Chapter 24

Basics of Electro-Magnetic Welding (EMW)

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The use of lightweight multi-material components has gained high potential in various automobile and nuclear reactor applications [1]. It is reported that joining of many dissimilar advanced high-strength metals for customized engineered properties are uniquely possible through electromagnetic welding (EMW) process [2]. The process eliminates the use of any consumable electrodes, gas fumes and occurrence of heat affected zones as often seen in various conventional welding methods [3]. In fact, EMW is an environmental-friendly joining technology which doesn't require any post cleaning or finishing operation [4]. Under the action of high power magnetic pulse generated from an electromagnetic coil, the flyer tube collides with the inner plug at an extremely high speed, leading to attain a strong interfacial bond at interface. EM welding is achieved without any contact between coil and job piece. Here tool and job-piece are inductively coupled with each other. EM welding has got merits over conventional welding processes such as arc welding, gas welding and resistance welding, when used for some special applications. This sophisticated technique has many advantages such as precision, reproducibility, high production rate, no tool marks, minimization of manual error, automation ease, etc. The preparatory procedures such as preheating, lubrication, etc. are not needed in this welding. Since EM bond is achieved by impact of flyer over plug, this method is ideally suited for welding of dissimilar metals having wide difference in their melting points. Conventional welding processes are not suitable in welding dissimilar metals with wide difference in their melting points. In electromagnetic welding work piece collision velocity is one of the key parameter. Researchers have conducted many experiments to investigate the effect of increasing impact velocities on weld strength. It is claimed that a minimum velocity of 350 m/s is essential to achieve bonding in soft metals [5]. The technology is well suited to join multi-materials of flat or circular shaped components, forming a wavy morphological pattern at the weld interface possibly due to interface melting. Interface characterization is performed to identify the possible welding mechanisms at the weld zone.

Recently EM welding technology has become very popular in welding of rector components.

John McGinley of European commission [6], Dr. Guoping Cao of University of Wisconsin Madison [7] and Jung-Gu Lee et. al of Korean Atomic Energy Research Institute (KAERI) have demonstrated EM welding of reactor components [8]. BARC has demonstrated electro-magnetic welding of flared D9 tube to cylindrical SS316 L (N) plug [9]. On industrial front electro-magnetic welding technology has been utilized for the Lamborghini Hurricane car hood [10].

24.1. Electromagnetic welding setup

Electromagnetic welding setup comprises three parts, control cabinet, pulse generator and work station. In control cabinet high voltage (HV) charging power supply and associated control components are included. Pulse generator consists of number of energy storage capacitors, trigger generator and high current switch. Work station consists of electromagnetic coil (EM coil) and job-piece. Schematic of electromagnetic set up is shown in Figure 24.1 [11].

Electromagnetic welding equipment falls in medium capacitance (**Capacitance >10 µF but <500 µF**) and medium voltage (**Voltage >10 kV but <50 kV**) category. These machines cater to the widest industrial applications. Electromagnetic forming/welding, magnetizers/demagnetizers, lightning current generators and electro-magnetic guns/launchers etc., are some important applications in this category. The designs tend to become more challenging as one goes high in voltage and low in capacitance. This has direct bearing on shorter rise time requirements one has to meet besides catering to larger load currents. Typically, loads are inductive in the range of 0.01-100 µH leading to current periods of 10 to 100s of microseconds with current magnitudes up to 100s of kilo-amperes. Only few switching devices like triggered spark-gap switches, meet these requirements [12].

