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Effect of Variable Tube Wall Thicknesses of Al-Mg-Si Alloy Tube During Electromagnetic Compression using Four Turn Axi-Symmetric Coil

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Abstract: Electromagnetic compression (EMC) is a solid state, high velocity process of deformation of materials. In this process the enhancement of the formability is achieved due to high strain rate forming. In the present study Aluminum alloy AA6061 tube has been compressed using four turn axisymmetric coil. The effect of variable tube wall thicknesses i.e. 1.0, 1.7, and 2.4 mm during the compression of the Al-Mg-Si Aluminum alloy tube electromagnetically has been studied. A constant gap between coil inner diameter (ID) and workpiece outer diameter (OD) was maintained. It has been found that the tube deformation was maximum when the wall thickness was minimum. For compression, 8 kJ energy was used with double power bank. A three dimensional (3D) model of four turn compression coil has been proposed using LS-DYNA software. Comparison between the numerical simulation and experimental results showed a close agreement between both the results. Compression using EMF process can be used in modern industries like automotive, aerospace and nuclear power plants.

Keywords: High strain rate, power bank, AA6061, Electromagnetic compression.

I. INTRODUCTION

Electromagnetic compression is high velocity forming process, in which material deforms plastically more than the conventional process. Due to this feature more formability than the conventional methods is attained by the components. Automotive, aerospace, nuclear and medical sectors may like to use this process due to the specific requirement and performance [1]. Key features of this technique is to minimize the springback, wrinkling, and enhancement of formability [2]. Reduction of the weight to improve the fuel efficiency for automotive industries is the need of the day [3]. Electrohydraulic forming (EHF) improved the formability of the lightweight materials like Al-Mg alloy (AA5052) using the process parameters like stand-off distance (SOD), wire diameter, electrode gap (EGAP), and the medium (oil and water) [4-5]. Limiting dome height was also determined by using the full factorial design method.

FLD and strain distribution have also been investigated. Field shaper geometry is used for crimping of aluminum (Al) terminal over the Al wires for cables [6].Numerical simulation was also done for the process to find out the various parameters like current density, magnetic field, and Lorentz force. Forming by different methods were done and some of the conventional problems were solved by this methods like coil design and temperature developed due to flowing of high current [7]. Numerical modelling and temperature effect which were produced during high current generated in a very short time was analyzed [8]. Al tube 1050 with 1.0 mm tube wall thickness for tube expansion and its modelling using ABAQUS software has been reported [9]. Different models were used for analyzing the EM structure mechanism for the electromagnetic forming process (EMF) [10]. Variable tube thicknesses of Al6061-T6 along the length have been investigated experimentally as well as numerically. Two coils were used for the experimental purpose namely, C53 and C100 made of copper with field shaper [11]. A 3D simulation with the help of MAXWELL software has been used to find out the distribution of magnetic field. Field shaper and its effect has also been explained in the study [12]. Four turn compression coil with field shaper of 10 mm web length and 40° angle was used to find out the deformation at 2.4 and 3.6 kJ energy using the analytical and experimental methods [13]. Riveting of aluminum alloy was performed using the electromagnetic riveting method [14]. Mechanical properties were investigated by the Split Hopkinson pressure bar (SHPB). Johnson-Cook's multi-field material model was used to find out magnetic pressure, adiabatic temperature and deformation during the analysis. Maximum temperature and discharge voltage was found to be 252°C and 2.0 kV respectively [14]. Joint strength of frame structure for automotive applications was analyzed by numerical simulation and strength test characteristics. The effect of geometrical parameter was also investigated. Design of axial joint and torque has also been studied for electromagnetic forming process [15]. Tube expansion using of aluminum 6061 alloys with 40 kJ magnetic pulse welding (MPW) and different process parameters like rise time, peak current, magnetic field, geometry of the workpiece has been investigated [16].Tube bulging with the help of numerically simulation and effect of magnetic pressure on it using ANSYS software has been carried out[17].

