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Transient Phenomena in Electromagnetic Forming Processes

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Abstract

The paper deals with finite element model for analysis of electromagnetic forming process of thin metallic sheets. The investigation starts with the FLUX simulation of transient electromagnetic field phenomena, continues with a transient structural analysis using ANSYS Structural under loads previously evaluated and ends with an ANSYS Multiphysics fully coupled analysis. The paper emphasizes the complexity of magnetoforming modeling and presents some results of a research project.

Introduction

Because of multiple advantages, the use of workpieces aluminum and its alloys made has extended in many sectors e.g. in automotive industry. As a consequence, taking into account the particularities in processing such materials, unconventional technologies such electromagnetic forming (EMF) are developed. The increasing number of EMF applications during last years justifies the necessity of a rigorous analysis that is possible only through numerical models of different magneto-forming devices.

1. Electromagnetic Forming of Metal Sheets – Facility and Characteristics of the Process

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, eddy currents are induced in the workpiece and repulsive forces occur between the coil and the workpiece. 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.

A rigorous analysis of the magnetoforming process is very difficult because of coupling of different types phenomena: electromagnetic – mechanical/structural – thermal, the analysis of EMF being a *multiphysics* problem. The magnetic field in the device that is the source of energy for forming process is generated by a damping oscillating current that flows through the forming coil, so that electromagnetic problem is a magnetic field – electrical circuit coupling. 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.

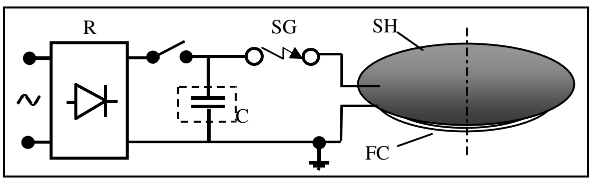

Fig. 1. EMF facility for forming metal sheets:
R - rectifier; C - capacitor bank; SG - spark gap;
FC – flat forming coil; SH - workpiece (sheet)

2. Models and Formulations of Phenomena Involved in EMF Process

2.1. Electromagnetic field model

Frequently, the magnetoforming device, workpiece and tool coil, has axial symmetry, as is depicted 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, $\boldsymbol{J}_{ex} = \boldsymbol{J}_{ex\ \varphi}$. As a consequence, the time dependent magnetic vector potential $\boldsymbol{A}(r, z, t)$ has component only in the same direction. The governing equation in terms of $\boldsymbol{A}$ is:

$$-\left[\frac{\partial}{\partial \mathrm{r}}\left(\frac{\nu}{\mathrm{r}}\cdot\frac{\partial}{\partial \mathrm{r}}(\mathrm{r}\cdot\boldsymbol{A})\right)+\frac{\partial}{\partial \mathrm{z}}\left(\nu\cdot\frac{\partial \boldsymbol{A}}{\partial \mathrm{z}}\right)\right]+\sigma\frac{\mathrm{D}\boldsymbol{A}}{\mathrm{Dt}}=\boldsymbol{J}_{\mathrm{ex}} \qquad (1)$$

where ν is magnetic reluctivity and $\sigma = 1/\rho$ is electric conductivity. The total derivative in (1) has the expression $\frac{\mathrm{D}\boldsymbol{A}}{\mathrm{Dt}}=\frac{\partial \boldsymbol{A}}{\partial \mathrm{t}}-\mathrm{v}\times\mathrm{rot}\ \boldsymbol{A}$, with $\boldsymbol{v}$ the velocity. If the motion of workpiece is not considered (v = 0) the equation of the modified vector potential $r{\cdot}\boldsymbol{A}$ is:

$$-\left[\frac{\partial}{\partial \mathrm{r}}\left(\frac{\nu}{\mathrm{r}}\cdot\frac{\partial}{\partial \mathrm{r}}(\mathrm{r}\cdot\boldsymbol{A})\right)+\frac{\partial}{\partial \mathrm{z}}\left(\frac{\nu}{\mathrm{r}}\cdot\frac{\partial}{\partial \mathrm{z}}(\mathrm{r}\cdot\boldsymbol{A})\right)\right]+\frac{1}{\mathrm{r}}\sigma\frac{\partial}{\partial \mathrm{t}}(\mathrm{r}\cdot\boldsymbol{A})=\boldsymbol{J}_{\mathrm{ex}} \qquad (2)$$

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 $\boldsymbol{A}$ of transient magnetic field is solved using the step by step in time domain method. The study domain for a sheet magnetoforming application is shown in Fig. 2.

