

FINITE ELEMENT ANALYSIS OF MAGNETOFORMING OF THIN METAL SHEETS TAKING INTO ACCOUNT THE COUPLING BETWEEN ELECTROMAGNETIC AND MECHANICAL PHENOMENA

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Abstract: The paper deals with finite element models for electromagnetic forming processes applied to thin metal sheets. The complexity of analysis is due to the coupling between transient electromagnetic and mechanical phenomena assumed by magnetoforming process. The sequentially coupled electromagnetic – structural model is built using the capabilities of ANSYS Multiphysics software. In order to check the validity of APDL code, for electromagnetic field phenomena simulations using FLUX software are performed. The paper emphasizes the complexity of magnetoforming modeling and presents some results arising from a research project.

Keywords: electromagnetic forming, finite element model, transient analysis, coupled problems, sequential coupling, multiphysics.

1. INTRODUCTION

In the last few years, due to multiple advantages, the use of workpieces made by aluminum and its alloys has extended in many sectors e.g. in automotive industry. As a consequence, taking into account the particularities in processing such materials, high rate forming technologies such as electromagnetic forming, hydro-forming etc., used only in some special applications in '60-'70 and rarely used later, especially due to an insufficient control at that time, becomes nowadays actually.

Electromagnetic forming (EMF), or magnetoforming, is a high speed forming process where a pulsed magnetic field is used to processing metals with high electrical conductivity (aluminum, copper or their alloys) within a few microseconds. Usually, thin wall metallic pieces (sheets, tubes) are deformed at room temperature by intense impulsive forces generated by a rapidly time varying magnetic field.

The main components of EMF facility for forming metal sheets are presented in Fig.1.

By discharging the capacitor through the coil, a time dependent magnetic field is produced and eddy currents are induced in the workpiece. Between the coil and workpiece the repulsive forces occur. If the stress generated in the metallic piece exceeds the yield point of the material, plastic deformation is produced with high velocity and in a very short time.

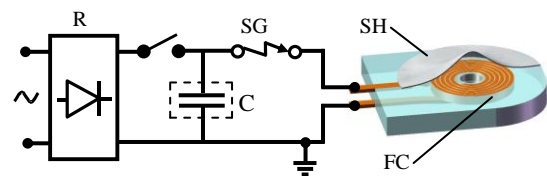


Fig.1. Main components of EMF system for metal sheets: R - rectifier; C - capacitor bank; SG - spark gap; FC - forming coil; SH - metal sheet

Electromagnetic forming involves a high frequency process, high power and coupled phenomena, in which the electrical and geometric parameters are time dependent. The non-uniform distribution of the current density in conductive regions, respectively the transient skin effect must be considered. In addition, the deformation of the workpiece modifies the magnetic field, which characterizes a strong coupling between electromagnetic and mechanical/structural phenomena [1]. The time dependence of source current imposes for EMF process a transient analysis, both for electromagnetic field and for structural analyses.

2. MODEL EQUATIONS FOR PHENOMENA INVOLVED IN EMF PROCESS

A. Electromagnetic Field Model

Frequently, the magnetoforming device, workpiece and tool coil, has axial symmetry,

as in Fig.1. Thus, the cylindrical coordinate system is used. The current density in the forming coil that is the source of electromagnetic field, has azimuthally orientation, $\mathbf{J}_{ex} = J_{ex} \varphi$. As a consequence, the time dependent magnetic vector potential $\mathbf{A}(r, z, t)$ has component only in the same direction. The governing equation in terms of \mathbf{A} is:

$$-\left[\frac{\partial}{\partial r} \left(\frac{v}{r} \cdot \frac{\partial}{\partial r} (r \cdot \mathbf{A}) \right) + \frac{\partial}{\partial z} \left(v \cdot \frac{\partial \mathbf{A}}{\partial z} \right) \right] + \sigma \frac{D\mathbf{A}}{Dt} = \mathbf{J}_{ex} \quad (1)$$

