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# CHAPTER 13

# Electromagnetic Forming of Aluminum Alloy Sheet Using a Grooved Die: Numerical Modeling[1]

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**Abstract**—A commercial ANSYS FE Code is employed for the simulation of the electromagnetic sheet-metal forming into a grooved die. An industrial pancake coil is considered as the forming tool. The deformation characteristics of the sheet (workpiece) as well as the electromagnetic parameters of the high-energy process are calculated numerically. An equivalent-circuit method is used to validate the electromagnetic model. The results from both analyses are in good agreement.

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## 1. INTRODUCTION

Electromagnetic forming is based on the repulsive force generated by the opposite magnetic fields in adjacent conductors. The primary field is developed by the rapid discharge of a capacitor bank through the forming coil, and the opposing field results from the eddy currents induced in the metallic workpiece [1]. The deformation of the latter is completed on a microsecond scale.

In fact, the electromagnetic and mechanical aspects of the process are strongly interrelated, since the workpiece deformation affects the magnetic field and, consequently, the Lorentz forces developed. An approximate but a more realizable approach is to treat the process as a loosely coupled problem, i.e., calculating first the magnetic forces (neglecting the influence of the sheet deformation on the magnetic field evolution) and then applying them as a load to the mechanical problem [2].

## 2. MODEL

The multipurpose FE Codes ANSYS 6 Multiphysics and ANSYS LS–DYNA 5.7 Ed are employed for simulating the process. The forming tool considered is presented in Fig. 1a. It is a single-layer seven-turn pancake coil with a ferromagnetic outer screen. The equivalent model is 2D axisymmetric (Fig. 1b). The *X*, *Y*, and *Z* axes correspond to the radial, axial, and circumferential direction, respectively.

This kind of analysis is easier and less expensive in CPU time and resources than the equivalent 3D analysis. However, if the shape of the die cave does not meet the axisymmetric condition, only a 3D model can be used to simulate the specific process.

According to the loosely coupling simplification, only the first pulse (approximately 70.5 μs) of the magnetic pressure developed is considered to be responsible for the workpiece deformation. The properties of the materials involved are given in the table. The constitutive behavior of the workpiece material is described in Fig. 2.

The quasi-static data are scaled, in order to adapt the high strain-rate conditions occurred during the process, by means of the Cowper–Symonds constitutive model

$$\sigma = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^m\right]\sigma_{QS}, \qquad (1)$$

where $\sigma_{QS}$ is the quasi-static flow stress (Fig. 2), $\dot{\varepsilon}$ is the strain rate, $C = 6500\ \text{s}^{-1}$, and $m = 0.25$ for aluminum.

### *Electromagnetic Model*

This is a transient analysis based on a magnetic vector potential formulation. The coil is considered as the cross section of seven separate coaxial circular loops of equivalent mean diameters. The mesh density of the model is high in regions of high-energy density such as the air gaps between adjacent current-carrying conduc-

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[1] The text was submitted by the authors in English.