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The magnetic pressure distribution has also been analyzed in the direction of tube thickness. Bulging of aluminum tube using two forming process EMF and electrohydraulic forming (EHF) has also been studied. Analysis showed better rebound effect in EHF than the EMF process [18]. Four turn compression coil and seven turn pancake coil has been reported [19]. The magnetic flux density and Lorentz force acting on the workpiece are calculated to find out the effect of charging voltage [19].

In the present work the tube compression of aluminum alloy 6061 has been carried out. Comparison of experimental outcome and numerical simulation results with different tube wall thickness at constant tube length has been done. A four turn axisymmetric copper coil was used for compression of tube. Simulation study was done to find out the process parameters like resultant velocity, displacement, plastic strain and magnetic field, which were difficult to measure experimentally.

II. EXPERIMENTAL

Tube of different tube wall thicknesses, 1.0, 1.7 and 2.4 mm of AA6061-T6 aluminum alloy were compressed using a constant energy of 8.0 kJ. The applied energy was in the form of combination of two single banks i.e. double capacitor bank. The tube deformation was analyzed by both i.e. numerical and experimental methods at constant gap and length i.e. 0.5 and 52 mm respectively. A four turn compression coil was used for experiments. The maximum capacity of bank was 40 kJ, it had four module each having 10 kJ and charging voltage of 20 kV. 224 µF was equivalent capacitance of the machine set up. System could deliver 320 kA. Maximum current used was at 10-15 kHz frequency. A schematic circuit diagram of EMF system used for the experiments is shown in Fig.1.

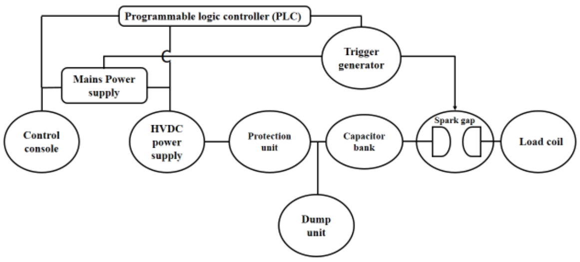

Fig.1 Schematic circuit diagram of EMF set up

This set up facilitated a provision of selection of power banks as per requirement and features available in the control console of the machine set up. Double power bank system was selected .The capacitance of double power bank is 112 µF. The coil used for experiments was made of OFHC copper, properties of which are shown in Table-I. Outer diameter of 200 mm and internal diameter of 57 mm with total coil width with active copper plates is shown in the Figs. 2 and 6. Coil dimension is also shown in Fig. 3. A 40 kJ energy is stored in the capacitors by charging to a high voltage upto 20 kV. The stored energy in the capacitor bank is described by equation (i)

$$E=0.5\ CV^2 \qquad \text{(i)}$$

Where E is the discharge energy, C is the total capacitance of the used capacitor bank and V is the selected charge voltage. The Lorentz force $\vec{F}$ established in term of current density $\vec{J}$ and magnetic flux density $\vec{B}$ is given by equation (ii)

$$\vec{F} = \vec{J} \times \vec{B} \qquad \text{(ii)}$$

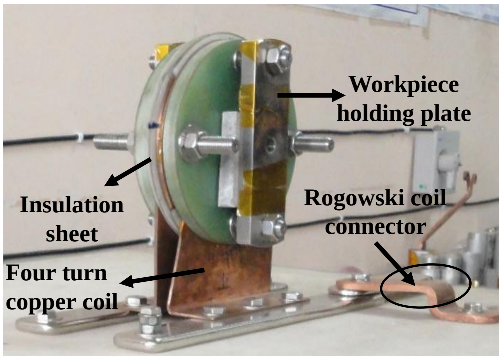

Fig. 2 Actual photograph of four turn copper coil

Table-I The mechanical properties of OFHC copper coil [20]

