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Experimental and numerical simulation study of electromagnetic tube forming

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Electromagnetic forming is a high velocity forming process where Lorentz force is used for workpiece expansion. The required velocity for forming is achieved by a pulsed magnetic field. In the present work, Electromagnetic expansions of aluminum tubes are carried out using 20 kJ systems at different energies. A 2D coupled numerical simulation is also performed that shows the tube velocity and deformation under transient magnetic pressure. From the observed results, magnetic to mechanical pressure relation is studied that helps in controlled forming operation.

***Key Words** : Electromagnetic forming, Magnetic pressure, Plastic deformation, Coupled simulation*

1.0 INTRODUCTION

Electro Magnetic Forming (EMF) is emerging as a promising technology in aerospace and automobile industries because of its advantages of forming light weight materials. In Electro Magnetic Forming process (EMF), magnetic pressure is generated by an electromagnetic coil after passing a current pulse of large peak magnitude through it. Magnetic field generated by coil generates eddy current in workpiece which is placed surrounding the coil. Interaction of magnetic field and current density of generates Lorentz force that expands the workpiece. A comprehensive review of EMF process is presented by [1]. EMF is very fast and complex electromagnetic-structural coupled process which is difficult for mathematical analysis. A numerical simulation technique helps to analyze the transient EMF process. Very few coupled simulations modeling have been observed in the literature for EMF analysis. Advantages of sequential coupling method over loose coupling method are shown in [2] for electromagnetic tube compression. Linking of electromagnetic numerical code to structural code using numerical solution is done [3] where author highlights the need of coupled simulation and supports [4] the ignorance of strain effect in aluminum alloy tube deformation analysis. Workpiece inertia do play role in EMF and same is explained in [5]. Comparison of in house code results with experimental results from literature results has been done [6]. FEM simulation of sheet forming analysis has been performed [7-9] and compared with literature experimental results. Models like Johnson–Cook and rate dependent power law [7] are used to define material behavior considering strain and strain rate effect. A coupled simulation is performed [9] using COMSOL considering effects of the work piece displacement and velocity on the coil current and magnetic forces.

In the present work, expansion study of aluminum 1050 alloy tube is carried out by numerical and experimental methods. A 2D axis symmetric, magnetic-structural coupled simulation is carried out using COMSOL FEM software. With 20kJ experimental system, expansion of aluminum tubes is carried out at different input energies. Relation of magnetic pressure with yield stress

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for deformation is determined from experimental results for a given system.

2.0 EXPERIMENTAL TESTING

Electromagnetic forming system used for analysis in this paper is a 20 kJ system and consist of high voltage power supply and energy storage capacitor of capacitance 400 uF with maximum charging voltage of 10 kV. The discharge coil is solenoidal and made up of copper. Work piece used for deformation analysis is aluminum tube. The coil is fixed in epoxy with air gap of 0.7 mm is present between epoxy fiber and tube. The detail parameters of the system are given in table 1.

Electromagnetic forming uses high energy magnetic field to deform materials. This field is produced by a transient current that flows through the coil. Energy is stored in the electrostatic form in the capacitor bank by charging the capacitors from high voltage power supply. Using spark gap switching, the capacitive energy is discharged into the coil.

TABLE 1

SYSTEM PARAMETERS

	Parameter	Value
System	Resistance (R)	23.17 mΩ
	Inductance (L)	6.98 µH
	Material	Copper
Coil	Number of turns (n)	21
	Active length (l)	83 mm
	Diameter	77.2 mm
	Material	Aluminum
Workpiece	Internal diameter	1050
(Aluminum	Thickness (t)	82.8 mm
Tube)	Ultimate Tensile stress	1.4 mm
	(σ_{UTS})	80 MPa
	Yield stress σ_y	22 Mpa
	Conductivity	34.45MS/m

Trigger control is used for controlling the switching action of the spark gap. Figure 2 shows schematic of system and Figure 3 shows electrical equivalent and simplified circuit of the system.

