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# On The Simulation of Electromagnetic Forming Process of Tube Using Multiphysics Software

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**Abstract:** Electromagnetic forming (EMF) is a typical high speed forming process using the energy density of a pulsed magnetic field to form workpieces made of metals with high electrical conductivity like e.g. aluminium. This forming process can be very advantageous as compared to conventional forming process.

High velocity forming methods successfully address problems faced in conventional forming techniques. They can be effectively used for forming metals with low formability like aluminum alloys and high strength steel. Electromagnetic forming (EMF) is an HVF method that is gaining wide acceptance due to its advantages and scope for commercialization.

EMF process is simulated by a commercial finite element analysis (FEA) solver, COMSOL Multiphysics to predict the formability, reduction in wrinkling, and better distribution of strain. There are two main goals of this work:

1. Demonstrating steel/Aluminium tube compression with an electromagnetic forming process
2. Demonstrating that this process can be simulated in COMSOL Multiphysics with a relatively simple model that has good correspondence to experimental data.

Also, the validated COMSOL model should be able to predict deformation at energy levels that cannot be achieved within safe operating limits of the equipment used presently, but can serve as a guide for next generation equipment.

**Key words:** High Velocity Forming, Electromagnetic Forming,

## 1. Introduction:

Electromagnetic forming (EMF) is non contact type High velocity forming (HVF) method where large forces can be produce to deform the conductive metallic workpiece. EMF can be used to accelerate the sheet or workpiece on the order of 50 m/s to 250m/s over distance of few millimeters, as it acquires kinetic energy, which is dissipated as plastic work during metal formation [1].

Magnitude and time of application of pressure are the most important and main factors which distinguishes the HVF method from conventional forming process. In the case of HVF, a very high pressure is applied in very short time duration such that inertial forces and kinetic energy in the workpiece are significant [1]. Owing to the rapid release of energy involved in them, they are also referred to as High Energy Rate Forming (HERF) processes. Under dynamic forming conditions, physics is very different and inertia becomes an important factor. In conventional forming conditions, inertia is neglected as the velocity of forming is typically less than 5 m/s while typical high velocity forming operations are carried out at workpiece velocities of about 100 m/s.

In this paper, Simulations were carried out on the electromagnetic compression of high strength (440MPatensile strength) 76.2mmdiameter, 2.3mm wall thickness tubes in COMSOL using AC/DC module and Structural-Mechanics module. Simulation results obtained show good matching with experimental results. The results in the available literature [2] are used to validate the simulation results.

## 2. Electromagnetic Forming Process:

The working principle of EM forming is based on application of Ampere's law, 'Current-carrying conductors, when placed near each other exert a force on each other'

If the currents are in the same direction, there is a force of attraction, whereas if the current directions are opposite to each other, a repulsive force acts on the conductors. This repulsive force is used for shaping and joining of metals by means of high strength transient magnetic field. The force between infinitely long parallel conductors is given by [3],

$$F = \frac{\mu_0}{2\pi d} I_1 I_2 \qquad (2.1)$$

Where, $F$ = Force; N/m, I1, $I2$ = Current; A d = Spacing between conductors $\mu_0$ =permeability of free space; H/m

### 2.1 Process Description of EMF of Tubes:

The damped sinusoid current set up in the coil produces a transient magnetic field given by equations (2.2) and (2.3).

$$\nabla \times \overline{H} = \overline{J} \qquad (2.2)$$

$$\overline{B} = \mu \overline{H} \qquad (2.3)$$

Where,
H = Magnetic field intensity μ = Permeability of free space, J = Current density, B = Magnetic flux density

Hence, an electromotive force (EMF) is induced in the workpiece, which is placed co-axially outside the coil in its near proximity, and the polarity of this EMF is such that the current induced in the workpiece opposes the cause as given by equation (2.4),

$$\nabla \times \bar{E} = \frac{-\partial \bar{B}}{\partial t} \qquad (2.4)$$

Where
E is electric field intensity.
The induced current can be derived from equation (2.5) after accounting for material conductivity

$$\bar{J} = \sigma \bar{E} \qquad (2.5)$$

Where,
σ is conductivity of the workpiece
A typical waveform of the primary current flowing through the solenoid and the induced current through the workpiece is shown in Fig. 2.1. [3]