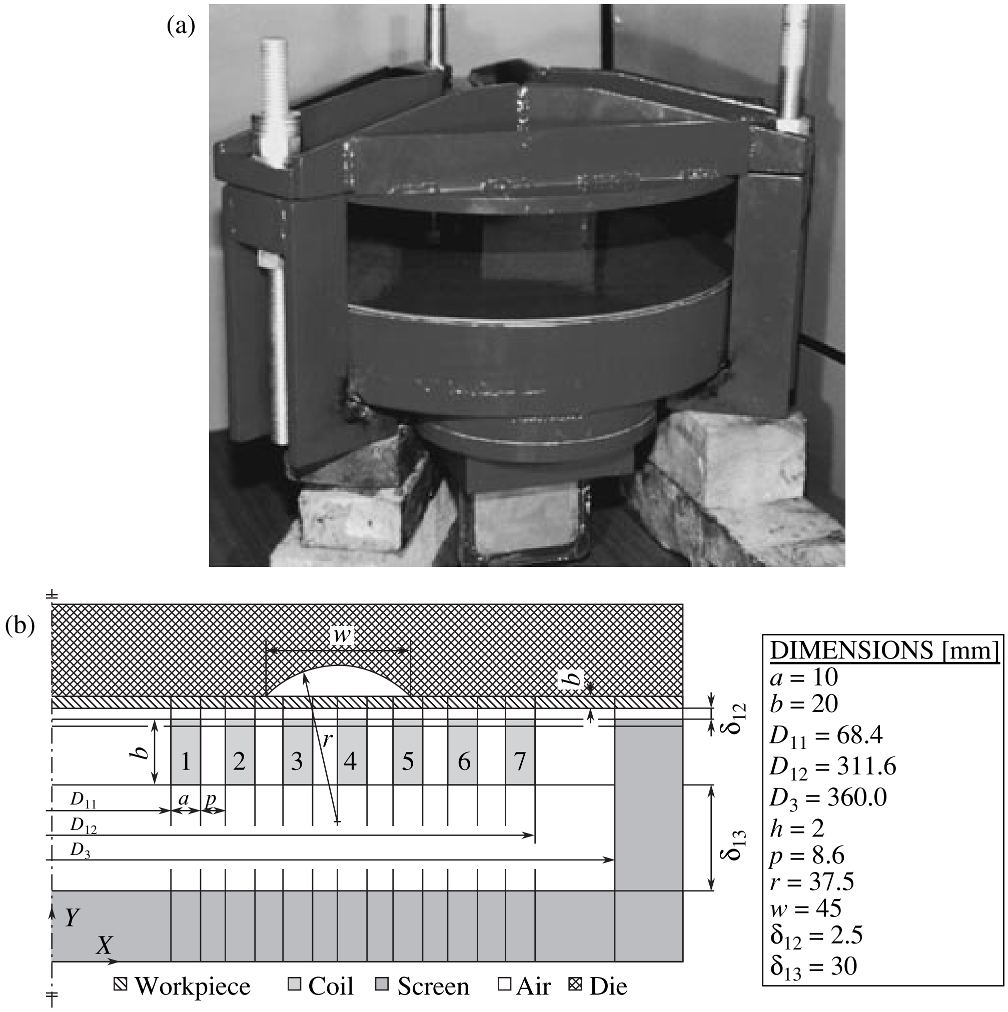

**Fig. 1.** (a) Pancake coil and (b) an equivalent model of the cross section of the forming tool.

tors and skin-depth regions. The input load is the current flowing in the coil. In practice, it can easily be measured by means of a Rogowski coil connected to an oscilloscope. In the magnetic-forming process, the current is approximately expressed by the following equation:

$$I(t) = \frac{V_0}{\omega_d L}\exp(-\gamma t)\sin(\omega_d t), \qquad (2)$$

where $V_0$ = 5 kV is the initial voltage stored in a capacitor bank of 480 μF, $\omega_d$ = 43564 rad/s is the angular frequency, $L$ = 1.08 μH is the equivalent inductance, and $\gamma$ = 4805.8 $s^{-1}$ is the damping exponent. The current is applied in increments of 1 μs to a total duration of 75 μs, in the upper skin depth of each turn, which is given by the well-known equation

Material properties of each entity

| Entity | Material | $\rho_e$ [Ω m] | $\mu_r$ | $E$ [GPa] | $N$ | ρ [kg/m$^3$] |
|---|---|---|---|---|---|---|
| Coil | Cu | 1.79E–8 | 1 | | | |
| Sheet | A.A. 1100-O | 3E–8 | 1 | 69 | 0.33 | 2710 |
| Screen | Mild St. | | 2500 | | | |
| “Air” | Insulator | | 1 | | | |
| Die | H13 Tool St. | 20E–8 | 2500 | 210 | 0.3 | 7800 |

