Chapter 32

Electromagnetic Expansion

—Hitesh Choudhary

Electromagnetic forming is the high velocity forming process, uses the Lorentz's force, which is generated by discharge of capacitive stored energy in a solenoid coil. The electromagnetic forming process consists: a capacitor bank to, an electromagnetic coil, and a conductive work-piece. The stored charging energy of a capacitor $E(t) = (1/2)CV(t)^2$ (C is the capacitance and V is the voltage of capacitor), is discharged by closing high voltage high current switches. The current flows in the coil, determined circuit parameters (R, L and C). Depending upon the geometry resulting deformation of work piece can be generally classified into 3 types, tube compression, tube expansion and sheet metal forming. In electromagnetic expansion coil is placed inside of the tube.

32.1. Current and Magnetic Field Calculation

Electromagnetic forming/joining process arrangement and electrical equivalent circuit is shown in Figure 32.1.

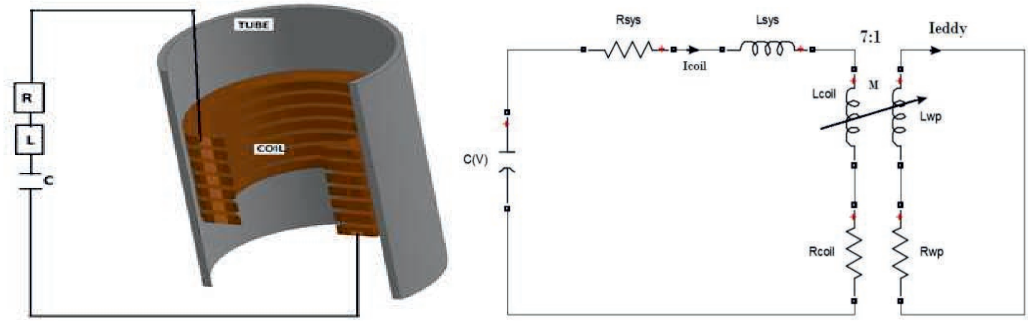

Figure 32.1. Electromagnetic expansion process arrangement and equivalent circuit.

The current in the coil is under damped sinusoidal as the circuit is having resistance, inductance and capacitance connected in series, mathematical equation for current is:

$$i(t) = \frac{V}{W_d L} e^{-\epsilon W_n t} \sin(W_d t) \tag{32.1}$$

Here,

V is voltage in capacitor, L is equivalent inductance, R is equivalent resistance.

C is equivalent capacitance of bank, W_d is damped frequency of oscillations.

W_n is natural frequency of oscillations, ϵ is damping coefficient.

When current given by Eq. (32.1) passes through solenoid coil magneto motive force (MMF), magnetic field intensity (H) and magnetic field (B) can be expressed by following equations:

$$MMF = Ni(t) = \frac{NV}{W_d L} e^{-\epsilon W_n t} \sin(W_d t) \text{ ampere turns} \tag{32.2}$$

$$H = \frac{Ni(t)}{l} = \frac{NV}{l W_d L} e^{-\epsilon W_n t} \sin(W_d t) \text{ ampere turns per meter} \tag{32.3}$$

$$B = \mu_0 H = \frac{\mu_0 Ni(t)}{l} = \frac{\mu_0 NV}{l W_d L} e^{-\epsilon W_n t} \sin(W_d t) \text{ ampere turns per meter} \tag{32.4}$$

L is coil's mean length, P is Magnetic Pressure, N is no of turns of the coil. The magnetic pressure is derived by the simplified equation

$$p(t) = \frac{1}{2} \mu H_{gap}^2 \tag{32.5}$$

By using Eqs. (32.3) and (32.5) the simplified pressure equation is

$$p(t) = 4.97 \frac{N^2 V^2}{f^2 L^2} (Mpa)\, e^{-2\epsilon W_n t} (1 - \cos(2 W_d t)) \tag{32.6}$$

Typical current and pressure with respect to time is plotted and shown is Figure 32.2.

