEM) based on the ANSYS software package is used, whose feature is the ability to implement a comprehensive solution to this class of problems. Using numerical calculations and optimization for pulsed metal forming, in particular pressure pulsed magnetic field (PMF), a nomogram was constructed to determine the required technological regimes that take into account the properties of the material and the pressure amplitude of the pulsed magnetic field.

1. Introduction

Nowadays the important problem in aircraft construction is the creation of reliable and high-resource pipelines that operate under difficult loading conditions. The pipelines of modern aircraft are subjected to high pressures, hydraulic shocks and pulsating loads, so they have high demands on the mechanical properties of the material, the quality of the inner and outer surfaces, shape retention, and minimal wall thinning.

A large number of pipeline failures are associated with a decrease in wall thickness in places of bending, transition from one diameter to another and joints. Significantly reduce the efficiency of such factors as the undulation of the walls and excessive ellipse, phenomena, accompanying the processes of manufacturing pipelines [1].

The actual problem is how to minimize production costs and at the same time ensure the specified accuracy of geometric parameters, the specified mechanical properties, the required surface roughness and performance characteristics of parts, assemblies and systems for applications in aircraft structures, modern metals and alloys.

In this regard, one of the important tasks in the manufacture of aircraft is the development of new and improvement of existing technologies.

Currently, one of the most promising technologies is the technology of electromagnetic forming (EMF) process for metals, based on the use of large electrodynamic forces arising in conductive materials during the interaction of an external pulsed magnetic field (PMF) with eddy currents induced in the material [2, 10]. These are typical high-speed forming technologies that have various advantages
compared to quasistatic forming, such as single-sided stamping, improved sheet metal forming and high precision forming.

2. Statement of the problem
In the manufacture of pipelines, welded fittings of sheet material are used [1]. As a result of welding, a deviation from the round shape occurs, which requires calibration. For aluminum alloys, rubber-pad stamping can be used for calibration, but for stainless steels like 08X22H6T, 08X21H6M2T, 08X18Г8Н2Т or titanium alloys there will be significant springing.

In this work, we study the pulsed pressure treatment of thin-walled welded metal pipes when the welding zone of a thin-walled pipe touches the die.

As a result of numerical simulation analysis using ANSYS finite element complex, in order to obtain a given shape without springing, it should be noted that the loading scheme during shaping should have the form, as shown in Figure 1. The pressure P is evenly distributed on the inner surface of the tubular part.

It is necessary to set the optimal pressure amplitude \( P_0 \), at which the tubular part is formed along the die, without springing and changing the wall thickness. By finding the minimum required pressure, the reduction in wall thickness is minimized.

![Figure 1. Scheme of loading of a tubular part during magnetic pulse calibration](image)

3. Magnetic pulse stamping of tubular parts
The EMF process is mainly suitable for the deformation of highly conductive metal materials such as aluminum, copper and copper alloys. EMF is also an energy-saving and environmentally friendly production technology. The ultimate shaping of aluminum alloy material can be significantly enhanced by using EMF. EMF requires only one shape (for example, a die) for forming tubular workpieces with high accuracy. The values of the pressure amplitude PMF and pulse duration are determined based on the electrical parameters of the EMF process [3, 8]. The current flowing in the inductor when the capacitor Bank is discharged, approximately expressed by the harmonic oscillation equation:

\[
I = \frac{U}{L \omega} \exp \left( -\frac{R}{2L} t \right) \sin \omega t
\]  

(1)

For magnetic-pulse “expansion” tubular parts, the pressure of PMF (P) on the fixed workpiece is approximated by a decaying quadratic sinusoid and the coefficient of pressure attenuation of PMF is introduced depending on the gap between the inductor and the workpiece [4] as shown in Figure 2:

\[
P = P_0 \frac{\Delta}{\Delta + \mu} \exp(-\beta t) \sin^2(\omega t)
\]  

(2)
Where $P_0$ represents the conditional pressure amplitude, $\Delta$ represents the gap between the inductor and the workpiece, $\mu$ represents removing the workpiece from its original position, $\omega$ represents circular frequency of the discharge current and $\beta$ represents attenuation coefficient.