where v is magnetic reluctivity and $\sigma = 1/\rho$ is electric conductivity. The total derivative in (1)

has the expression $\frac{D\mathbf{A}}{Dt} = \frac{\partial \mathbf{A}}{\partial t} - v \times \text{rot } \mathbf{A}$, with

v the velocity. If the motion of workpiece is not considered ($v = 0$) [2] the equation of the vector potential $r \cdot \mathbf{A}$ is:

$$-\left[\frac{\partial}{\partial r} \left(\frac{v}{r} \cdot \frac{\partial}{\partial r} (r \cdot \mathbf{A}) \right) + \frac{\partial}{\partial z} \left(\frac{v}{r} \cdot \frac{\partial}{\partial z} (r \cdot \mathbf{A}) \right) \right] + \frac{1}{r} \sigma \frac{\partial}{\partial t} (r \cdot \mathbf{A}) = \mathbf{J}_{ex} \quad (2)$$

The second term in the left part of the equation represents the density of induced currents, non-null in the conductive regions of the study domain. This equation of state variable \mathbf{A} of transient magnetic field is solved using the step by step in time domain method. The electromagnetic computation domain for a sheet magnetofforming application is shown in Fig.2.

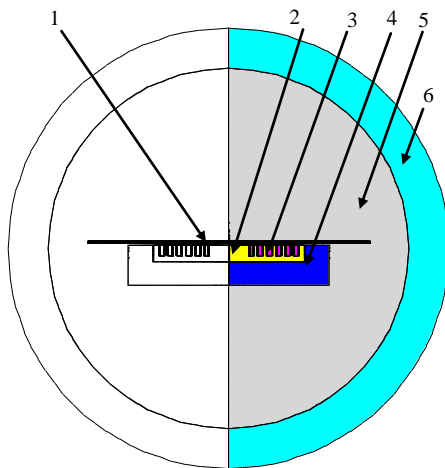


Fig.2. 2D computation domain for electromagnetic field: 1 - metal sheet; 2 - insulation; 3 - tool coil; 4 - magnetic shield (optional); 5 - air; 6 - infinite region

The source \mathbf{J}_{ex} , which is non-null only in coil region, is an unknown value as it follows: if the forming coil is of thin wire type, the current density \mathbf{J}_{ex} is constant in whole the coil region and if the forming coil is of solid conductor type, the current density is not constant over the coil cross-section.

At any time step, the second relation between \mathbf{A} and \mathbf{J}_{ex} are given by the model of electrical circuit, so the magnetic field – electric circuit coupling is considered. In some studies, a measured current is used as excitation for the simulation of the forming process in coupled simulations [3], but the necessity of preceding measurements is unsatisfactory when simulation tools are applied to predict the forming result.

The equation of magnetic vector potential being solved iteratively in time domain, the value of the time step must be evaluated in accordance with the period T of damped oscillation of circuit. For example, a time step equal to $(1/40) \cdot T$ determines a good accuracy of results.

The electromagnetic interaction involves repulsive forces between forming coil and sheet. By computing the force vector in each element of the piece, at each time step, the final position of each element after the action of electromagnetic forces can be found.

B. Structural model

From mechanical point of view the electromagnetic forming is characterized by a large plastic deformation of the processed material, which occurs in a very short time. The general theory of plasticity adequately describes the time-independent aspect of the behavior of materials, but this is inadequate for the analysis of time-dependent behavior. An approach to achieving a satisfactory formulation for time-dependent behavior has been to generalize plasticity to cases within the strain-rate-sensitive range [4]. Such a generalization has been provided by the theory of viscoplasticity. In the last decades, various forms of the theory of viscoplasticity have been provided (Perzyna, Cristescu, Peirce). An approach to the construction of equations for viscoplastic materials can be made using the extreme principle. This also can be used as a basis for the finite-element formulation of viscoplastic analysis.