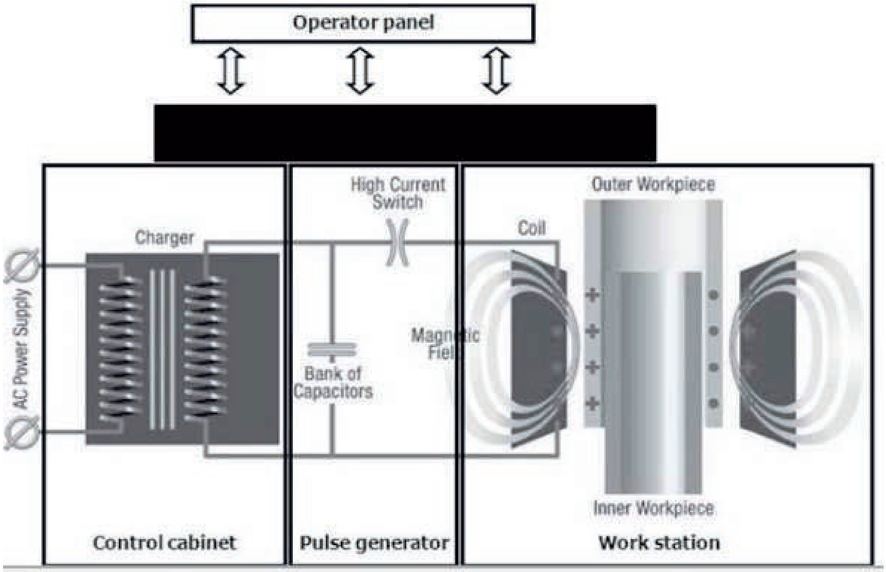


Figure 24.1. Schematic of Electromagnetic welding setup.

24.2. Principle of operation of EMW

Maxwell Equations:-

Coil current density ($\boldsymbol{J}$) generates magnetic field intensity ($\boldsymbol{H}$) and magnetic field density ($\boldsymbol{B}$) around coil. Rate of change of flux (ϕ) inside coil induces voltage (V) in conducting job piece which produces eddy current density ($\boldsymbol{J_w}$) in closed conductor.

$$\nabla \times H = J \text{ (coil current density)} \quad (24.1)$$

$$B = \mu H \quad (24.2)$$

$$\phi = B.A \quad (24.3)$$

$$V = -\partial\phi / \partial t \quad (24.4)$$

$$E = -\partial V / \partial r \quad (24.5)$$

$$J_w = \sigma E \text{ (Eddy current density)} \quad (24.6)$$

Direction of eddy current is opposite in phase to coil current as EM systems are dominantly inductive in nature. Volumetric Lorentz force ($\boldsymbol{F_v}$) is generated due to the interaction of Eddy current density ($\boldsymbol{J_w}$) in work piece and magnetic field produced by coil ($\boldsymbol{B}$) in the vicinity of job-piece.

$$F_v \text{ (Lorentz Force)} = J_w \times B \quad (24.7)$$

$$P_m = (\tfrac{1}{2}\mu_0)\, B_i^2 - (\tfrac{1}{2}\mu_0)\, B_o^2 \quad (24.8)$$

Unidirectional pressure is exerted on Job-Piece due to magnetic field gradient across its wall thickness. B_i is magnetic filled at outer surface of job-piece and B_o is diffused magnetic field at inner surface of job-piece. If pressure exerted (P_m) is sufficiently higher than hoop stress of job-piece (cylindrical), then job-piece will be pushed into plastic region [13].

In electromagnetic simulation magnetic vector potential is used to specify electric field.

Magnetic vector potential $\vec{A}$ is used as a system variable such that,

$$\nabla \times \vec{A} = \vec{B} \tag{24.9}$$

$$\nabla . \vec{A} = 0 \tag{24.10}$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} \tag{24.11}$$

where $\vec{B}$ represents magnetic flux density (T), t represents time (s) and $\vec{E}$ is the electric intensity.

Equation (24.12) is obtained for the tube area by substituting electromagnetic field's constitutive equations (24.9-24.11) into Maxwell's equation.