**Figure 2.** Dependence of the measurement of the discharge current $J$ and pressure $PMF$ $P$ in time: 1 - current curve; 2 - pressure curve.

When analyzing the works devoted to the issues of numerical modeling using the ANSYS finite element complex given in [2, 7, 9], we can conclude that since the duration of the current discharge is much shorter than the duration of the workpiece deformation process, it is possible to neglect the influence of the movement of the workpiece during the discharge on the discharge parameters.

In this work, numerical modeling was carried out to study the dynamic behavior of a tubular part during pulse calibration.

As it is seen from Figure 1, the general EMF scheme in the expansion process where $P$ represents the amplitude of the pulse loads. As a result, we obtain the deformation of the tubular part using a finite element model by using the influence of electromagnetic force.

### 4. Mathematical statement of the problem (choice of mathematical model)

Finite element analysis is one of the main methods of EMF analysis. In this work, we use the ANSYS software. The program solves a number of differential equations for deriving pressure, velocity, and deformation at different points in time [5, 6]. When choosing a mathematical model, it should be noted that the choice should be based on what result you want to get. The most effective is called such a mathematical model that provides a reliable solution (for example, with an acceptable error) with the least amount of time and computing power. At the same time, the solution using the FEM does not provide more information than is laid down in the solved mathematical model. For example, if the model does not include nonlinear properties of the material initially, the body will not begin to behave nonlinearly in the process of solving the problem. At this stage, the selection of equations describing the process under study is carried out. The analysis of processes is carried out on the basis of numerical modeling in the framework of continuum mechanics [7]. We use equations that are a consequence of the laws of conservation of mass, momentum, and energy. The system is closed by the relations of the elastoplastic behavior of the Prandtl-Reiss material. The basic equations have the following form as follows:

**4.1. The equation of the trajectory of material particles:**

$$\dot{x}_i = v_i \quad (3)$$

**4.2. The continuity equation:**

$$V_0\rho_0 = V\rho \quad (4)$$

**4.3. The law of changing the momentum of a material particle:**
\[ \rho \dot{v}_i = \sigma_{ij,j} \] (5)

4.4. Change in internal energy:

\[ \rho \dot{e} = \sigma_{ij} \dot{E}_{ij} \] (6)

4.5. Strain rate tensor:

\[ \dot{E}_{ij} = 0.5(v_{ij} + v_{ji}) \] (7)

4.6. The components of the stress tensor are represented as follows:

\[ \sigma_{ij} = -P \delta_{ij} + s_{ij} \] (8)

where \( s_{ij} \) represents the components of the stress tensor deviator, which is responsible for the resistance to the shape change of the material particle and \( \delta_{ij} \) represents Kronecker symbol. In the above equations (3-8), the following notation is used: each of the indices \( i, j \) sequentially takes the value \((1, 2, 3)\); summation is performed over a repeating index, a dot over the symbol represents the time derivative along the trajectory; index after the decimal point represents the derivative with respect to the corresponding coordinate; \( x_i, v_i \) represent the components of the position and velocity vectors of the material particle, \( \rho_0, \rho \) represent the initial and current density of the medium, \( \mu \) represents shear modulus and \( P \) represents the pressure.

4.7. The equation of the elastoplastic flow process is written in the Prandtl-Reiss form:

\[ \dot{s}_{ij} + d \lambda s_{ij} = 2\mu \left( \dot{E}_{ij} - \frac{\dot{E}_{ij}}{3} \delta_{ij} \right) \] (9)

4.8. Under the condition of Guber-Mises plasticity:

\[ s_{ij} s_{ij} \leq \frac{2}{3} Y_0^2 \] (10)

where \( Y_0 \) represents the dynamic yield strength.

The load on the workpiece (see Figure 1) is set in the form of a uniformly distributed pressure from the inside of the pipe. The pressure value in time is set according to the first half-cycle of the quadratic sinusoid of pressure (equation 2), graphically presented in Figure 2.