The effective stress $\bar{\sigma}$ depends on the strain-rate dependent function Φ , which is to be determined by the properties of the

material. If we choose the function $\Phi = ((\bar{\sigma} / \sigma_0) - 1)^{1/m}$, then results [4]:

$$\bar{\sigma} = \sigma_0 \left[1 + \left(\frac{\dot{\epsilon}}{\gamma} \right)^m \right] \quad (3)$$

Equation (3) is a familiar rate-dependence law (Perzyna model) and the exponent m is the strain-rate sensitivity index. This equation is also used to model viscoplastic material behavior in the ANSYS finite element analysis software [4]. As it is stated in [4,5], this kind of material models the best impact-like deformation processes

3. FULL TRANSIENT SEQUENTIALLY COUPLED ELECTROMAGNETIC – STRUCTURAL MODEL OF EMF

The sequentially coupled electromagnetic - structural model is built using the capabilities of ANSYS Multiphysics software [5]. Data flow for this sequentially coupled analysis using physics environments approach is depicted in Fig.3. In this approach, a single database exists for entire model. The database must contain the elements and nodes for both physics analysis. For each element or solid model entity it is defined a set of attributes: coordinate system, dimensions, material properties etc. These attributes can vary during analysis and different regions of the model may be inactive for a particular physics solution [7].

We illustrate the statements of the analysis and the results on a concrete application. This application consists of electromagnetic forming of 1 mm thin aluminum alloy sheet, the geometry of the system being illustrated in Fig.2. The forming coil has 6 turns by solid copper conductor, like in Fig.4. The gap between coil and sheet is 1 mm wide (Fig.6c). The coil region is considered a solid conductor, taking into account the non-uniform distribution of current density in cross-section.

For transient magnetic application, both 2D and 3D structure is considered and because the differences are not significant concerning the values of electromagnetic forces, the deformations was studied only in 2D geometry. The electrical circuit consists of a 200 μ F capacitor initially charged at 4 kV,

an ideal switch and negligible junction conductors.

At each time step, electromagnetic simulation gives at each finite element the volume density of electromagnetic force. These force vectors in the sheet region are shown in Fig.5. The computation domain for electromagnetic problem and the corresponding mesh is shown in Fig.6, in which the 2D 8 nodes quadrilateral elements having 8 nodes or tri-option with 6 nodes were used. Finite element model uses PLANE53 elements with axisymmetric option and with up to 4 degree of freedom per node: z component of magnetic vector potential AZ, time-integrated electric scalar potential VOLT, electric current CURR and electromotive force EMF. The attached circuit model uses CIRCU124 circuit elements with up to three degree of freedom: voltage VOLT, current passing through CURR and potential drop along component EMF. The magnetic field – electric circuit coupling is realized by EMF and CURR DOF's. Because of semi-infinite extension of computation domain, a single layer of INFIN110 elements was used. For accurate results, the mesh must be refined in accordance with field, currents and force distributions. For electromagnetic model, the computation domain contains all regions illustrated in Fig.2 while for the structural computation only the sheet region was extracted, other regions being considered with null elements.

Structural computation uses quadrilateral 8-node PLANE183 elements. This element is capable to model a viscoplastic material and supports large deflection and rate-dependent plasticity.

A sequential coupling between electromagnetic and structural computation and a direct magnetic field – electric circuit coupling were considered. The entire problem is a full transient application and in this case the time step was 0.5 μ s.

During one time step, after electromagnetic calculations, the results file contains electromagnetic forces that are the nodal loads on the sheet in the structural simulation. After structural applications, the results file gives the nodal displacements (UX, UY in this 2D application) that are applied on node coordinates and the geometry are updated for next time step

The simulation may be stopped when the total amount of energy on the electrical circuit

is less than a specific quantity that can't produce any deformation in workpiece. Another criterion may be the time: the

simulation is useful for a time equal to a maximum two periods of current in electrical circuit.

