Finite Element Modeling and Simulation of Electromagnetic Forces in Electromagnetic Forming Processes: Case Studies using COMSOL Multiphysics

Alle Navee Kumar[1], Mashuq-Un-Nabi*[2]
[1]Electrical Engineering Department, IIT Delhi; [2] Electrical Engineering Department, IIT Delhi
*Corresponding author: Assistant Professor, Electrical Engineering Department, IIT Delhi, New Delhi-110016. E-mail: mnabi@ee.iitd.ac.in

Abstract: Electromagnetic Forming (EMF) is a promising and relatively new manufacturing technology having significant advantages over conventional forming processes. A primary characteristic of this process is use of non-contact electromagnetic forces to achieve forming and shaping of various metal work pieces. Mechanically, this is a high-strain rate forming process. From the modeling and simulation perspective, it can be identified as a coupled multyphysics problem, involving circuits, electromagnetic fields and structural deformations. A basic requirement in modeling and simulation of EMF processes is the computation of Lorentz forces over the job piece as well as the coil. In the present work, modeling and computation of such forces for a stranded coil and job piece geometry are reported. The results of simulation of this configuration and impulse excitations are presented. These are startup simulations related to a project on modeling and simulation of electromagnetic forming processes taken up at Indian Institute of Technology Delhi.

Keywords: Finite Element Modeling, Multiphysics, Electromagnetic Forming Process, current impulse, Lorentz force, High strain rate.

1. Introduction

Electromagnetic Forming is a relatively new manufacturing technology having significant advantages over conventional forming processes. The significant advantages are use of non-contact forces leading to absence of contamination, fast processing, in addition to desirable mechanical features like reduced springback, improved formability and less wrinkling [1].

The process is a high velocity forming process where the force deforming the work piece is electromagnetic force. A current pulse generated by discharging a capacitor bank is used to create a high magnetic field around a coil. This field induces eddy currents in the work piece. The two currents create forces of magnetic repulsion leading to the deformation of the work piece.

Simulations of a flat spiral coil placed below a metal sheet with different coil dimensions and configurations are discussed in [1] using ANSYS and LS-DYNA. The simulation results are of loosely coupled electromagnetic and structural computation. Relationship between geometry of forming coil, length of pressure pulse and the behavior of work piece during plastic deformation is studied in [2]. Simulation of ring expansion by electromagnetic forming and validation with an experiment is done in [3]. Also, experimental verification of results is done for forming of thin sheets to different shapes in [4], both using LS-DYNA. The transient phenomenon of forming process is studied in [5] using LS-DYNA. Free-form and cavity fill forming simulations using ANSYS are reported in [6].

1.1 Physics of Electromagnetic forming systems

The electromagnetic fields involved in the EMF process are governed by the Maxwell's equation, written in terms of the electric field intensity E and magnetic induction H as

$$\nabla \times \vec{E} = \mu \frac{\partial H}{\partial T} + \mu \left[\vec{v} \times \vec{H} \right] \quad (1)$$

$$\nabla \times H = J \quad (2)$$

$$J = \sigma E \quad (3)$$

Where $div\ E = 0$ and $div\ H = 0$

E = Electric field intensity;

H = Magnetic field intensity;

J = Current density;
μ = Permeability of metal;
σ = Material electrical conductivity;
v = Velocity of moving conductor;

The forcer per unit volume acting on the conductor placed in the magnetic field with field intensity H is equal to

$$F = \mu \left[J \times H \right]$$

These forces when coupled with structural mechanics equations will yield the corresponding deformations of the workpiece.

In this work, the basic COMSOL multiphysics is used to compute the forces on the workpiece and coil, revealing the expected deformation zones, prior to a full-scale coupled electromagnetic-structural analysis to be reported later.

2. Simulation setup

For the present work an axisymmetric problem is taken up as shown in the Fig 1, with the actual physical setup being as shown in Fig 2. The Finite Element model as shown in Figure 1 is axis symmetric view of a flat spiral coil placed below a thin aluminum sheet. A schematic 3-dimensional view of EMF setup showing the coil and sheet configuration is shown in Figure 2. The dimensions of the geometry are listed in Table 1.