Properties	Value
Poisson's ratio	0.34
Density	8960 (kg/m^3)
Young's Modulus	124 (GPa)

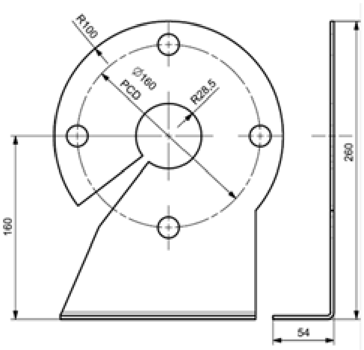

Fig. 3 Dimension of the compression coil

The chemical compositions of AA6061-T6 are listed in Table- II and its mechanical properties are listed in Table-III. During the experiments a very high current was used so the arc prevention was a must.

Table-II The chemical compositions of AA6061 (tube)

Elements (wt. %)					
Cu	Fe	Si	Mg	Mn	Al
0.18	0.57	0.73	0.51	0.092	Rest

Table-III The physical and mechanical properties of Al alloy AA6061-T6 [21]

Properties	Value
Poisson's ratio	0.33
Density	2700 (kg/m^3)
Young's Modulus	69 (GPa)

A high insulating tape/sheet was used for coil safety purpose. Rogowski coil is used to measure the high current that was passing through primary circuit. Fig. 4 shows true stress and strain curve of the AA6061-T6 at both quasi static [21] and high strain rate [22] conditions.

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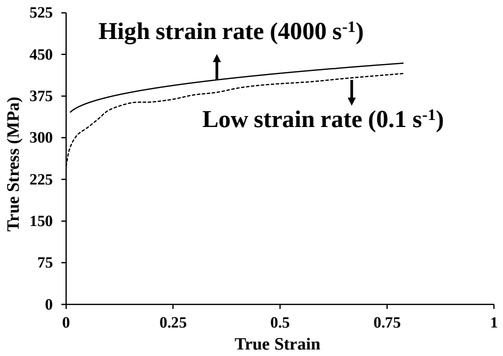

Fig. 4. True stress- strain curve of AA6061-T6 at quasi and high Strain rate [21, 22].

III. FE ANALYSIS

On the basis of actual dimensions of the coil and tube FE model of parts and assembly of coil was created in LS-DYNA as shown in Fig.5 (a) and Fig. 5 (b). Sectional view of coil is also shown in Fig. 6. The materials properties are listed in the Table-II and Table-III. The peak current pulse used for simulation is also shown in Fig. 7.

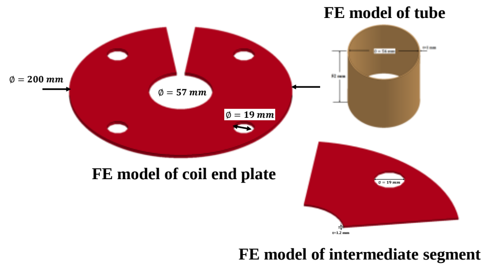

Fig.5 (a) FE model of coil parts

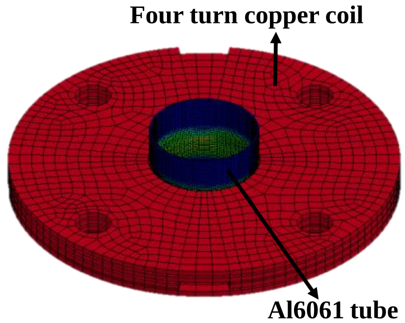

Fig.5 (b) FE model of assembly of four turn coil and tube

Johnson-Cook material model

Johnson-Cook (J-C) constitutive equation was used for FE analysis and predict the nature of tube deformation. This equation is a combination of the plastic strain and plastic strain rate given by equation (iii)

$$\sigma = (A + B\varepsilon^n)\,(1+ C \ln \dot{\varepsilon})\,\left(1- \left(\frac{T-T_r}{T_m-T_r}\right)^m\right) \qquad \text{(iii)}$$

Where σ is equivalent plastic stress (MPa), ε is equivalent plastic strain, T is temperature (°C), T_m is melting temperature and A, B, C, m and n are material constants. The values of Johnson-Cook material constant parameters given in Table-IV.

