Chapter 27

Simulation & Experimental Validation of Magnetic Field Density and Impact Velocity in Magnetic Pulse Welding Process

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Do you ever get surprised that welding can happen without heating the metal? Yes, there are few techniques of welding in which heating of metal is not required. One of those techniques is Electro-Magnetic Welding (EMW). It comes under the class of Pressure welding, in which momentary high impulse pressure is applied between two metals to get them welded. EMW, being a solid-state welding technique uses Lorentz force developed in metal to accelerate them and impact the other metal to which it gets welded. This force can also be utilized for forming, cutting of metals. It has significant advantages over other welding techniques like it avoids formation of inter-metallic, heat affected zones (HAZ), avoiding alteration of main material properties. In the present article, we will study about two important aspects. The magnetic field estimation techniques using simulation and experimental validation using Faraday rotation method and simulation of velocity and its experimental validation using fiber optic cut method. The Electro-magnetic Welding (EMW) technology is a solid-state welding process in which one metal is accelerated towards the other metal using Lorenz force. When the time-varying magnetic field interacts with induced currents in the cylinder, the Lorentz force is developed. The analytical equations, numerical simulations and experimental validation for Expansion MPW technique is discussed in this article.

Expansion MPW configuration is chosen in the present study. When an Al-5052 tube, with 66 mm ID, 2 mm thickness is freely expanded, measurement of the tube velocity at different positions is attempted. The dimensions and material properties of the tube is

Table 27.1. Dimension of Al5052 Tube.

Material	Inner Diameter	Outer Diameter	Thickness
Al 5052	66 mm	70 mm	2 mm

27.1. Schematic Layout of EMW Expansion Process

The experimental set up consists of an energy storage capacitor bank, high current switch, tool coil and work piece. The layout of set up is as shown below (Figure 27.1).

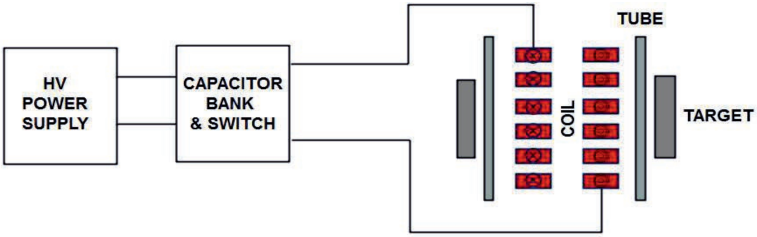

Figure 27.1. Schematic layout for expansion EMW process.

27.2. Magnetic Field-Simulation & Experimental Validation

27.2.1. Simulation

In EMW techniques, electro-magnetic coil is used to generate time varying magnetic field which further induces eddy current in the work piece (driver) with finite electrical conductivity, σ. With operating frequency in the range of 10-100 kHz, displacement current component in Maxwell equations can be neglected. Hence, this problem is a Magneto-quasi Static problem. As per Ampere's law, these currents give rise to magnetic field, B inside the coil.

Denoting Electric Field Intensity as E and Current Density as **J**, we can express point form of Ohm's law as

$$J = \sigma E \tag{27.1}$$

The induced electric field obeys

$$\nabla \times E = -\frac{dB}{dt} \tag{27.2}$$

Writing B in terms of magnetic Vector potential, A

$$\nabla \times E = -\nabla \times \frac{dA}{dt} \tag{27.3}$$

From the above equation we can write,

$$E = -\frac{dA}{dt} - \nabla V \tag{27.4}$$

Since, here $\nabla V = 0$

Hence ohm's law can be written as

$$J = -\frac{\sigma dA}{dt} \tag{27.5}$$

Which further yields,

$$\nabla \times \left(\frac{1}{B} * \nabla \times A\right) = -\frac{\sigma dA}{dt} + Jc \tag{27.6}$$

By solving the above equation, we can find the value of magnetic vector potential, A and hence magnetic field density, B can be found. This magnetic field density can be found in the region of interest, by dividing the domain into various parts and solving the above equation. This task can be performed by Finite Element Method (Figure 27.2).