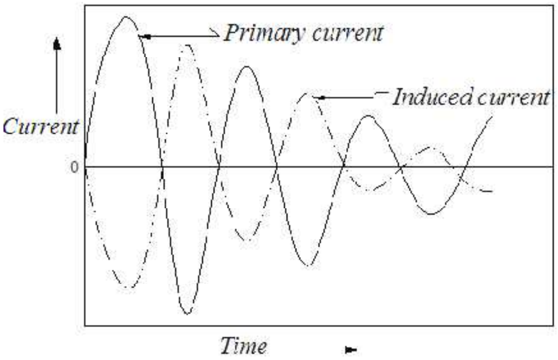


**Fig.2.1. Primary and induced currents in EMF process**

Finally, the workpiece experiences a repulsive force (Lorentz Force) given by equation (2.6), which arises on account of the interaction of the induced current and the magnetic field [4].

$$\bar{F} = \bar{J} \times \bar{B} \qquad (2.6)$$

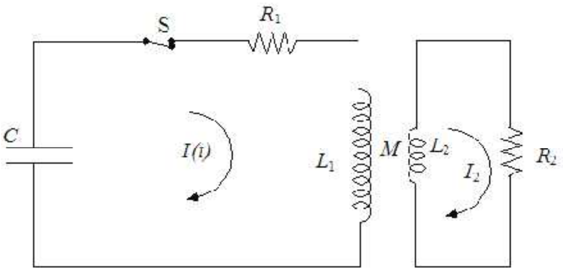


**Fig.2.2 Circuit diagram for the EM forming process.**

## 2.2Analytical Formulation for EMF

The capacitor bank *C* is charged to a voltage *V*0 by high voltage charging power supply. When the discharge circuit switch S is closed, the capacitor is discharged suddenly through the work coil. The values of resistance *R*1 and inductance *L*1 of the discharge circuit are such that the current *I(t)* is oscillatory and heavily damped. The presence of the workpiece around the coil affects the discharge characteristics considerably and in the circuit diagram , the workpiece is represented by the secondary circuit carrying the induced current *I*2 and linked inductively with the primary (discharge) circuit with mutual inductance *M*. *R*2 and *L*2 are the resistance and inductance of the workpiece respectively.

The behavior of such a system is described by the following differential equation, which can be derived from Maxwell's equation

$$\frac{d^2 I(t)}{dt^2} + 2\xi\omega \frac{dI(t)}{dt} + \omega^2 I(t) = 0 \qquad (2.7)$$

Where,
*I (t)* is the current caused by discharging capacitor

ξ is damping factor= $\frac{1}{2} R_1 \sqrt{C/L_1}$ (2.8)

ω is frequency= $\sqrt{\frac{1}{CL_1}}$ (2.9)

Solving the above differential equation provides the current as a function of time in the circuit.

$$I(t) = \frac{V_0}{\omega L}\, e^{\frac{-R_S t}{2L}} \sin(\omega t) \qquad (2.10)$$

Where,
V0 is original voltage across the capacitor.

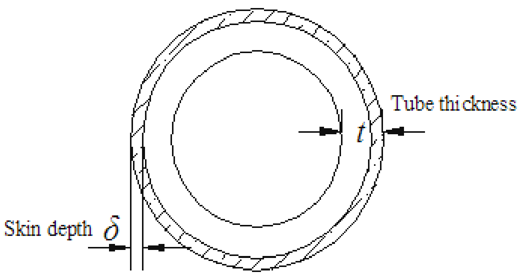


**Fig 2.3 Skin depth inside a conductor tube**

Current in a conductor does not flow uniformly throughout its cross-section. It flows in the skin depth as shown in Fig. 2.3. The frequency is selected such that the skin depth in the workpiece is small as compared to the job thickness. Under this condition, an appreciable amount of magnetic field is confined within the tube [3]. Skin depth is given by,

$$\delta = 1 / \sqrt{(\pi\sigma\mu f)} \qquad (2.11)$$

Where, δ = Skin depth (in m), σ = Conductivity of the medium through which current is passing (in mho/m), μ = Permeability (H/m), *f* = Frequency of field variation, i.e., frequency of the current flowing through the inductor.