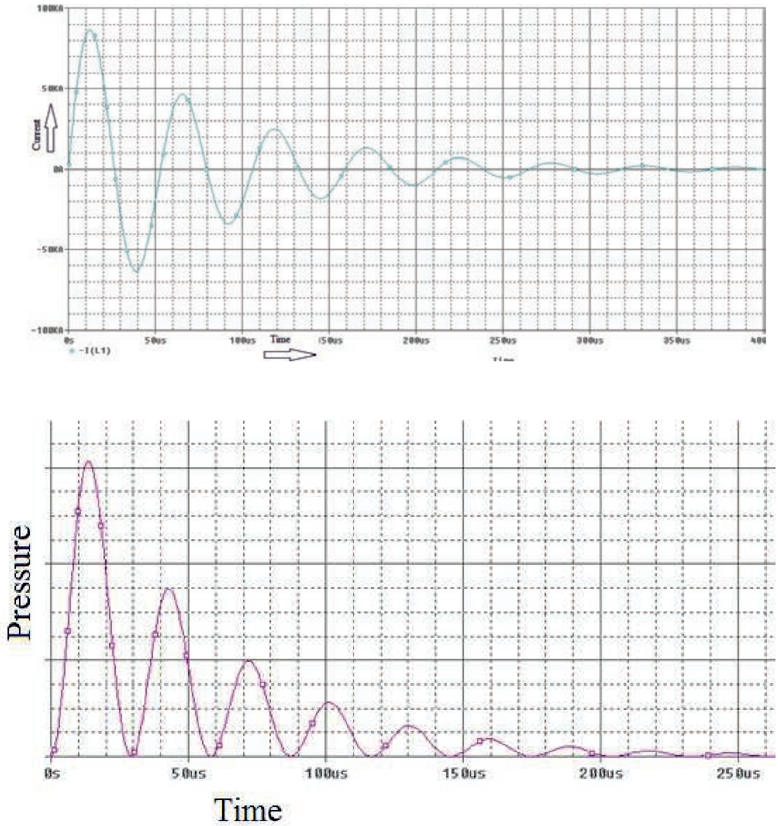

Figure 32.2. Typical damped sinusoidal current waveform and Pressure plot with respect to time.

32.2. Coil design and simulation

The coil design is dependent on the work-piece dimensions. The length and inner diameter of work-piece is required to start the designing of coil. Conductor material, number of turns, insulating material, and coil pitch, conductor dimensions and its reinforcement is very critical to make non destructive coil. FEM simulation plays very critical role in selection of above mentioned points in coil design.

The field/current ratio $^{B}/_{I}$ (at coil center) for a coil with N turns is given by

$$B_0 = \mu_0 \frac{NI}{2\beta r_1} \Gamma(\alpha,\beta), \;\; \Gamma(\alpha,\beta) = \frac{\beta}{\alpha-1} \ln \frac{\alpha+\sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}} \tag{32.7}$$

$$\beta = \frac{l}{2r_1}, \alpha = \frac{r_2}{r_1}$$

The inductance of coil with uniform winding density is given by

$$L = \frac{\mu_0 \pi}{8} r_1 \frac{(\alpha+1)^2}{\beta} N^2 g(\alpha,\beta) \tag{32.8}$$

$g(\alpha,\beta) < 1,$ is a geometry dependent factor.

Resistance of coil is given by

$$R = \frac{\rho}{f}\frac{N^2}{r_1}\frac{\pi}{2}\frac{(\alpha+1)}{\beta(\alpha-1)} \quad (32.9)$$

f = filling factor

Multi-physics simulation of coil is done which provides magnetic field with and without tube, pressure (radial and axial) exerted on the coil and tube deformation.

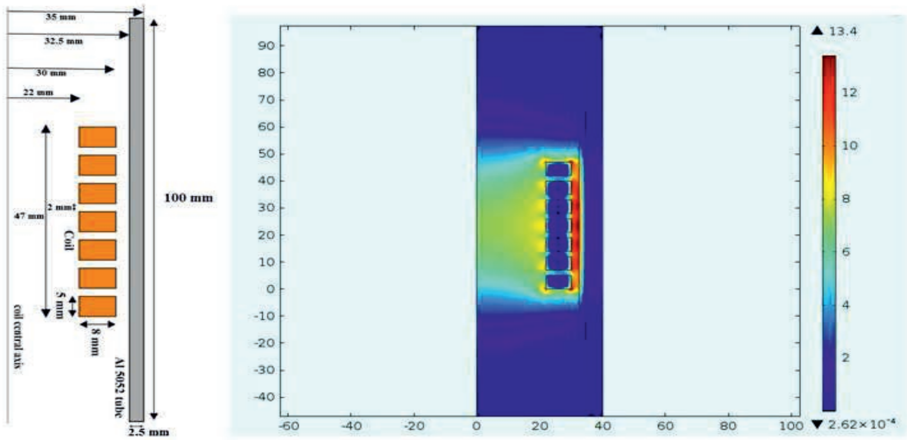

Figure 32.3. 2D axis-symmetric simulation of coil along with tube at 100 kA peak.