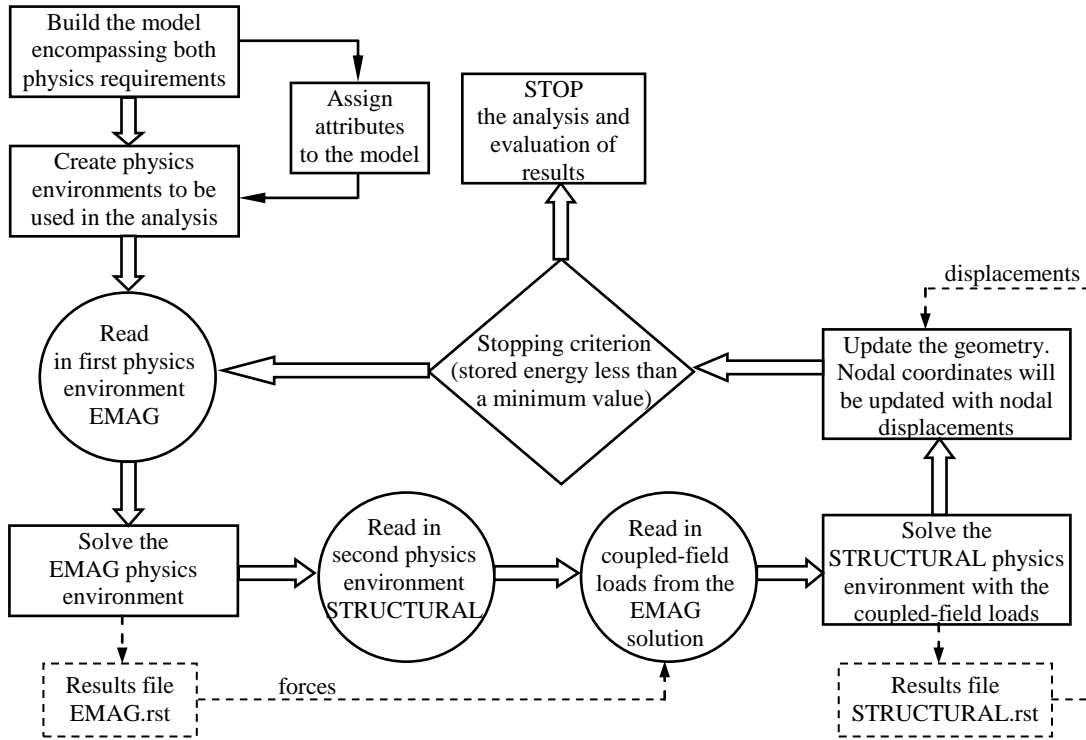


Fig.3. Data flow for a sequentially coupled electromagnetic – structural analysis

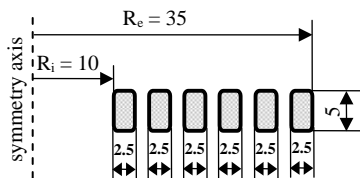


Fig.4. The geometry of the forming coil

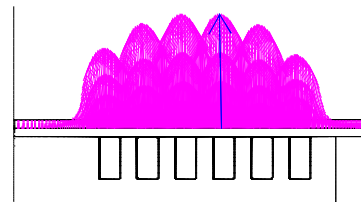


Fig.5. The vectors of volume density of electromagnetic force acting on the sheet

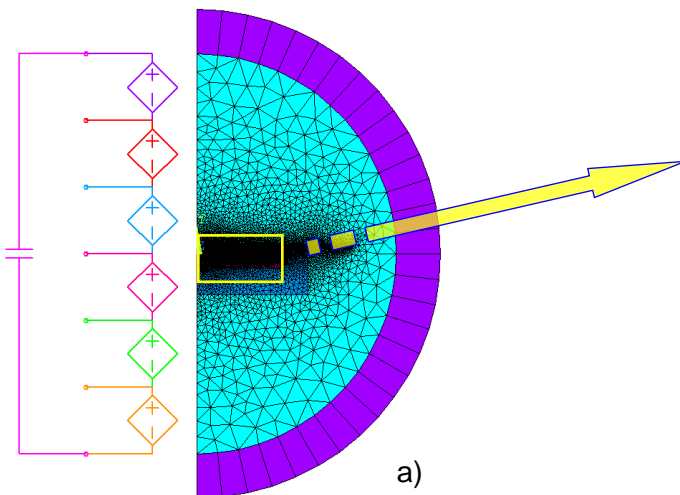


Fig.6. ANSYS Multiphysics model of magnetoforming process: computation domain (a) and mesh details (b), (c).