## 2.3 Modeling of EMF Process:

A 9-turn helical solenoid coil in conjunction with a capacitor bank was used to compress high strength steel tubes of different diameters and thicknesses. Solid model of coil and workpiece is shown in fig. as well as the front view, top view and side view is also shown in fig.2.4 [2] with all dimensions to have better idea while modeling a simplified simulation model. To reduce calculation FEA model should be as simple as possible so Axisymmetric model of the electromagnetic system used in the analysis is shown in Fig. 2.5

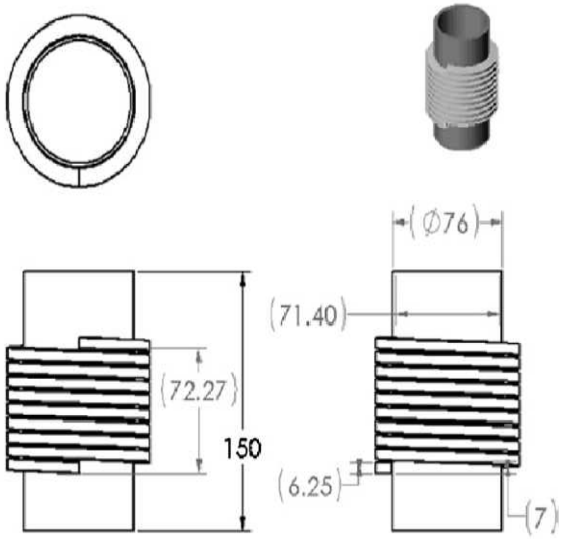


**Fig.2.4.Model of electromagnetic system**

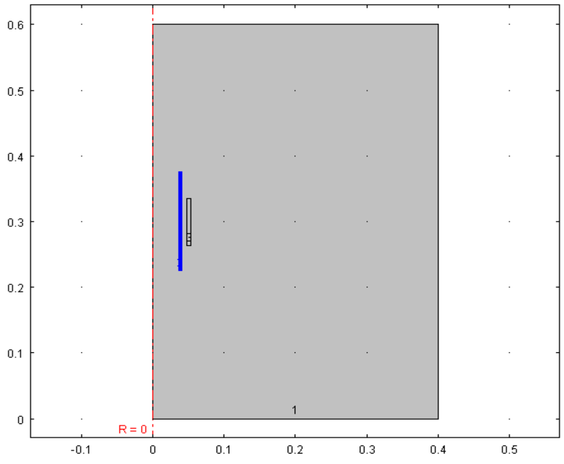


**Fig.2.5. Simplified Final Geometry**

## 3. Simulation:

These papers solve time dependant Maxwell's equations in magnetic fields and results of magnetic fields i.e. Lorenz forces used as input variables for solid mechanics. It gives strong coupling between to physics. The simplified flow chart of couple simulation is shown in fig.3.1.

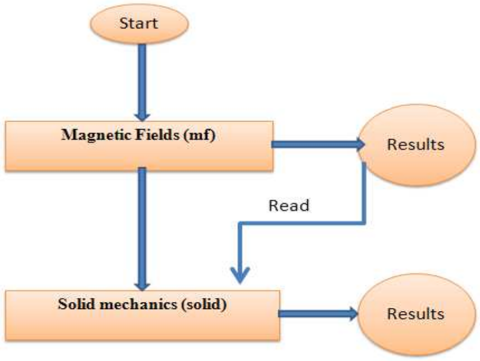


**Fig 3.1 Flow chart of Coupled Simulation**

### 3.1 Physics

**3.1.1 Magnetic field (mf):** The Magnetic Fields interface provides the equations, boundary conditions, and external currents for modeling magnetic fields, solving for the magnetic vector potential. The main feature is the **Ampere's Law** feature, which adds the equation for the magnetic vector potential and provides an interface for defining the constitutive relation and its associated properties such as the relative permeability. In Magnetic field module boundary conditions used are as follows

**(a) Ampere's law:** Ampere observed that current flowing through a wire created a magnetic field around the wire, and formulated the equation.

$$\oint \bar{B}.d\bar{s} = \mu_0 i_{enc} \tag{3.1}$$

Where, $i_{enc}$ is current enclosed, $\mu_0$ is magnetic permeability of free space,

Ampere's law is used by simply selecting any closed loop, traversing it with small elements$d\bar{s}$, and solving the resulting equation. It is key to note that any closed loop can be selected - a flat disc, or perhaps a shape more similar to a grocery bag - and it will give the same results. Ampere's law predicted the magnetic field very accurately.