5. Calculation of the mechanical characteristics of the process

Calculation of the mechanical characteristics of the process is an important step of the method, which allows determining the specific features of the performed technological operation. In this case, both the general regularities of the operation known during quasistatic metal forming, and specific relations of dynamic deformation of metals are used.

In the calculation, such mechanical characteristics of the process are determined as the work of deformation of the workpiece, necessary for the manufacture of a given part; kinetic energy of the deformable section of the workpiece; the required value of the pressure PMF. When analyzing the calibration processes, the required value of the pressure PMF is determined.

When processing tubular workpieces, the amplitude value of the pressure PMF should be sufficient both for the formation of the part and for its calibration without springing. The amplitude value of the pressure for quasistatic deformation to the boundary of the die can be determined in accordance with the well-known Laplace's equation:

\[ P = \frac{Y_0 \delta_0}{R_{min}} \] (11)

where \( R_{min} \) represents the minimum radius of curvature of the workpiece profile and \( \delta_0 \) represents the thickness of the workpiece. As a result of the analysis, when calculating the calibration processes of
tubular parts, the value of the pressure amplitude of the PMF should be 2...3 times higher than the pressure value which determined by the equation (11).

6. Result of the simulation, tubular parts are deformed by the pressure PMF

To assess the possibility of implementing such an approach in relation to this problem, this process was modeled using the ANSYS/Explicit Dynamics finite element complex, whose feature is the ability to implement a comprehensive solution to this class of problems. Figure 3 shows, as an example, a 3D model of this problem and the result of the deformation of the tubular part.

![3D model of the tubular part](image)

**Figure 3.** 3D model of the tubular part: a – Initial state, b – Deformed state.

For the analysis, aluminum pipes made by welding were selected with different yield strength, thickness and diameter (as shown in table 1). As a die, a material was chosen whose yield strength exceeded the yield strength of the workpiece several times. The results of numerical modeling of loading processes of a tubular workpiece to obtain parts with a given accuracy were summarized in the form of nomograms. Nomograms for determining the optimal pressure (P) depending on the dynamic yield strength of the workpiece (\(Y_0\)) and the geometric parameters of the part (\(D_0, \delta_0\)) are presented in Figure 4.

| \(Y_0\) (MPa) | \(D_0=50\) (mm) | \(D_0=55\) (mm) | \(D_0=60\) (mm) |
|--------------|------------------|------------------|------------------|
| 185          | 14               | 13               | 12               |
| 200          | 15               | 14               | 13               |
| 250          | 17               | 16               | 15               |
| 325          | 22               | 20               | 19               |

**Table 1.** Determination of the optimal pressure value (P, MPa) at the wall thickness of the tubular workpiece \(\delta_0 = 1\) mm.

Thus, numerical modeling is necessary to study unobservable values (for example, behavior and strain rate during a process) in order to understand the physical phenomena. In addition, the simulation method can be useful in predicting experimental results that cannot be performed due to equipment limitations.
Figure 4. Nomogram for determining the optimal amplitude PMF (P) depending on the dynamic yield strength of the workpiece \( (Y_0) \) and the geometric parameters of the part \((D_0, \delta_0)\).

7. Conclusion
The conducted studies suggest the following:

- In the numerical simulation of pulsed pressure processing used for calibration tubular parts by manufactured welding, it was determined that the most effective method is to expand the workpiece into the covering die, where the pipe weld zone touches the die.
- As a result of the calculations of the calibration processes of tubular parts, the value of the pressure amplitude of the PMF should be 2...3 times higher than the value of the quasistatic deformation pressure.
- Based on the results of optimizing the parameters of magnetic pulse forming of tubular parts, a nomogram was constructed that allows finding the value of the pressure amplitude of the PMF for calibrating tubular parts with maximum accuracy.
- As a result of calculations, we can determine the optimal value of the PMF pressure for tubular parts with a dynamic yield strength from 120 to 330 MPa, a thickness from 1mm to 2mm, and a diameter from 50mm to 60mm.

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