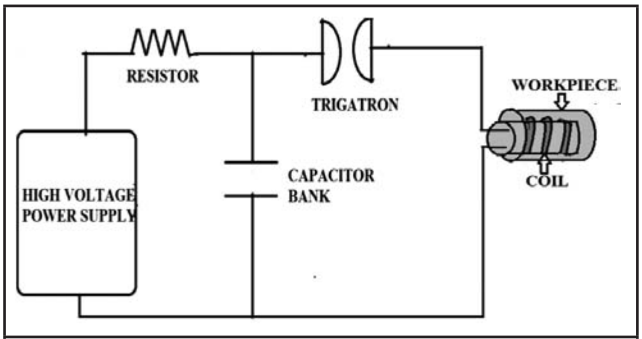

FIG 1. SCHEMATIC OF THE SYSTEM

The energy stored in capacitor C is given by

$$E = \frac{1}{2}CV^2 \quad ...(1)$$

Where E is stored energy, V is the charging voltage of the capacitor bank. The resulting current i(t) flowing through the coil is damped sinusoidal in nature and determined by the resonant circuit formed by equivalent resistance, inductance and capacitance of the system. Differential equation of simplified circuit can be written as

$$L\frac{di(t)}{dt} + Ri(t) + \frac{1}{C}i(t) = 0 \quad ...(2)$$

Assuming initial current flowing is zero and initial capacitor voltage V, the current equation is simplified to

$$i(t) = \frac{V}{WL}e^{-\beta t}\sin Wt \quad ...(3)$$

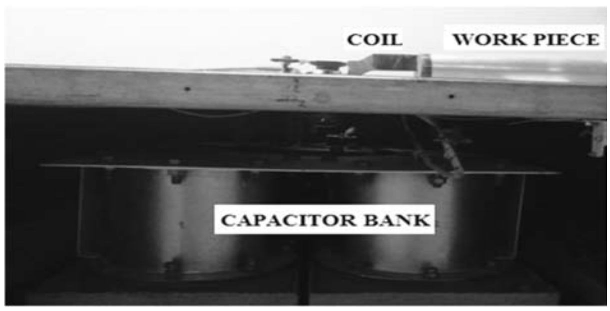

FIG. 2. EXPERIMENTAL SYSTEM

For the system under consideration, the capacitor value known prior and values of resistance and inductance are estimated by current measurement. A rogowski coil is placed around the coil and current flowing through the coil is measured by digital oscilloscope. Figure 3 shows the experimental system arrangement and current waveform obtained at 2.04 kJ shown by Figure 4.

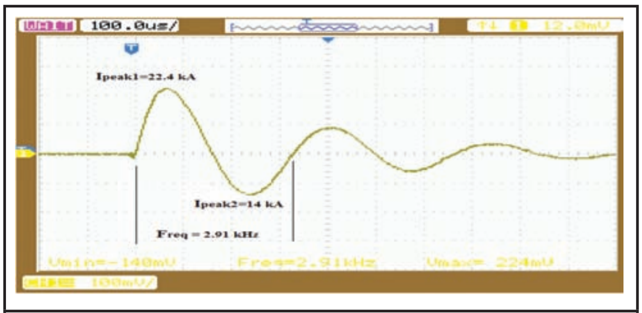

FIG. 3. CURRENT WAVEFORM AT 2.04KJ

The magnetic flux density generated by the coil is given by simple relation,

$$B = K_h \frac{\mu_0 n i}{l} \quad ...(4)$$

Where Kh is the correction factor depends on coil length and coil diameter [10]. It is 0.7 in this case. μ_0 is the magnetic permeability of free space, n is the number of turns of coil and l is coil length. Magnetic pressure generated by the coil is derived from the energy density associated with the magnetic field, taking into account B is

$$P_{mag} = \frac{B^2}{2\mu_0} \quad ...(5)$$

3.0 NUMERICAL COUPLED SIMULATION

A coupled, 2D axis symmetric FEM simulation is carried out with COMSOL. Advantage of coupled simulation is that mechanical deformation changes with respect to changes in electromagnetic pressure are carried out simultaneously. This is closer to practical phenomenon and improves the accuracy. Due to axial symmetry only half portion is considered that provides a reduction in solving time without affecting accuracy for numerical predictions. The deformation of the work piece is calculated by solving structural field in "structural mechanics" model, which uses magnetic force as a body force imparted on the work piece.

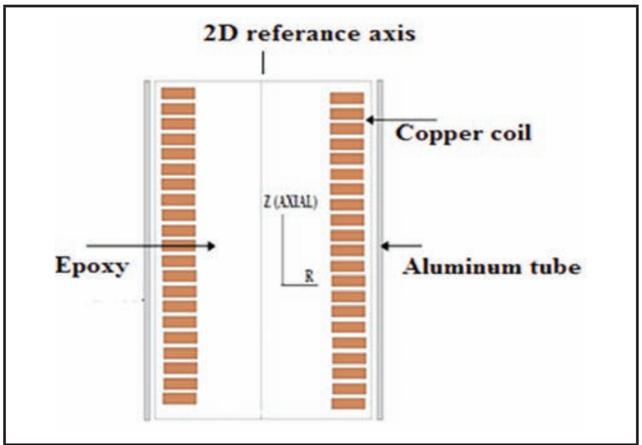

FIG. 4. COIL AND TUBE ARRANGEMENT IN 2D FOR SIMULATION

Plastic deformation is considered and flow stress approximated by hollomon's power law given as,

$$\sigma = \sigma_0(\varepsilon^p)^n \, D \, (\dot{\varepsilon}^p)^m \quad ...(6)$$

Where σ is effective flow stress, σ_0 is strength coefficient εp is effective plastic strain, n is hardening coefficient, D is multiplying factor, $\dot{\varepsilon}p$ is strain rate and m is the rate dependent exponent. The values are taken from literature [12,7].