**(b) Multi-turns coil domain:** The Multi-Turn Coil Domain feature is valid for 2D and 2D axially symmetric models. It adds an externally generated current density to the right-hand side of the equation that the Magnetic Fields interface defines. When specifying a total current $I_{coil}$, the out-of plane component of the current density is defined as:

$$J = \frac{NI_{coil}}{A} \tag{3.2}$$

Where N is the number of turns which you have specified and A is the total cross-section area of the coil domain.

**(c)Magnetic Insulation:** The Magnetic Insulation feature adds a boundary condition that sets the tangential components of the magnetic potential to zero at the boundary:

$$n \times A = 0 \tag{3.3}$$

In axisymmetric models, boundaries on the symmetry axis are boundaries where only a condition for the axial symmetry exists. COMSOL Multiphysics adds a default Axial Symmetry feature node that is active on all boundaries on the symmetry axis.

**3.1.2 Solid Mechanics:** The Solid Mechanics interface has the equations and features for stress analysis and general linear and nonlinear solid mechanics, solving for the displacements. The Linear Elastic Material Model is the default material model, which adds a linear elastic equation for the displacements and has a Settings window to define the elastic material properties

(a) **Linear Elastic Material Model**: Define the solid model and the linear elastic material properties.

(b) **Free:** The Free feature is the default boundary condition. It means that there are no constraints and no loads acting on the boundary.

(c) **elastoplastic material model** :The elastoplastic material model supports three types of hardening models: perfectly plastic hardening, isotropic hardening, and kinematic hardening. Hardening function is defined to get better accuracy in results whose equation we can write as

$$\boldsymbol{\sigma_{yhard}} = \boldsymbol{\sigma_{exp}}\left(\boldsymbol{\varepsilon_{pe}} + \frac{\boldsymbol{\sigma_e}}{\boldsymbol{E}}\right) - \boldsymbol{\sigma_{ys}} \tag{3.4}$$

where $\sigma_e$ is the effective stress and $E$ is the Young's modulus for the material, $\sigma_{exp}$ the experimental stress function, $\sigma_{ys}$ is the yield stress for the material

**(d) Body load: Select a Load type**

For 3D models, Load defined as force per unit volume (the default) (SI unit: $N/m^3$). (2D models) Load defined as force per unit area (SI unit: $N/m^2$). The body load as force per unit volume is then the value of $F$ divided by the thickness. The Load list normally only contains User defined.Here expression of **Lorenz forces (mf.FLtzr)** is used as load.

## 4. Results:

The results from available literature and simulation which is carried out using COMSOL multiphysics for compression of 76.2mm diameter tubes are shown in Table 4.1. The current rise time was determined as the time required for the primary current to reach the maximum value. The deformation is calculated is in radial direction. As there is deformation in axial direction also but we are neglecting the axial deformation.

| Energy (kJ) | Rise time (µS) | Final deformation Expt. (mm) | Final deformation simulation (mm) |
|---|---|---|---|
| 8 | 28 | 0.7 | 1.5 |
| 12.8 | 28 | 2.25 | 2.24 |
| 15.8 | 28 | 3.05 | 2.98 |
| 21 | 28 | 4.5 | 4.29 |
| 24 | 28 | 6 | 5.1 |