The source $\boldsymbol{J}_{ex}$, 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 $\boldsymbol{J}_{ex}$ 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.

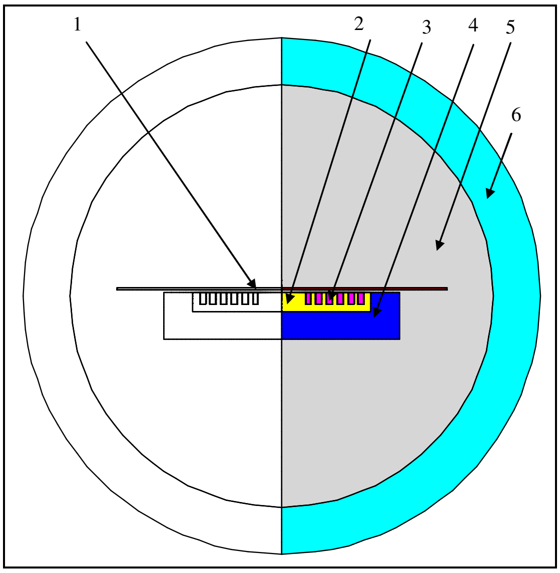

Fig. 2. Magnetoforming of flat sheets – 2D computation domain: 1-metallic sheet; 2-electric insulation; 3-forming coil; 4-magnetic shield; 5-air; 6-“infinite” region

At any time step, the second relation between $\boldsymbol{A}$ and $\boldsymbol{J}_{ex}$ is 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 [2,3], 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)·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.

2.2. 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 $\overline{\sigma}$ depends on the strain-rate dependent function Φ, which is to be determined by the properties of the material. If we choose the function $\Phi = \left((\overline{\sigma}/\sigma_0) - 1\right)^{1/m}$, then results [4]:

$$\overline{\sigma} = \sigma_0 \left[1 + \left(\frac{\dot{\varepsilon}}{\gamma} \right)^{m} \right] \tag{3}$$

Equation (3) is a familiar rate-dependence law 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 [5]. As it is stated in the references [4] and [5], this kind of material models the best impact like deformation processes.

3. Different Approaches in Numerical Modelling of Electromagnetic Forming Process

It is different strategies to couple transient electromagnetic with transient structural in EMF applications. It is very difficult to model the entire process in a single code, as a multiphysics application. Tacking into account the specific requirements for finite elements for different types of phenomena, only a sequential coupling is possible

Other method consists of coupling different finite element software, specialized for electromagnetic analysis, as is FLUX software, and for structural analysis, as is ANSYS Structural package. In this case, the difficulty is due to different file formats for data exchange.

3.1. Modeling Transient Electromagnetic Field Phenomena

Using the professional software FLUX as computation support the numerical model corresponding at domain depicted in Fig. 2, taking into account the coupling with electrical circuit, in which the turns of forming coil are considered solid conductors, is realised in [6]. Even if the motion of workpiece is neglected in such model, these computations are useful to predict if the impulsive forces are as great as is necessary for initiating the plastic deformations of sheets, in different configurations of magnetoforming devices and for different metals and dimensions of sheets. In addition, such studies give the possibilities for an optimum design of devices in order to obtain the predicted forces, taking into account the variation of all system variables (geometric and electric parameters, materials properties).

3.2. Transient Structural Modeling

One simplified method of EMF analysis consists of solving the transient electromagnetic problem for a non-deformed shape of the workpiece and saving the exerted forces in the workpiece material, at each time step. These forces will represent the loads at each time step in a transient structural application. This method does not consider the modification of forces due to the modification of the gap between coil and the workpiece

The forces that act on sheet at each time step determine local displacements that give the deformed shape of the sheet and final position of all nodes at the end of the step. In addition, the structural simulation based on viscoplastic model previously described gives as results other important quantities and make possible the study of the forming process.

3.3. Fully Coupled Electromagnetic – Structural Model

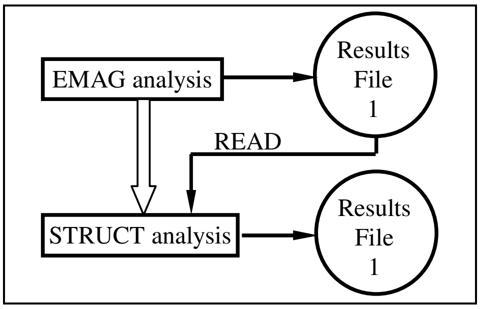

Fig. 3. One step in sequential coupling in an electromagnetic – structural coupled problem solving.