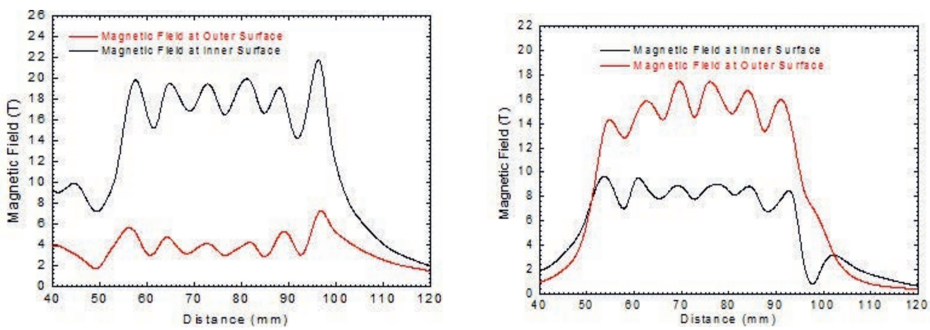

Figure 32.4. Magnetic field distributions at ID and OD of coil at peak current of 150 kA.

Forces on coil are due to presence of current in conductor and magnetic field. Forces on coil in axial and radial direction is evaluated using force density (volumetric force) as shown in Figure 32.5. Acting forces are plotted at peak current. The design of coil i.e. its insulation selection, conductor cross section, interturn gap, axial constraints (using ss nut and bolt) are based on the insulation strength to bear such an enormous force. The expansion of the tube is simulated and is shown in Figure 32.6.

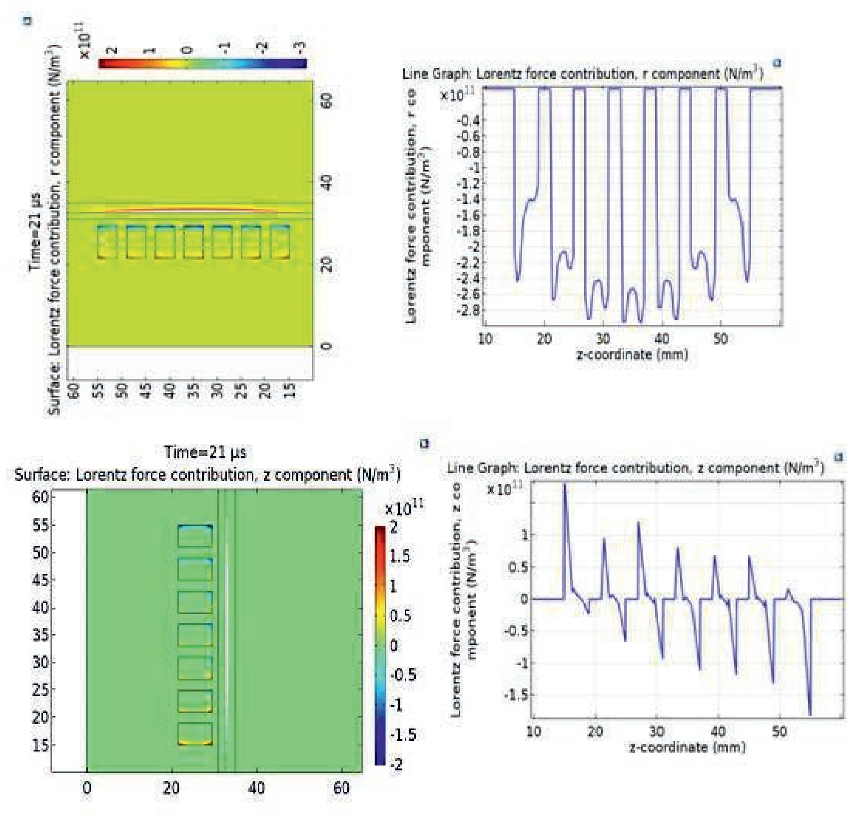

Figure 32.5. Radial and Axial force acting on coil surface near to tube.