Table-IV J-C material model values

Material	A (MPa)	B (MPa)	C	n	m	T_m(K)
AA6061	324	114	0.002	0.42	1.34	925

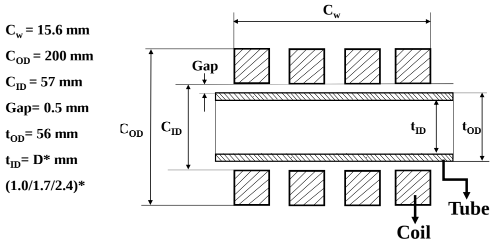

Fig. 6 Sectioned view of coil and tube assembly in compression coil

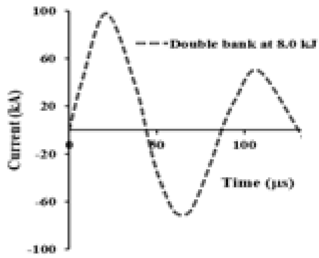

Fig. 7. Current pulse at 8.0 kJ double capacitor bank

IV. METHODOLOGY

Double capacitor bank with 40 kJ energy was used for the study. The workpiece geometry used in the experiments is shown in the Table-V. Deformed samples of AA6061-T6 tube was measured by digital vernier caliper having least count 0.01 mm. Element 3D solid 164 has been selected for simulation study. Some of typical cards and boundary condition applied for running the program. Selected power bank and experimental matrix are shown in the Table-VI and Table-VII.

Table-V Tube geometry of the workpiece (tube)

OD (mm)	ID (mm)	Thickness (mm)	Gap (mm)
56	54	1.0	0.5
56	52.6	1.7	0.5
56	51.2	2.4	0.5

Table-VI The power bank combination during the experiments

Power Bank combinations	Equivalent Capacitance (µF)	Calculated Energy (kJ)
Double	112	8.0

Table-VII Experimental matrix

Gap (mm)	Energy (kJ)	Voltage (kV)	Length of tube (mm)
0.5	8.0	12	52

V. RESULTS AND DISCUSSION

Al alloy 6061 tube with varying wall thicknesses were compressed electromagnetically. Tube was placed within the axi-symmetric four turn coil as shown in Fig. 2. The compressed tube with different wall thicknesses in actual and simulated condition are shown in Fig. 8. Table VI shows the OD values of the compressed tubes in actual and simulated conditions.

Table-VIII. OD of the Tubes after compression.

Actual tube OD	Tube wall thickness	Experimental OD (mm)	Simulated OD (mm)
56	1.0	30.32	27.11
56	1.7	42.57	46.02
56	2.4	49.32	51.39

Fig. 8 shows the deformed AA6061 tube model with respect to the peak value of the current pulse considered for simulation. This peak current exerted pressure on the deformable workpiece in discharge chamber.

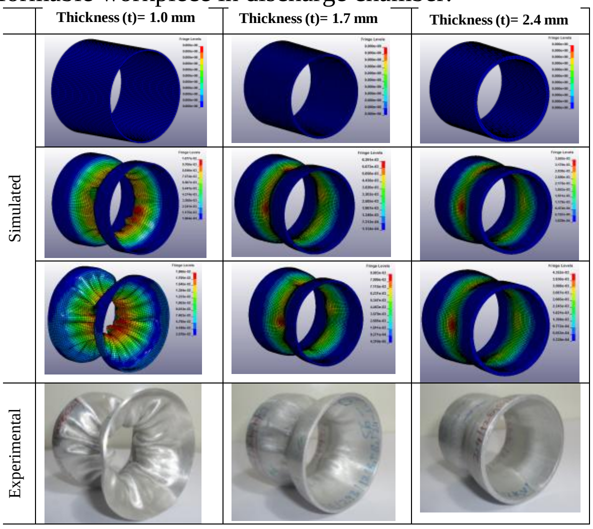

Fig. 8 Simulation of tube deformation and final experimental deformation of the tube at different tube wall thicknesses