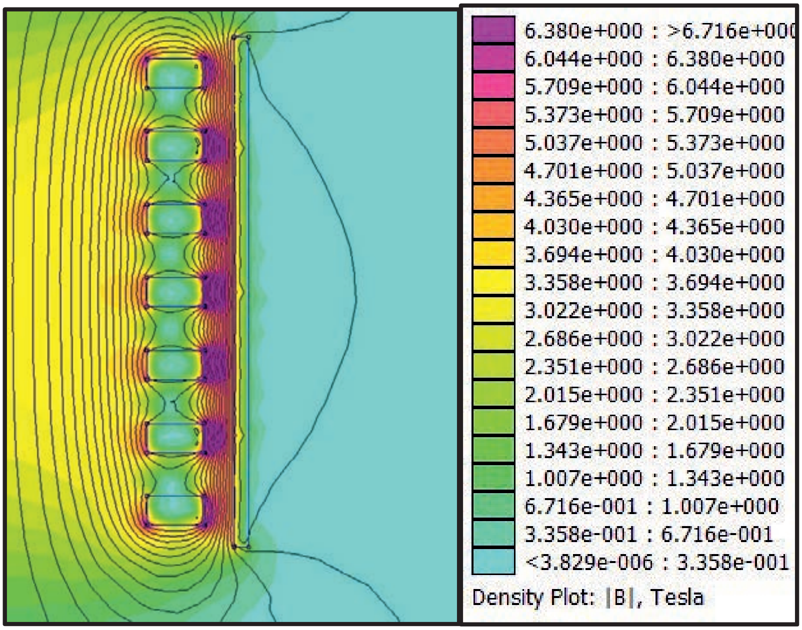

Figure 27.2. Magnetic Field Simulation in FEMM.

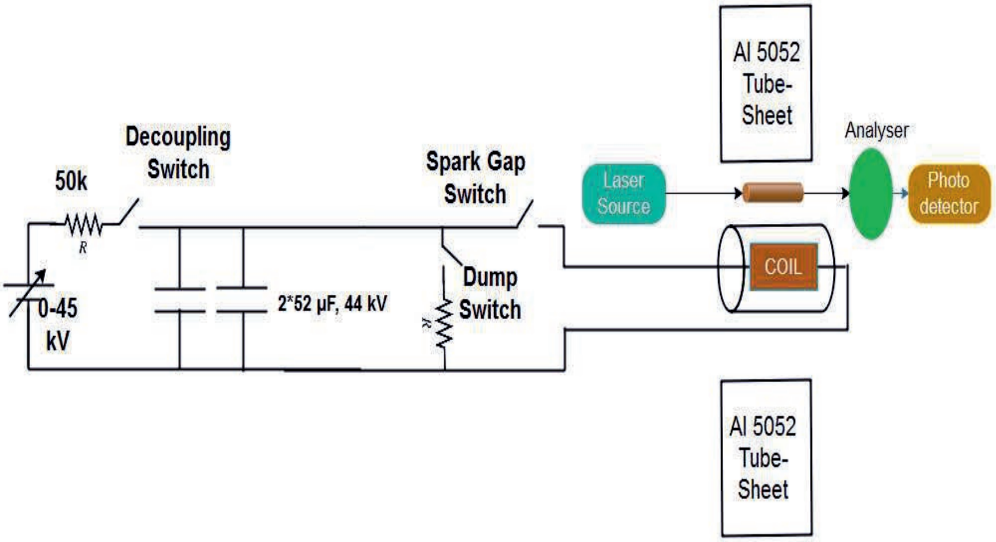

Figure 27.3. Schematic layout of the measurement setup.

Figure 27.4. Set up for field measurement in Expansion EM Forming.

27.2.2. Experimental Validation

The schematic layout of experimental setup for field measurement is in Figure 27.3. The Capacitor bank, with capacitance of 104 µF is charged to 10 kV/5.2 kJ and discharged into a copper coil. When a peak discharge current of 80 kA, 13 kHz is passed through the copper coil, the magnetic field is measured by using Faraday Rotation technique (Figure 27.4).

It has been observed that for the same operating parameters, the Peak magnetic field noticed in the experiment is found to be **4.8 T**, whereas **5.6 T** in simulation. Hence, the deviation between experimental and simulation is 15 %. This can be attributed to errors in measurement and helicity of the multi-turn coil.