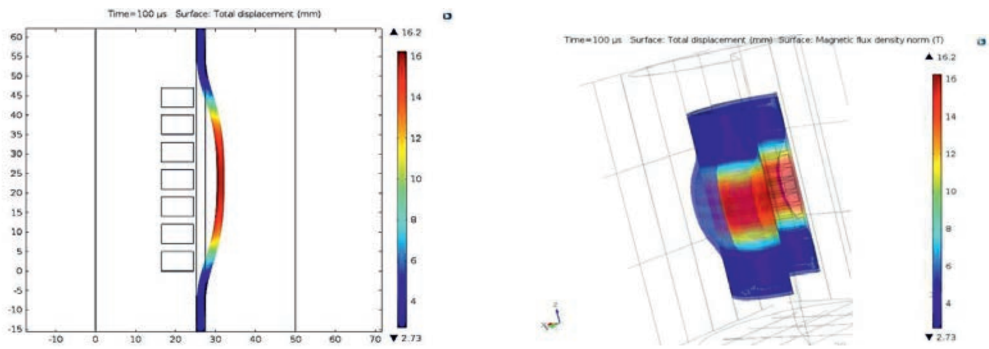

Figure: 32.6. Simulation of EM expansion of tube.

32.3. Electromagnetic Expansion of AA5052 (Aluminum alloy) Tubes

The current in the coil produces time varying magnetic field in air gap region of tube and coil. The eddy current in the tube induced due to time varying magnetic field which causes Lorentz force at the tube ID, hence tube expannded radially outward.

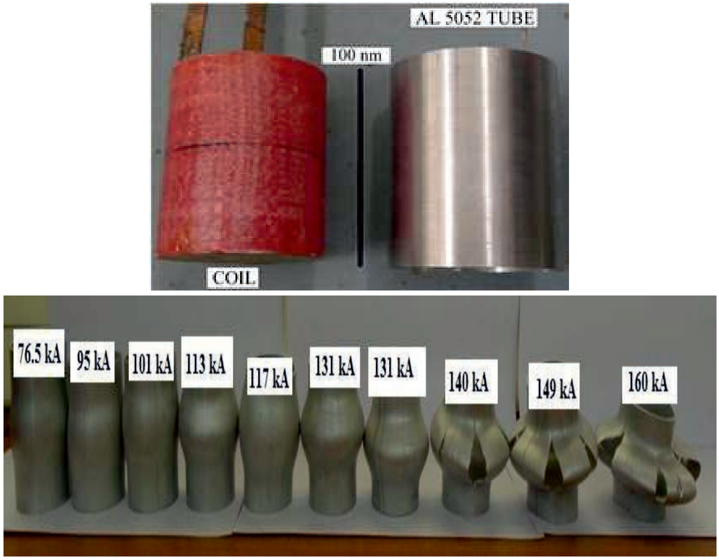

Figure 32.7 (a) Coil and tube (b) expanded tubes at different currents..

Designed coil for AA5052 tube expansion experiment are shown in Figure 32.7. (a) and expanded tubes at different coil current are shown in Figure 32.7. (b).

32.4. Joining of Tube to Tube-Sheet Using Electromagnetic Pulse

Joining of Aluminium alloys and steel is very difficult due to different metallurgical and physical properties. Thermal conductivity of AA-5052 138 W/m.K and of SS is 14 W/m.K. Melting temperature of Aluminum is 660 °C and of SS is 1370 °C. To join AA-5052 tube to SS-304 tube sheet for nuclear applications electromagnetic welding is tried. The coil current, standoff distance and tubesheet angle is decided using multiphysics simulation. Figure 32.8 shows fixture arrangement and welded joint.

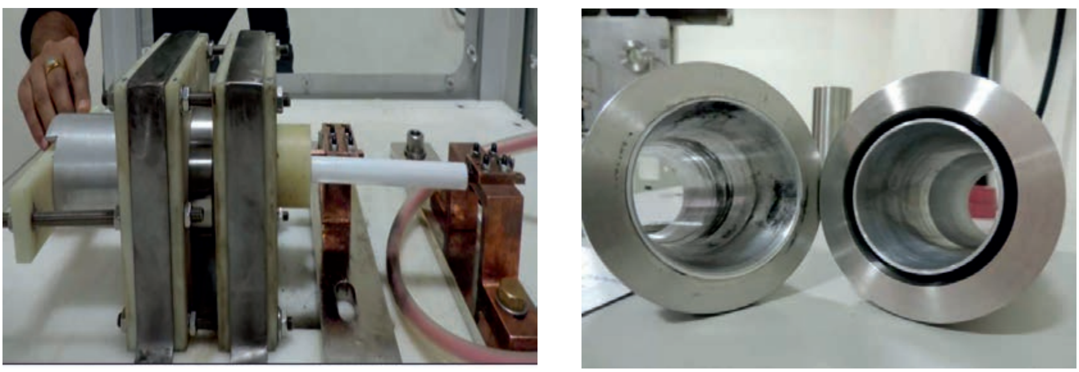

Figure 32.8. Fixture arrangement and welded joint.

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