The corresponding parameters like resultant velocity, displacement, plastic strain and the magnetic field are discussed. Resultant velocity is more important parameter in material deformation. Maximum deformation was observed in 1 mm tube thickness hence it was considered for all parameters as clearly observed in Fig.8. It was observed that the resultant velocity increased at lower tube thickness. At higher tube thickness the velocity decreased. At the peak the velocity was found to be 517 m/s at approximately 30 µs Fig. 9 shows the plot of velocity vs time.

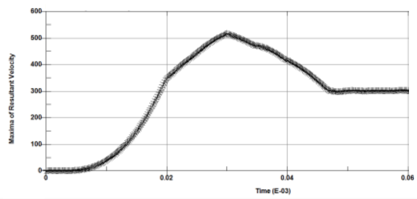

Fig. 9 resultant velocity vs time

Resultant displacement is shown in Fig. 10. The maximum deformation was found at about 15 mm, 60 µs at 8.0 kJ energy of double capacitor bank. It was found at the middle of the tube surface when the plastic deformation was initiated.

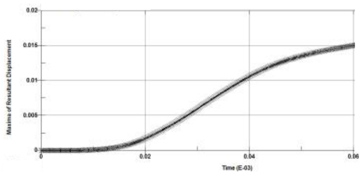

Fig. 10 Resultant displacement vs time

Effective plastic strain at its peak was more than 0.80 at a gap 0.5 mm as shown in Fig. 11. The value decreased with increasing of tube thickness.

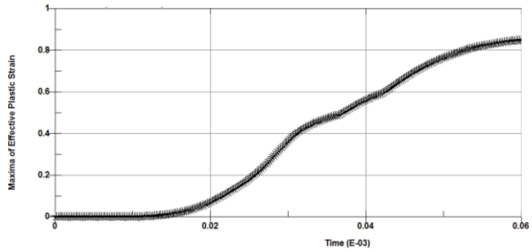

Fig. 11 Effective plastic strain vs time

Magnetic field was found 14 T at 20 µs and at 1 mm tube thickness as shown in the Fig. 12. The magnetic field with double capacitor bank were obtained through numerical simulation. The magnetic field increased because of increase of the current density due to high discharge voltage.

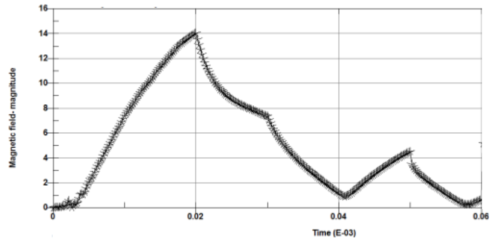

Fig. 12 Magnetic field vs time

VI. ACKNOWLEDGMENT

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VII. CONCLUSIONS

The effect of the tube wall thicknesses on compression of Al-Alloy tube was to be investigated in the present study. Following are the findings of this study:

1. The gap between the conducting coil and aluminum tube plays an important role in the tube deformation at constant tube wall thickness.
2. Increased tube wall thickness leads to decreased deformation of the tube. It was even negligible with maximum tube wall thickness.
3. Numerically simulated parameters like resultant velocity, displacement, plastic stain and magnetic field were in good correlation with the experimental results.
4. The effect of bank combinations shows that the lower the tube thickness higher the value of process parameters like resultant velocity, displacement, plastic stain and magnetic field.
5. Wrinkling effect on the tube depends upon the thickness of the tube. It was maximum in the case of thinnest wall thickness tube.

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