27.3. Tube Impact Velocity-Simulation & Experimental Validation

As per Faraday's second law, a time varying applied magnetic field will develop induced currents, **Je** in the cylinder, which in turn try to buck out the original magnetic field. Assuming a time varying magnetic field in z-direction, the field is spatially constant in z-direction. Now, since the fields are z directed, the currents induced in cylinder are in theta direction. Here the sheet is thin, so let us assume that the current density is uniform over the cross section. Also, it is a closed cylinder, so current density is Divergence free. In steady state condition, the magnetic field density penetrated into the thin cylinder can be estimated using

$$Hi = Ho\left(e^{-\left(\frac{t}{\delta}\right)}\right) \tag{27.7}$$

For a particular material combination, to achieve a good weld, the flyer tube needs radial acceleration inwards/outwards (in case of compression/expansion welding respectively) to gain the required impact velocity (Vimp) before collision with the other metal. The magnetic pressure to be applied for attaining the required velocity can be deduced from the following equations.

The Lorentz Force per unit volume acting upon the cylinder is given by

$$F = J \times B \tag{27.8}$$

The magnetic pressure, Pmag acting upon the tube can be deduced by integrating the force on the tube.

$$Pmag = \int_0^t F.dt = \frac{\mu}{2} * Ho^2\left(1 - \exp\left(-\frac{2t}{\delta}\right)\right) \tag{27.9}$$

Here

t is tube thickness

ρ is density of tube material

Vc is the tube impact velocity

s is the initial stand-off

σy is yield strength of material

r is the tube initial radius

δ is skin depth

The magnetic pressure in Eq. (27.3) can be generated by discharge of stored energy in capacitor bank into the electro-magnetic tool coil. This pressure can be used to apply the radially inward force on the job circumference. To maximize, the acceleration of the tube, the magnetic field is to be screened from entering into the tube. This can be possible when the thickness of the tube to be at least one skin depth. Skin depth can be deduced from the following expression shown in Eq. (27.4).

$$Skin\ depth\ \ \delta = sqrt\left(\frac{1}{\pi f \mu \sigma}\right) \tag{27.10}$$

The tube velocity and displacement can be obtained by integrating the pressure with time. The velocity at a time instant Tp can be found by

$$v(Tp) = \int_0^{Tp} \frac{P.A}{m} dt \tag{27.11}$$

The Magnetic pressure equation shown in Eq. (27.9) is time varying in the actual case when the discharge current is sinusoidal. Hence, the pressure pulse and the acceleration will be in sinusoidal. So, to properly estimate the impact velocity, a numerical code in MATLAB has been developed, which takes the time varying magnetic pressure into consideration for the calculation of Impact Velocity. Also, the other parameters like strain hardening, strain rate are taken into consideration while simulation by incorporating Johnson Cook's model into the developed MATLAB code. Using this simulation, the end plug or target can be easily designed to achieve sufficient impact velocity for successful welding.

When the Capacitor bank, with capacitance of 104 µF is charged to 20 kV/20 kJ and discharged into a copper coil to discharge a peak current of 150 kA, 13 kHz. The impact velocity is simulated as mentioned in the previous sections. At the point of measurement experimentally using Fiber Optic technique, the simulated velocity is found to 340 m/s, at a radial distance of 3 mm.

Experimentally, the velocity of freely formed tube has been measured using fiber optic cutting method. Four fibers have been arranged at different radial gaps of 0.8 mm as shown in Figure 27.7 Lasers have been passed through these four optical fibers. When the expansion of tube takes place, the expanding tube disturbs the optical fiber and interrupts the laser reaching the detector. This instant of disturbance has been captured using a digital oscilloscope and photo detector. From the Figure 27.7, the time of flight between two fiber cables kept at a radial distance of 3 mm is 320 m/s. The deviation from experimental and simulation is found to be 5.8 %. This deviation may be due to experimental errors.