Radius of aluminum sheet placed above coil	10cm
Cross section of the coil turn	5mmX5mm
Gap between coil and aluminum sheet	7mm
Separation between the coil turns	1.5mm
Air surrounding the coil-aluminum sheet setup	0.5mX1m

Table 1. Dimensions of the setup drawn using COMSOL

Axis symmetric simulation is performed in the present work. 3-dimensional modeling and simulation of the same is also equally possible for the study using COMSOL. The coil configuration discussed here is a flat spiral wound with equal spacing in between each turn. Also the dimensions of each coil turn are maintained same.

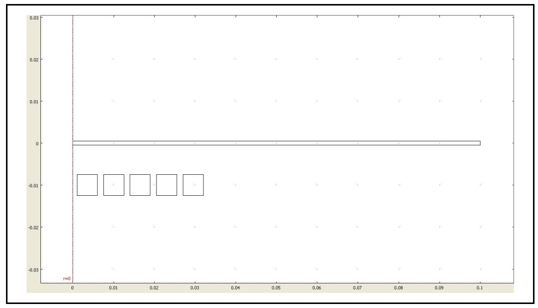

Figure 1. The setup showing cross section of coil turns beneath a thin aluminum sheet.

The simulation could also be carried out for different coil configurations. It involves varying the gap between each coil turn and varying the coil dimension for each turn. Such an analysis would lead to optimization of coil dimensions for a given process [3]. In the same way, the forming process can be optimized for different excitations. Here, a pulse signal has been used. In general, the forming process would involve discharging of heavily charged capacitor bank through the coil [4, 5, 6]. The current profile in this case would be a high frequency decaying sinusoidal signal.

In simulating a 3-dimensional setup using COMSOL, the coil has to be connected to the source. Therefore, care has to be taken in assembling the leading and trailing ends of coil with source. This aspect of design using COMSOL needs to be explored.

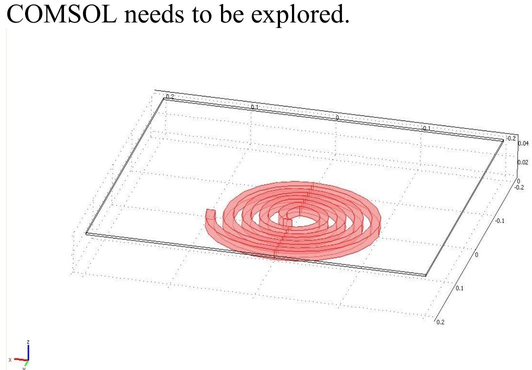

Figure 2. 3-dimensional view of the aluminum sheet placed above the spiral coil.

The materials for the setup are loaded from the default material library of COMSOL. The coil is of copper and sheet is chosen to be aluminum.

3. Circuit using Spice Editor

Spice editor option of the COMSOL has been used for the present simulation in order to generate a current pulse of desired nature. Each turn in the coil is in turn divided into 4 turns. This would make a total of 20 turns of coil to be excited. The coil is treated as an inductor and its properties are obtained from Spice editor. A current source (PULSE) is placed in series with the inductor in the netlist and is coupled to the FEM part. The characteristics of the current pulse are shown in Figure 3. The maximum current density across each turn is 1e9 A/m^2.

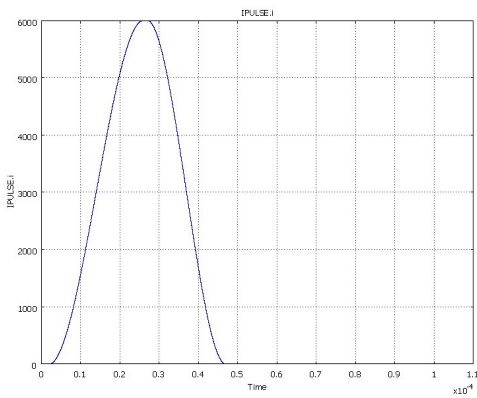

Figure 3. Current pulse generated by Spice Editor.

Delay time	2µsec
Rise time	24µsec
Pulse width duration	2µsec
Fall time	20µsec
Period	1sec

Table 2. Time specifications of the current pulse.

4. Simulation results

The current pulse shown in Figure 3 is the profile in each turn of the coil. The results obtained after the simulation are discussed here. UMFPACK linear solver is used and the time range is (0, 5e-5) with a time stepping of 1e-8.