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = -\gamma \frac{\partial \vec{A}}{\partial t} \tag{24.12}$$

where μ , γ and $\left(\gamma \frac{\partial \vec{A}}{\partial t} \right)$ denotes the magnetic permeability (H/m) and conductivity (S/m) of the medium and the current density (A/m^2) respectively. The magnetic force density, i.e., the magnetic force in unit volume of medium $\vec{f}$ is given by Maxwell's equation as follows,

$$\vec{f} = \vec{J} \times \vec{B} = (1/\mu) \left(\nabla \times \vec{B} \right) \times \vec{B} \tag{24.13}$$

where $\vec{J}$ and $\vec{B}$ are the coil current density (A/m^2) and magnetic flux density (T) respectively. The magnetic force can be achieved by substituting $\nabla \times \vec{A} = \vec{B}$ and Eq. (24.9) into Eq. (24.10).

24.3. Equivalent electrical circuit of EMW system

The overall electrical circuit for the electromagnetic welding system (Figure 24.2) is series R-L-C circuit. In EM welding an energy storage capacitor bank is charged by HV power supply. Capacitive stored energy is switched into inductive EM coil by triggering spark gap switches with trigger circuit. The current i(t) in tool coil, is determined by overall circuit parameters R, L and C. Time varying pulsed magnetic field is generated inside tool coil when damped sinusoidal current passes through it and induces eddy currents over job-piece. In EM welding, B field inside tool coil and conducting tube and the eddy currents on job-piece generates Lorentz force $\boldsymbol{J} \times \boldsymbol{B}$ in outward radial direction and this force expands the tube.

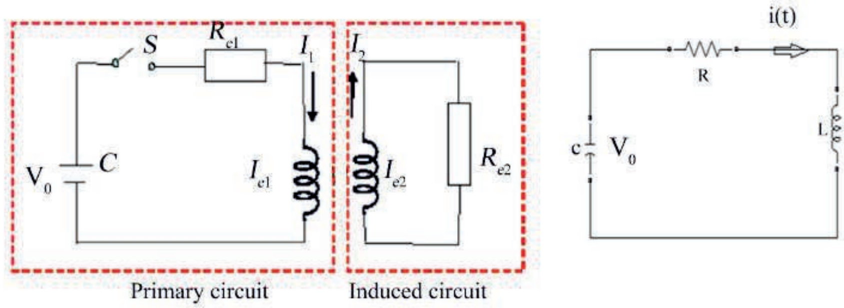


Figure 24.2. Electrical circuit of EMW set up (Left) and
Equivalent circuit in primary (Right).

The expression of current through the coil can derived using following set of equations.

KVL equation in loop results

$$V = \frac{\int idt}{C} + L\frac{di}{dt} + Ri \tag{24.14}$$

Taking Laplace of equation,

$$\frac{V}{S} = \frac{I(S)}{CS} + LSI(S) + RI(S) \tag{24.15}$$

Solving for $\boldsymbol{I(S)}$ results

Where $W_n = \frac{R}{2L}$,$W_n = \sqrt{\frac{1}{LC}}$ and $\xi = \frac{R}{2}\sqrt{\frac{C}{L}}$

Case I: When R=0 (ideal case with superconductor)

$$\boldsymbol{I(S)} = \frac{V}{L(S^2+W_n^2)}$$

$$\boldsymbol{i(t)} = \frac{V}{W_nL}\sin(W_nt)\,, I_p = \frac{V}{W_nL} \tag{24.16}$$

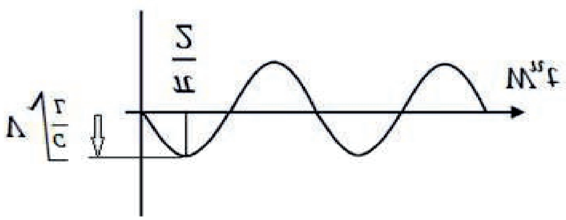


Figure 24.3. Current waveform without resistance.