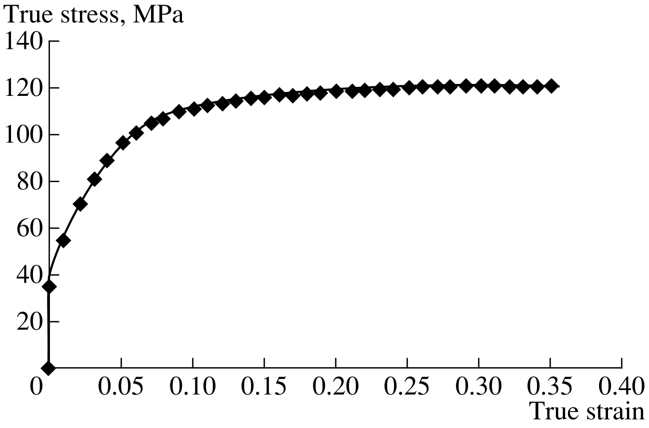

**Fig. 2.** Constitutive behavior of the workpiece.

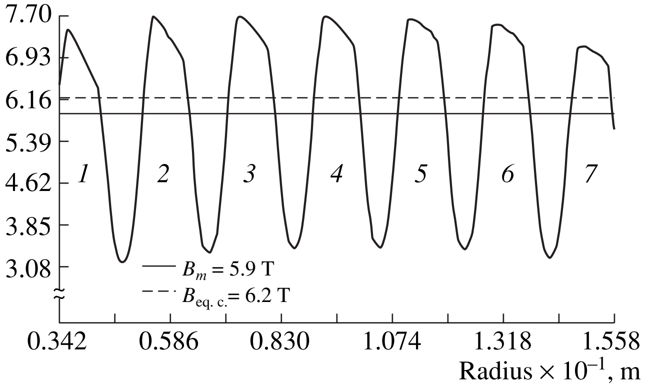

**Fig. 3.** Radial distribution of the maximum magnetic flux density in the working gap.

$$\delta = \sqrt{\frac{2\rho_e}{\mu_r\mu_0\omega_d}}, \tag{3}$$

where $\rho_e$ is the resistivity, $\mu_r$ is the relative permeability, and $\mu_0 = 4\pi \times 10^{-7}$ H/m. Flux-parallel boundary conditions are applied all around the model.

### *Structural Model*

The explicit ANSYS LS–DYNA Code is capable of simulating short-duration contact–impact problems. The 2D axisymmetric model developed consists of three entities (see below). The die and the base are both simulated as fully clamped rigid bodies. The through-thickness nodes on both sides of the workpiece are constrained in the radial direction. The applied loads are the nodal forces in the axial direction per unit length of periphery, uniformly distributed on the bottom nodes of each part of the workpiece. All of the external surfaces of each entity are permitted to come into contact with a static and sliding coefficient of friction between steel and aluminum of 0.4 and 0.2, respectively. Finally, the solution time is fixed at 2000 μs.

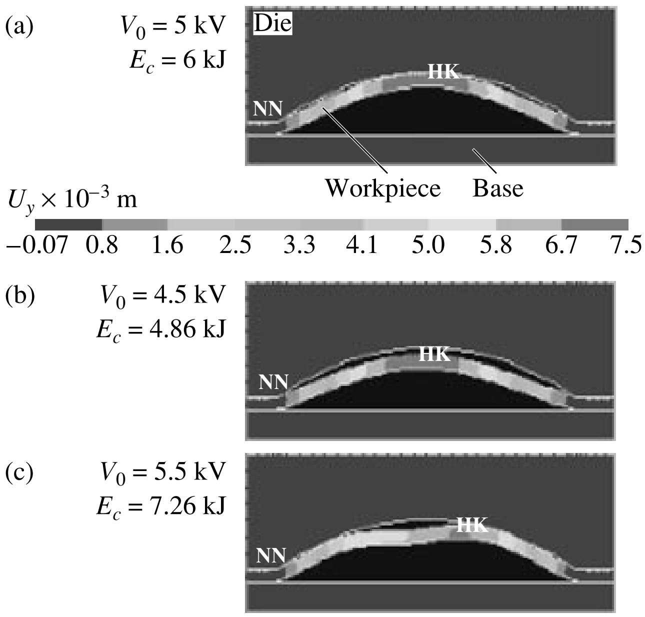

**Fig. 4.** Final shape of the workpiece for different initial charging voltage.

## 3. RESULTS AND DISCUSSION

It follows from Eq. (2) that the maximum of the input current occurs at 33.5 μs. The peak of the magnetic flux density in the gap between the coil and the workpiece (working gap) occurs also at the same time. The distribution of the magnetic flux density along the working gap is presented in Fig. 3. The mean magnetic flux density can be calculated from the following integral:

$$B_m = \frac{1}{0.1216}\int_{0.0342}^{0.1558} B(x)dx \Rightarrow B_m = 5.9 \text{ T}.$$