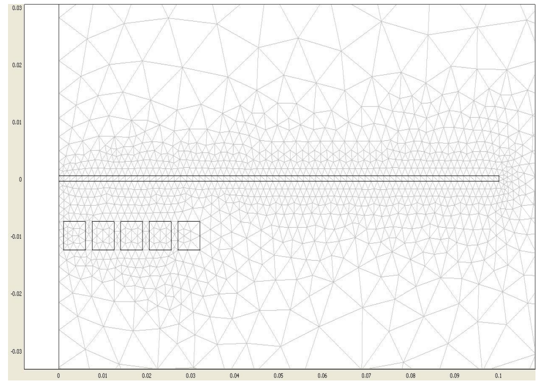

Figure 4. Meshing of the domain.

Meshing of the domain is shown in Figure 4. Refined mesh is opted for in order to eliminate errors due to skin effect. Simulation is carried out by exciting the coil with sinusoid signals of different frequencies. It is seen that at very high frequencies, the induced current density is comparatively less to generate required forces. It is observed that the excitation profile depends to some extent on the nature of material used in the work piece also. A contour plot of norm of magnetic field over the domain is shown in Figure 5.

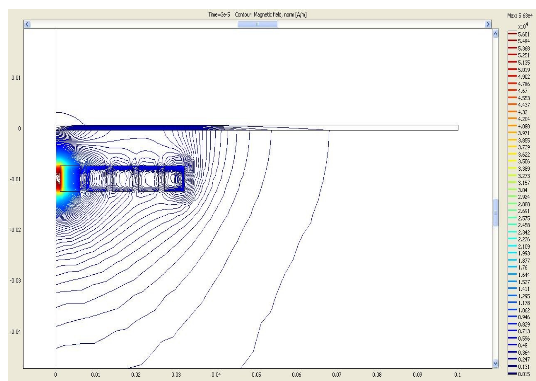

Figure 5. Contour plot of magnetic field [A/m]

The magnetic field pattern shows that there is significant flux passing through entire cross section of aluminum sheet. This would imply high amount of forces be generated throughout the sheet due to eddy currents. The maximum value of magnetic field in the entire domain is 5.63e4 A/m. Figure 6 shows Lorentz force distribution across the metal sheet and coil. The forces directly above the coil vary from 1e4 N/m^3 to 7e4 N/m3. The forces obtained are matching with that of real time forces. From the result, the force at the center of the disc i.e., at the axis in the figure is quite less compared to the surrounding area. It shows that the coil design needs to be restructured in order to give the metal sheet uniform force at the surface.

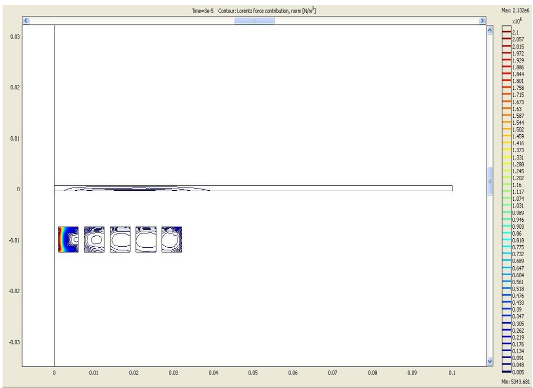

Figure 6. Contour plot of Lorentz force distribution.

It is also seen that the force on the coil is dominant especially on the central turn. This will imply that the coil should be strong enough to withstand heavy forces greater than that on the sheet. Different coil configuration could be tested to check uniform force distribution on each coil turn to ensure no deformation of coil during the forming process.

5. Conclusions

Forming of a thin metal sheet using a coil configuration with uniform spacing between the turns is presented here. Impulse current excitation is used to verify the force pattern on the metal sheet. It is observed that the magnitude of forces is high enough for a forming process. A further detailed simulation would require structural module in order to view the deformation in the metal sheet. This forms a strongly coupled electromagnetic-structural problem. The force computations and deformations have to be solved for each time step as the metal sheet deforms with time. Study of the force pattern with different coil configurations, dimensions and excitation needs to be done as an extension to the present work in order to optimize the forming process.

8. References

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