Case II: When R is finite:

Current through coil in practical case is given by equation

$$\boldsymbol{i(t)} = \frac{V}{W_dL}e^{-\xi W_nt}\sin(W_dt) \tag{24.17}$$

Where $W_n = \frac{R}{2L}$,$W_n = \sqrt{\frac{1}{LC}}$ and $\xi = \frac{R}{2}\sqrt{\frac{C}{L}}$.

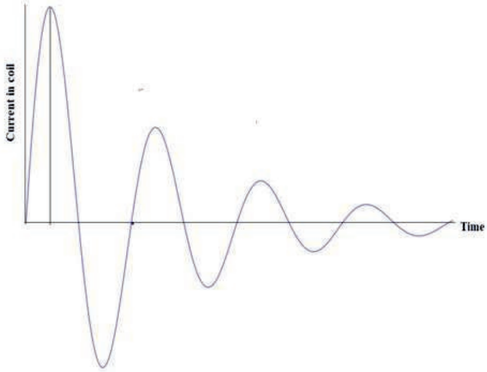


Figure 24.3. Current waveform with resistance

24.4. Method of generating magnetic pressure in EMW

Electromagnetic welding equipment is essentially an under damped R-L-C circuit, having very small overall resistance (5-15 mΩ). Figure 24.4 (a) shows directions of coil current, surrounding magnetic field and induced eddy current on conducting job-piece. It is evident by Lenz's law that eddy current are opposite in phase with respect to coil current. Magnetic pressure is generated by interaction of induced eddy current and magnetic field of coil. This pressure is unidirectional on job piece and acting in radially inward direction if job-piece is inside the coil or vice versa. Typical signature of coil current, job piece current (eddy current) and pressure pulse is shown in Figure 24.4 (b). It is the first half of pressure pulse which is actually causing plastic deformation in job-piece and imparting kinetic energy for collision. Remaining pulses of low magnitude are of no use as after first pulse job-piece material gets work hardened.