Because experimental tests [3] confirmed that the deformation of workpiece has a non-negligible influence on magnetic field distribution in the forming device and consequently on values of forces that exerts on sheet, the most accurate and only acceptable model consists of coupling transient electromagnetic field analysis with the transient structural one in a sequentially mode. Figure 3 illustrates one step in this simulation, where electromagnetic calculation includes a direct magnetic field – electric circuit coupling. This numerical model was built using the capabilities of ANSYS Multiphysics code.

4. Application and Results

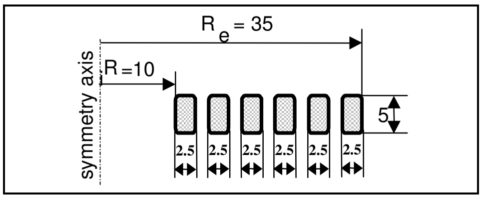

Fig.4 The geometry of the forming coil

The application which was the subject of the numerical analysis 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 Figure 4. The gap between coil and sheet is 1 mm wide.

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 μF capacitor initially charged at 4 kV, an ideal switch and negligible junction conductors.

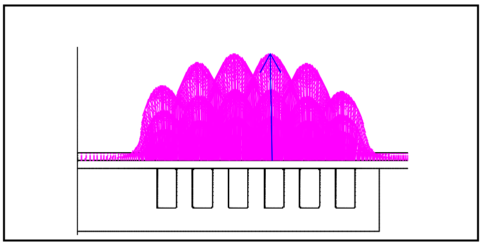

Fig. 5. The vectors of volume density of electromagnetic force on the sheet.

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 depicted in Fig. 5. The model is built in ANSYS Multiphysics 10. The computation domain for electromagnetic problem and the corresponding mesh is shown in Fig. 7, in which the 2D 8 nodes quadrilateral

PLANE53 elements and CIRCU124 circuit elements were used, coupled by EMF and CURR DOF's. For the structural computation only the sheet region was extracted, other regions being considered with null elements. A sequential coupling between electromagnetic and structural computation and a direct magnetic field – electric circuit coupling were considered. The entire problem is considered a full transient application.

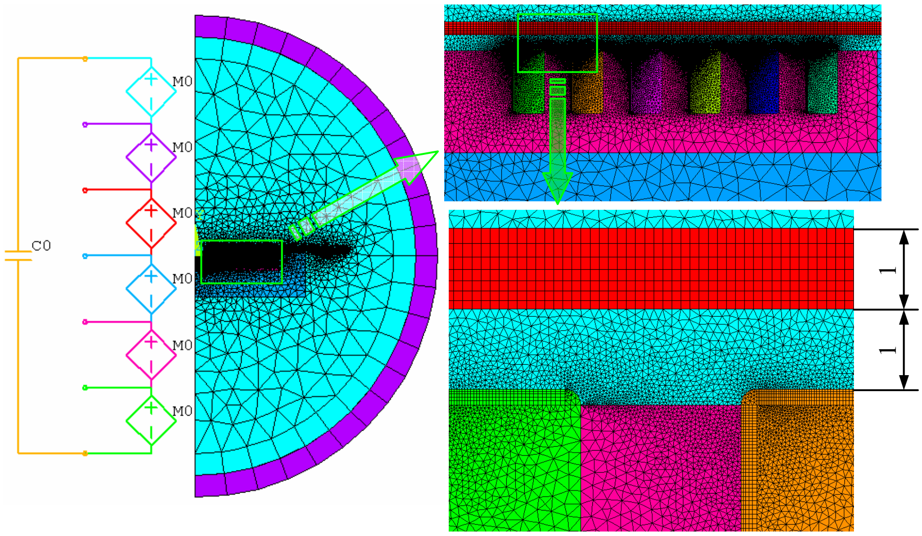

Fig.7. The computation domain and mesh in ANSYS model.

As results, Fig. 8 – 11 presents the time variation of the capacitor voltage, the coil current, the EMF drop across the coil turns and the magnetic flux density at the sheet surface in a point corresponding to the middle of coil.