4.0 RESULTS AND DISCUSSION

Electromagnetic forming of different aluminum tubes are performed for variable input energy keeping same operating conditions. Figure 6 shows Tube expansion images.

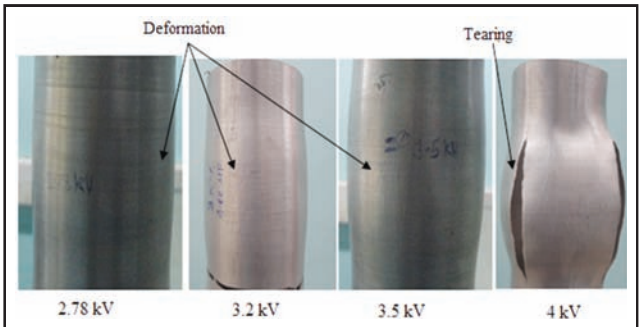

FIG. 5. IMAGES OF DEFORMED ALUMINUM TUBES

TABLE 2				
EXPANSION RESULTS OF AL 1050				
Sr. No.	Input Energy	Peak current	Experiment	Simulation
1.	1.54 kJ	19.8 kA	1.6 mm	1.1 mm
2.	2.04 kJ	22.4 kA	2.5 mm	2.3 mm
3.	2.45 kJ	24.6 kA	3.1 mm	3.6 mm
4.	3.2 kJ	28 kA	Tore	6.4 mm

As the energy is increased, expansion goes on increasing and at 3.2kJ, the tube got tore as the pressure applied was above its ultimate tensile strength. Table 2 shows comparison of experiment and simulation results of forming measured at central tube surface.

The required mechanical pressure for circumferential deformation of the work piece is given as

$$P_m = [\frac{2t}{D}]\sigma \qquad ...(7)$$

Where, σ = σy is yield stress for deformation to start and σ = σUTS for maximum deformation without breaking. t and D are the thickness and outer diameter of tube.

Using the values given in Table 1 and above formula, deformation pressure range for aluminum tube is obtained as 0.72 MPa to 2.6 MPa. For 3.2 kJ, magnetic field calculated by eq. (4) is 6 Tesla and magnetic pressure by eq.(5) is 14.56 MPa

From the observed deformation at 3.2 kJ where tube got tore, the generated magnetic pressure calculated by eq. 5 is above the maximum mechanical pressure of tube which is 2.6 MPa. Magnetic to mechanical pressure are related by a multiplying factor 'K' and its value lies in [1-10] considering the different effects [11].

$$P_{mag} = K x p_m \, P_{mag} \qquad ...(8)$$

Comparing this magnetic pressure to mechanical pressure gives a value of 'K' as 5.6 at tearing. It concludes that the factor 'K' in this experimental arrangement is must be less than 5.6 to obtain forming without tearing of workpiece. This factor is important in practical design and selecting system parameters that can generate required magnetic pressure for deformation without tearing.

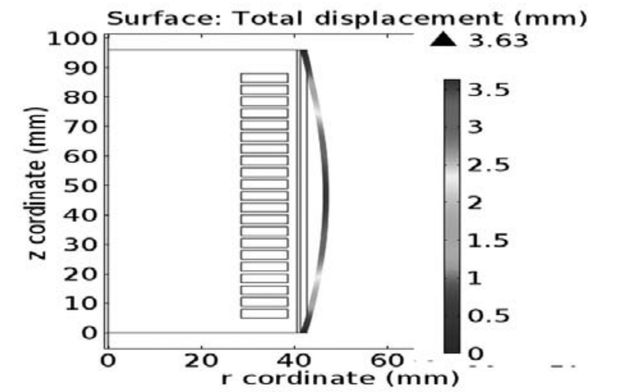

FIG. 6. TUBE DEFORMATION UNDER MAGNETIC PRESSURE AT 2.45 KJ

The non linear phenomenon of expansion of aluminum at regular time instances is shown in figure 6. Radial deformation increases with time and its magnitude at center of the tube is higher than at tube ends, which are governed by generated magnetic pressure variation by the coil.