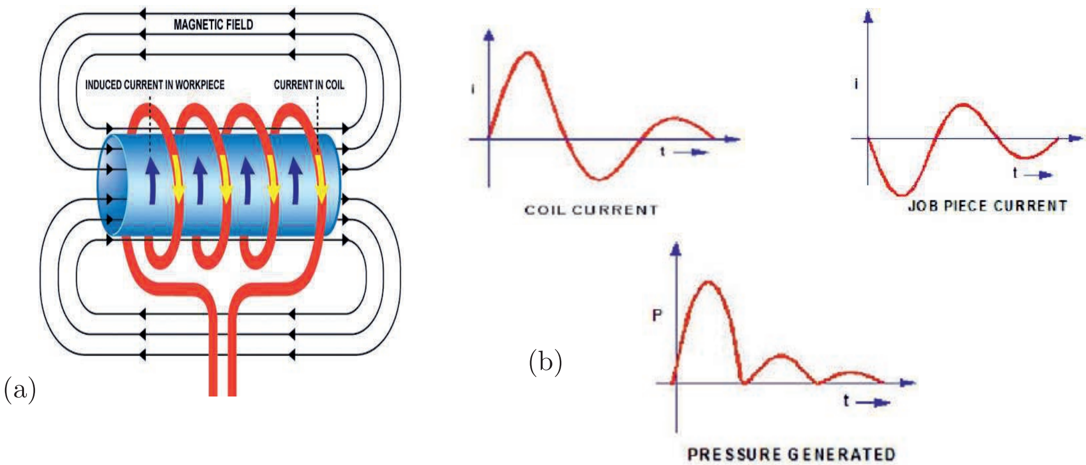
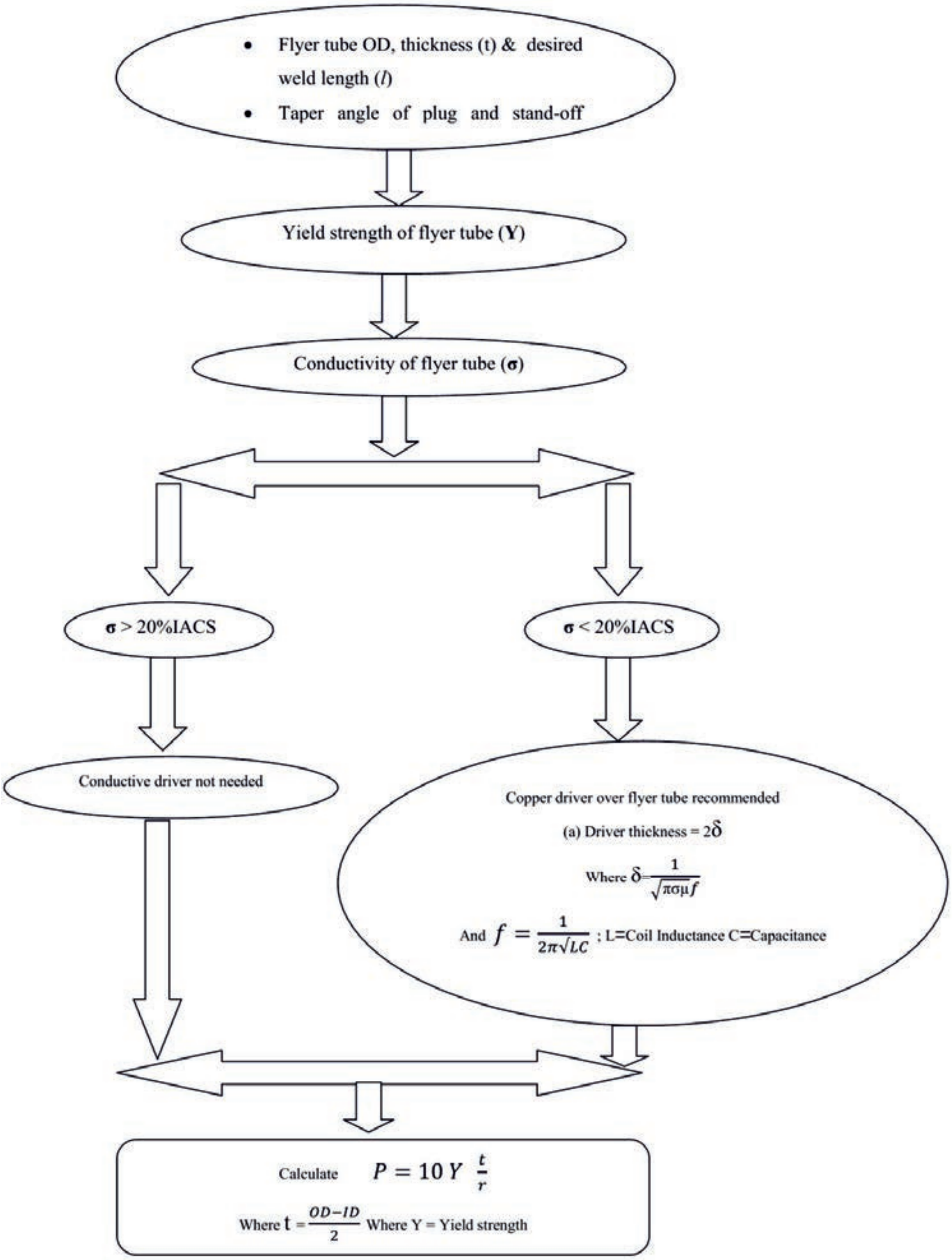
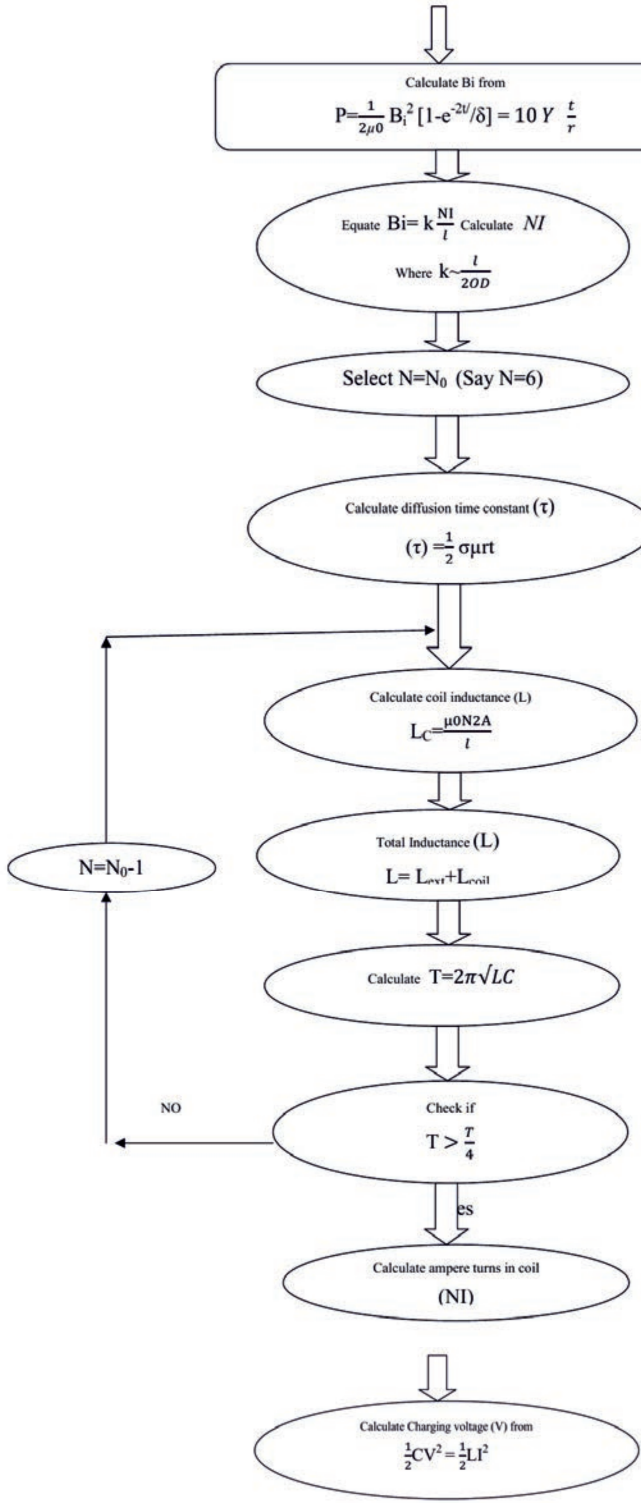


Figure 24.4. Directions of coil current, eddy current and magnetic pressure.

24.5. Flow chart for calculation of operating voltage (V) and coil turns (N)




Calculate Bi from
$P=\frac{1}{2\mu 0} B_i^2 [1-e^{-2t}/\delta] = 10\,Y\ \frac{t}{r}$
Equate $Bi= k\frac{NI}{l}$ Calculate NI
Where $k\sim\frac{l}{20D}$
Select $N=N_0$ (Say N=6)
Calculate diffusion time constant (τ)
$(\tau) =\frac{1}{2}\sigma\mu rt$
Calculate coil inductance (L)
$L_C=\frac{\mu 0N2A}{l}$
Total Inductance (L)
$L= L_{ext}+L_{coil}$
Calculate $T=2\pi\sqrt{LC}$
Check if
$T > \frac{T}{4}$
NO
$N=N_0-1$
es
Calculate ampere turns in coil
(NI)
Calculate Charging voltage (V) from
$\frac{1}{2}CV^2 = \frac{1}{2}LI^2$

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