**Table 4.1 Final Deformation of Workpiece in Experiment and Simulation**

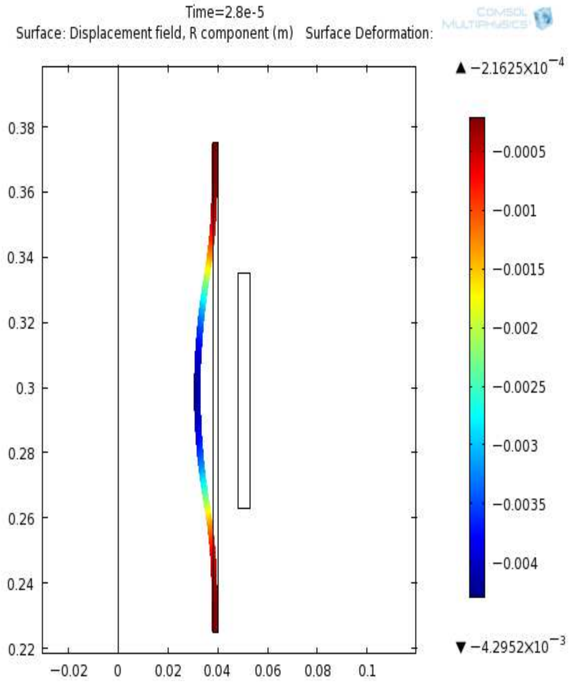
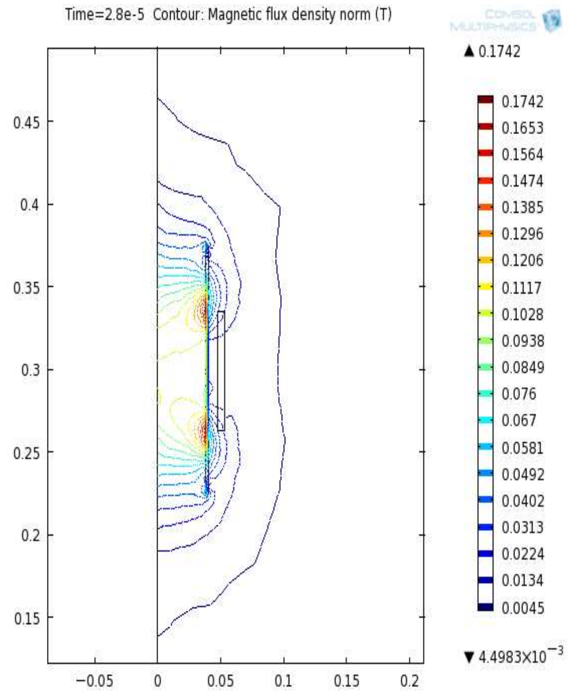


**Fig.4.1 surface deformation for 21kJ**

Simulation is carried out for 8kJ, 12.8kJ, 15.8kJ, 21kJ, 24kJ capacitor bank. Main aim of simulation is to calibrate deformation in radial direction. So for each energy level the by Appling boundary condition simulation is carried out and in results, deformation is plotted. The radial deformation which is in meter is shown in fig.4.1 for each energy level of capacitor bank.

Deformation in workpiece is different at different points along the length. So for better understanding color code is used for showing deformation in workpiece. The rainbow colors are used. Red is used for minimum deformation. While blue is used for maximum deformation for 21 kJ as shown in fig.4.1.



**4.2 Contour: magnetic flux density for 21 kJ**

## 5.Conclusion

Simulations were carried out on the electromagnetic compression of high strength (440MPatensile strength) 76.2mmdiameter, 2.3mm wall thickness tubes. Significant final deformations over a length of about 75mm were obtained with a fixed 9-turn helical compression coil. A graph of deformation in r-direction against energy level is plotted for experiment and simulation from experimental and simulation results respectively as shown in fig. blue line in graph is represent experiment data while the red line represent the simulation data.

There is large variation between experiment and simulation results at 8 KJ and 24 KJ as compare to other energy levels results. For energy between 12 KJ to 21 KJ results have better accuracy. From graph, it is clear that simulation values are closer to the experimental results. Comparisons between simulations and experimental data gave confidence that a simple numerical model can reliably predict system performance.

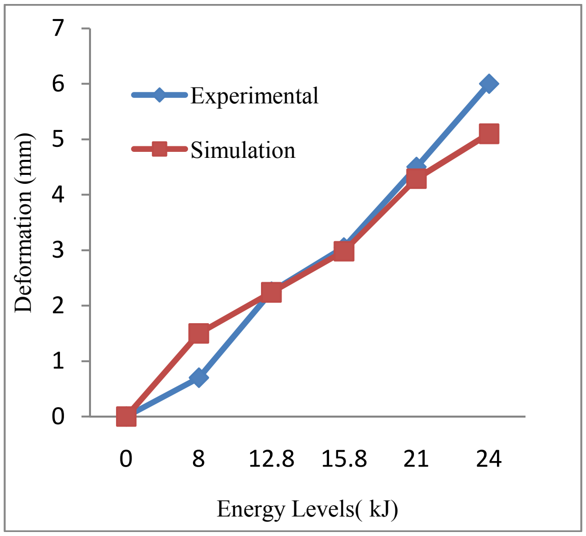


**Fig 5.1 graph of deformation (mm) against energy levels (kJ)**

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