As simulation results, Fig.7 presents the time variation of capacitor voltage (a), coil current (b) respectively magnetic field lines (c) and flux density chart (d) for a time step during the process. Fig.8 depicts the deformed sheet at different time steps and at the end.

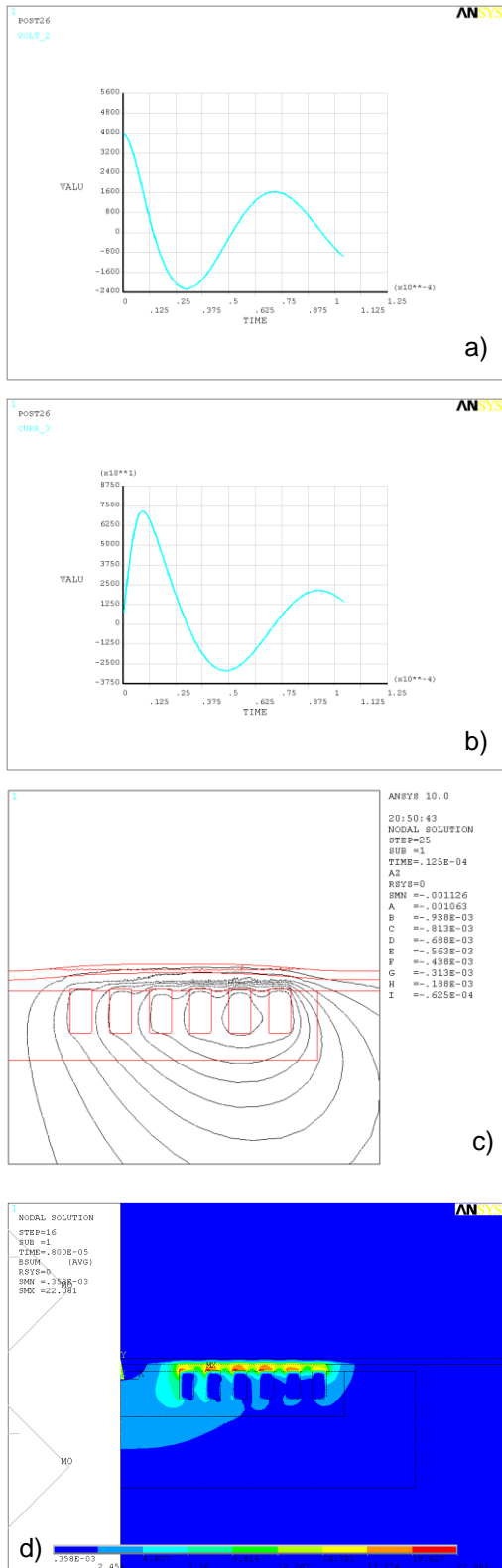


Fig.7. Simulation results concerning electromagnetic phenomena

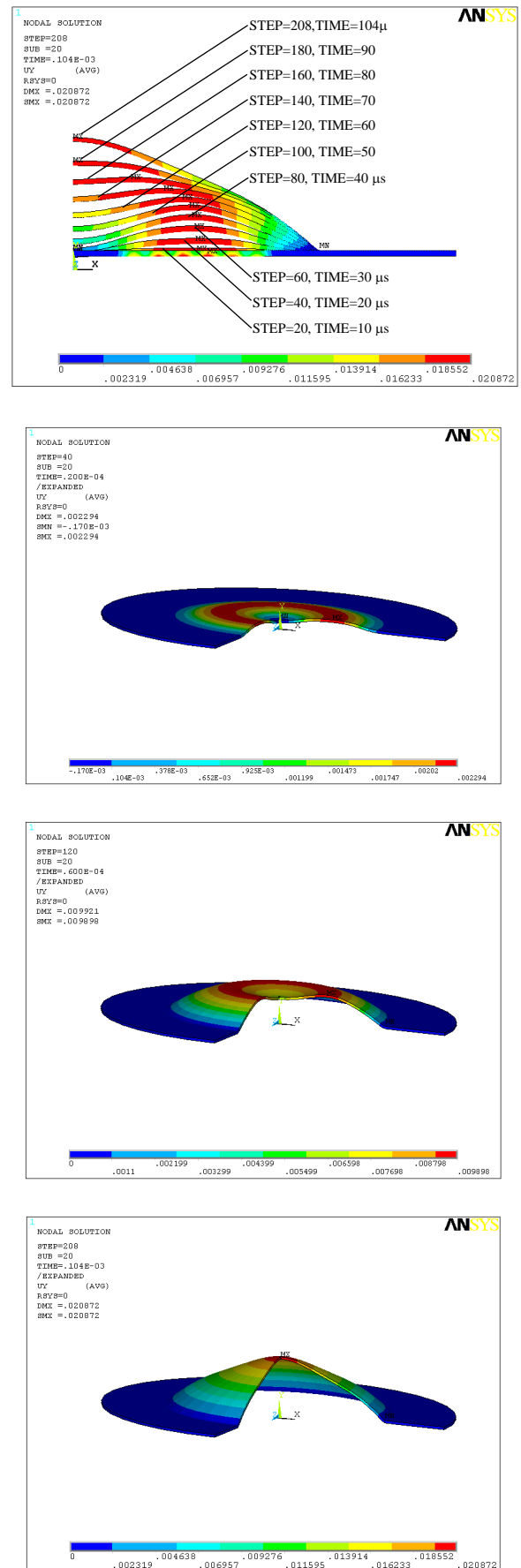


Fig.8. Simulation results concerning mechanical / structural phenomena

It can be seen that the total duration of the process is 104 μ s and the maximum deformation of the sheet at the end is 20.8 mm. The simulation results give important information about this high-speed process. For example, the sheet material reaches great velocities as at time step 46 (23 μ s) the axial component of velocity of sheet material overrides 200 m/s in some points (Fig.9).

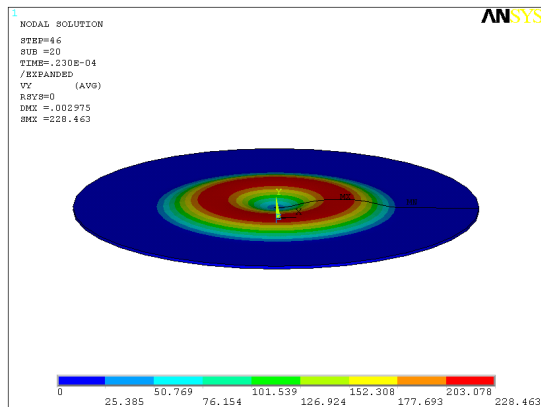


Fig.9. The chart of axial component of velocity at time step 46 (23 μ s)

A major difficulty appears during simulation concerning the mesh in gap between sheet and coil. Because of sheet deformation it is necessary the morphing mesh in this area or remeshing.

4. CONCLUSIONS

The presented model of electromagnetic forming is a complex but very useful tool for analysis of transient phenomena involved on this process. In addition, the model is suitable for design and optimization of the device.

Tacking into account the sequential electromagnetic – structural coupling, the direct magnetic field – electric circuit coupling and the realistic material properties models for the workpiece, including the rate dependent plasticity, we suppose that we obtain accurate results, in accordance with some references and experimental works.

However, the numerical results must be experimentally validated. High speed impact tests are necessary, in order to consider as computation data the mechanical properties of the sheet as close as possible to the real values.

Some aspects related to mesh morphing / remeshing in gap area must be improved in future work.

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