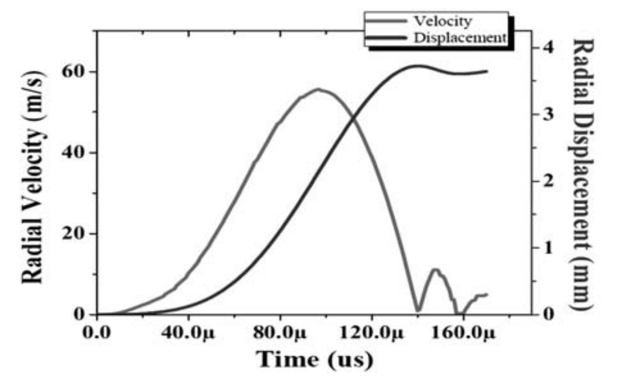

FIG. 7. RADIAL VELOCITY AND DISPLACEMENT OF TUBE WITH TIME AT 2.45 KJ

Peak velocity at tube center during deformation occurs at 94 us which lag behind magnetic coil peak current time by 15 us. This is due to the inertia effect of the tube. It shows electromagnetic tube forming is not a quasi static process supporting [5]. The velocity of tube forming as shown in figure 7 increase gradually and after reaching a peak, tube resistance against deformation causes the tube to decelerate so velocity starts decreasing. Practical phenomenon is well interpreted by FEM coupled Simulation.

5 0 CONCLUSION

Electromagnetic expansion of aluminum tube has been performed and the effect of different input energy on deformation is observed. Yield pressure multiplying factor to get deformation without braking of the work piece is determined analytically for given set up which can be important for deciding system parameters to get deformation without tearing. A coupled numerical simulation is carried out that helps to solve electromagnetic and mechanical aspects simultaneously. The simulation shows the effect of inertia forces cannot be neglected during electromagnetic tube expansion. Obtain results show good agreement with experimental results which are important for analysis, optimal design and system parameter setting.

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REFERENCES

[1] V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya and M. Kleiner, "Electromagnetic forming—a review", J. Mater. Process Technol, Vol. 211, pp.787–829, 2011.

[2] Y.Haiping, L. Chunfeng and D. Jianghua, "Sequential coupling simulation for electromagnetic mechanical tube compression by finite element analysis", J. Mater. Process Technol., Vol. 209, pp.707–713, Jan 2009.

[3] Y.U.Hai Ping and Li chun Feng, "Finite element analysis of free expansion of aluminum alloy tube under magnetic pressure", Trans. Nonferrous Met. Soc. China., Vol 15, 2005.

[4] S.H Lee and D.N. Lee, "A finite element analysis of electromagnetic forming for tube expansion," J. Mater. Process Technol., Vol.116, pp.250–254, Apr 1994.

[5] F.M. Song, X. Zhang, Z.R. Wang and L.Z. Yu, "A study of tube electromagnetic forming", J. Mater. Process. Technol., Vol.151, pp. 372–375, 2004.

[6] M.A. Siddiqui, J.P.M. Correia, S. Ahzi and S. Belouettar, " Electromagnetic forming process: estimation of magnetic pressure in tube expansion and numerical simulation", International Journal of Material Forming, Vol 2, pp.649-652, 2009.

[7] M. Ali, M. Abdelhafeez, M. Nemat-Alla and M. G. El-Sebaie, " Finite element analysis of electromagnetic bulging of sheet metals", International Journal of Scientific & Engineering Research.,Vol. 3, 2012.

[8] J. Correia, M. Siddiqui, S. Ahzi, S. Belouetta and R. Davies, "A simple model to simulate electromagnetic sheet free bulging process," International Journal of Mechanical Sciences, Vol. 50, pp.1466–1475, 2008.

[9] Q. Cao, L. Li, Z. Lai, Z. Zhou, Q. Xiong, X. Zhang and X.Han, "Dynamic analysis of electromagnetic sheet metal forming process using finite element method", The International Journal of Advanced Manufacturing Technology, Vol.74, pp 361-368, 2014.

[10] H. Knoepfel," Pulsed high magnetic fields", north Holland publishing company,1970.

[11] A.G. Mamalis, D.E. Manolakos, A.G. Kladas and A.K. Koumoutsos, "Physical principles of electromagnetic forming process: a constitutive finite element model", J. Mater. Process Technol., Vol.161, pp.294–299, 2004.

[12] Takatsu N., Kato M., Sato K., Tobe T, "High speed forming of metal sheets by electromagnetic forces", Int. J. Japan Soc. Mech, Vol. 60, No. 1, pp.142-148, 1988