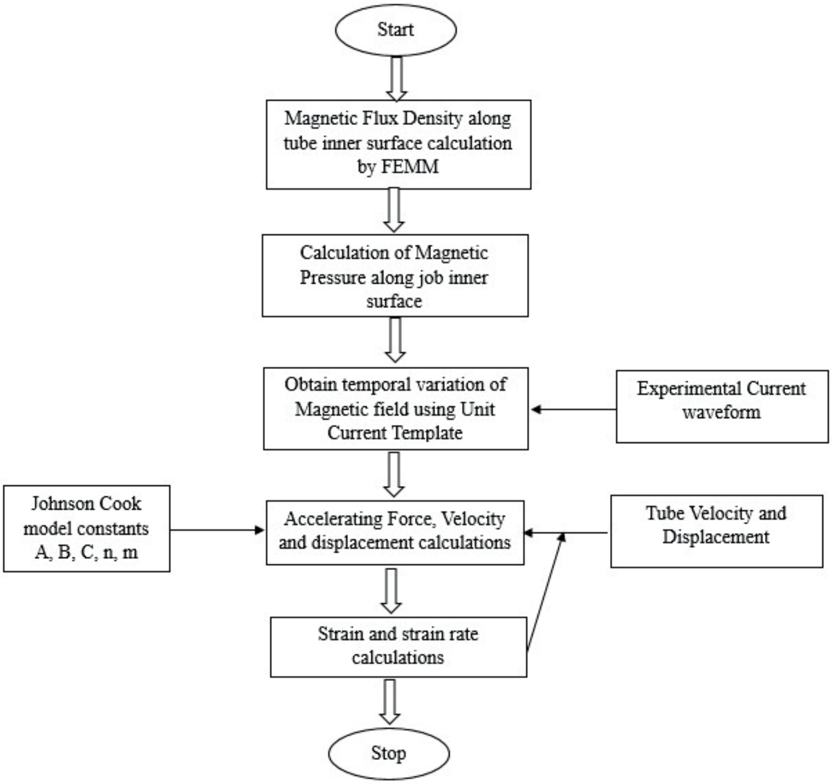

Figure 27.5. Flow chart to estimate Impact Velocity in EMW technique.

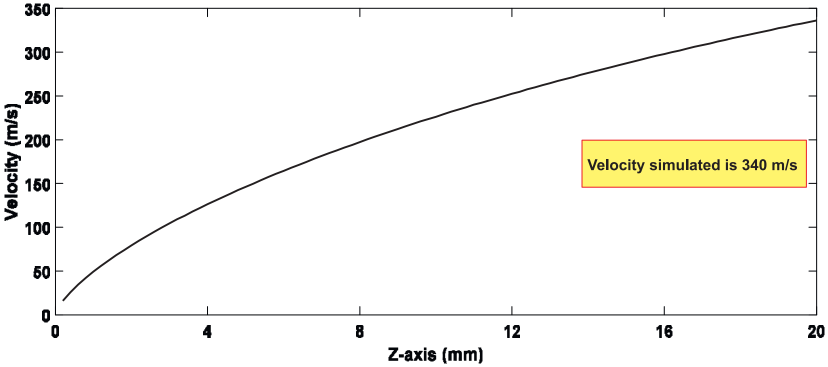

Figure 27.6. Simulated velocity plot of freely forming tube.

27.4. Conclusion

The basic analytical equations for estimation of magnetic fields and velocity of tube are discussed. The simulation of Magnetic field by using Finite Element Method and simulation of impact velocity by numerical code in MATLAB has been discussed with their results. The experimental validation of magnetic field by Faraday Rotation technique and tube velocity using optical fiber cutting method is also discussed.

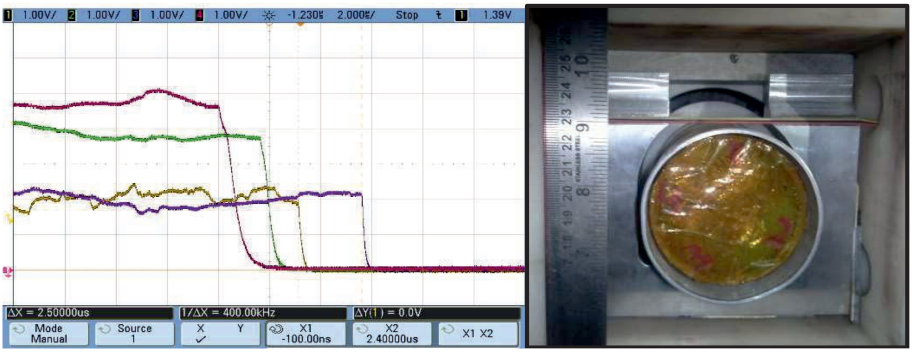

Figure 27.7. Experimental set up for velocity measurement of free forming tube.

References

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Questions

1. What is Skin Depth? Explain with the help of equation.

2. What are the applications of EMW technique?

3. What are the advantages and disadvantages of EMW technique?

4. Derive the expression for diffused field inside a cylindrical conductor with uniform conductivity throughout. And explain the significance of diffusion time.

5. Calculate the diffusion time constant of a 0.5 mm thin copper cylinder and 60 mm average diameter. Does it depend on frequency of excitation?

6. What is relation between magnetic vector potential and magnetic field density?

7. Why the displacement current term in Ampere’s law is neglected while calculating magnetic field in EMW technique?