The results obtained by both methods are in reasonable agreement, so the FE model is valid from the engineering point of view. It is also worth noting that because of the transient nature of the problem, the magnetic field penetrates the workpiece in about 40 μs. Moreover, the distribution of the Lorentz force per unit of periphery, along the radius of the workpiece follows the same pattern as the magnetic flux density. Finally, the interaction of the stray magnetic field with the die does not affect the loading regime of the workpiece (magnetic-pillow effect [1]), probably because of the high resistivity of the die.

The resulting shape of the workpiece is presented in Fig. 4. The workpiece begins deforming in about 40 μs. So, from this point up to the end of the applied pulse (70.5 μs), there is an uncertainty for its accuracy. The

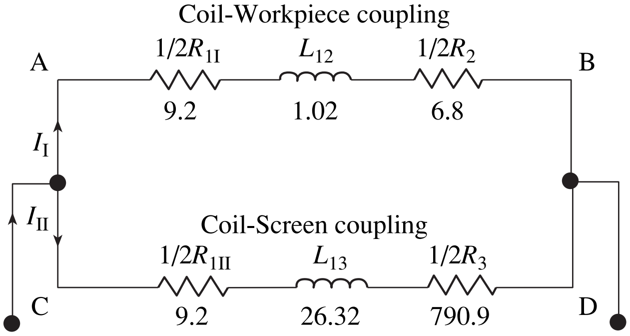

**Fig. 5.** Equivalent circuit of the forming tool (resistance in mΩ, inductance in μH).

impact of the workpiece onto the die is fulfilled in 120 μs. Only the top of the workpiece is finally in contact with the die. The other areas of the workpiece lose the contact with die due to the rebound effect after the impact and the springback of the workpiece material. Near both edges of the workpiece, the penetration of its material into the base is calculated to be small (lies in the range of 0.07 mm, which is negligible).

According to Fig. 4, a variation of the discharge by ±0.5 kV strongly affects the deformation process. This is believed to be due to the accuracy range of the present analysis because of the uncertainty of the last part of the applied pulse.

## 4. CONCLUSIONS

Following this step-by-step analysis, the electromagnetic forming operation presented can easily be predicted, enhancing in this way the potentiality for the industrial application of the process. The present analysis can be further developed by taken into account the coupling nature of each aspect of the process.

## *APPENDIX*

According to Göbl [3], there is a transformer coupling between the coil and the other parts of the forming tool. So, its operation can be simulated using an equivalent circuit (Fig. 5). It consists of resistances and inductances, which represent every part of the forming tool. The current is considered to be ac. This assumption is valid only for the first half-period of the current pulse.

The current $I_I$ can be determined by taking into account that the inductances $L_{12}$ correspond to the working gap and by applying the current and the voltage Kirchhoff's Laws to the equivalent circuit. So, the magnetic energy in the working gap can be expressed by the following equation:

$$E_{m12} = \frac{1}{2}L_{12}|I_1|^2 = \left(\frac{B_{12}^2}{2\mu_0}\right)v_{12}, \tag{4}$$

where $v_{12}$ is the effective volume of the corresponding gap which is given by the equation

$$\begin{aligned} v_{12} &= 0.25\pi(D_{12}+D_{11}) \\ &\times(D_{12}-D_{11}+\delta_1+\delta_{12}+\delta_2)(\delta_1+\delta_{12}+\delta_2). \end{aligned} \tag{5}$$

Finally, the magnetic flux density can be obtained from Eq. (4) and the corresponding calculated value is $B_{12} = B_{\text{eq.c}} = 6.2$ T.

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