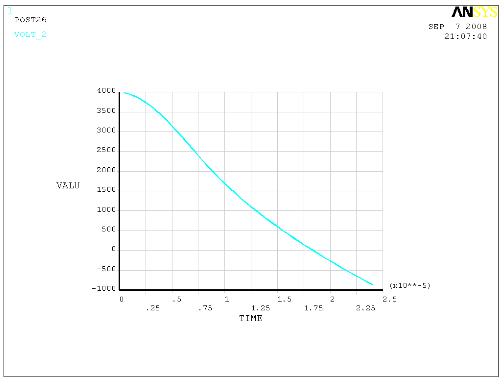

Fig. 8

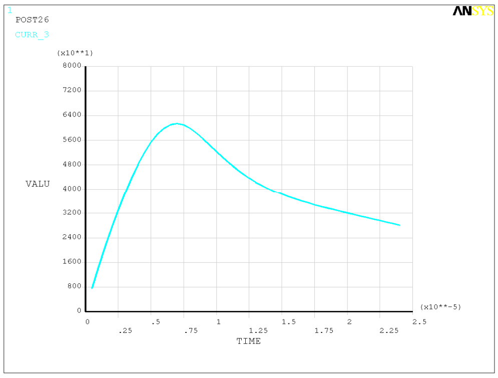

Fig. 9

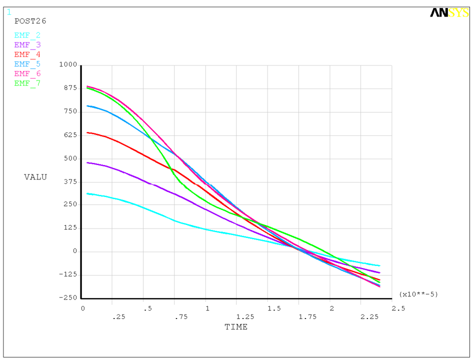

Fig. 10

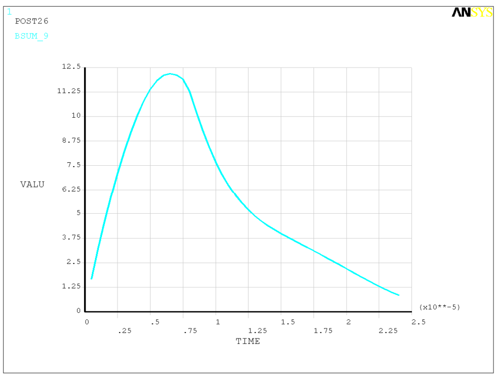

Fig. 11

The axial component of stress and the deformed shape at different two time steps is shown in Fig. 12 and 13. The time step was 0.5 μs.

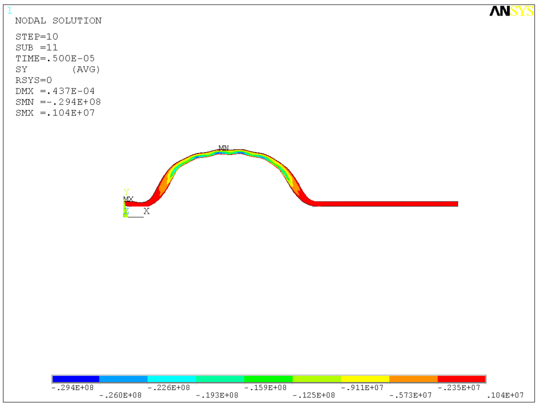

Fig. 12

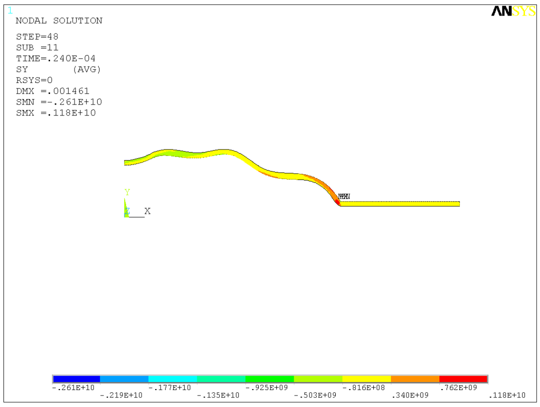

Fig. 13

Conclusions

The fully coupled electromagnetic – structural model for electromagnetic forming is a very useful tool for analysis of transient processes involved and for design and optimization of the device.

Ackowledgments

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