Finite element modelling and analysis of the effect of frequency on the electromagnetic compression of tubes

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Abstract. Electromagnetic compression of the tube is a high strain rate forming process, in this process formability of the material can be increased by reducing the spring back effect developed in the process. High electrical conductivity materials like copper, aluminum are generally used for electromagnetic compression. In electromagnetic compression, frequency of the current pulse is an important parameter to be analyzed. In this work the effect of current pulse frequency on the electromagnetic compression of the tube has been studied. The tube and coil were modelled and analyzed using finite element software LS-DYNA. It has been found that the deformation obtained during tube compression were increases first with the increase in frequency, obtained a maximum value and then decreases with the further increase in the frequency. The change in frequency greatly influences the deformation obtained during the electromagnetic compression of tubes.

1. Introduction

Electromagnetic (EM) compression is high energy and high strain rate forming process in which the amount of plastic deformation obtained is more than that of in the conventional forming process. It has many features like very rapid process, less spring back, high precision forming, and large forming limit [1]. EM compression can be used for different processes of the EM manufacturing such as cladding, welding, crimping. Typically, this technique was used for manufacturing of bimetallic tubes, joining of thin tubes of similar or dissimilar materials [2], internal metallic mandrel [3]. The peculiar advantages of EM compression technology are in assembly and joining of lightweight metals such as aluminum and magnesium, because it improves the formability, strain distribution and reduces wrinkles, spring-back and distortion [3].

In EM compression magnetic pressure is the driving force which causes the compression of the tube. When the current discharges from the capacitor bank an eddy current will produce in the tube. Because of the two opposing magnetic field, either by primary and eddy current magnetic pressure will generate in the tube [4]. The magnetic pressure generate in the tube causes the compression of the tube. In the EM module of LS-DYNA, magnetic field, electric field and eddy current were calculated by solving the Maxwell’s equations [5].

The current frequency is one of the key parameters of the electromagnetic compression process. The dimensions, shape and material properties of the forming components such as coil, workpiece and die will affect the frequency for a particular EM machine. The capacitance of the machine and inductance of the machine, coil and tube will determine the frequency of the current [3].

The components of EM compression of the tube and the process are shown in figure 1. It consists of power supply, capacitor bank to store the energy, high voltage switch, coil tool to generate magnetic

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fields, Rogowski coil to measure the discharge current, R-C Integrator will help while measuring the discharge current in the tube.

![Diagram of EM compression of tubes](image)

**Figure 1.** Different components and the process of EM compression of tubes.

### 1.1. Johnson-Cook materials model

In the finite element simulation the Johnson-Cook constitutive equation was used to model the behaviour of tubes. The Johnson-Cook equations which is combination of plastic strain and plastic strain rate can be described as [6]:

$$\sigma = (A + Be^n \left(1 + C \ln \varepsilon_p \right) \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right))$$  \hspace{1cm} (1)

Where $\sigma$ is flow stress of the material, $\varepsilon$ is equivalent plastic strain, $\varepsilon_p$ is plastic strain rate, $T$ is absolute temperature, $T_r$ is the room temperature, $T_m$ is the melting temperature of the material and $A$, $B$, $C$, $n$, $m$ are constants. Constants in this equation are obtained from simple mechanical tests such as isothermal tension test and torsion tests, which is given in table 1. For EM simulations the model was simulated for different values of discharge voltages, ranging from 3.0 kV to 5.4 kV. In the simulation the frequency of the current was also varied from 1 kHz to 35 kHz.

**Table 1.** Values of Johnson-Cook material constant parameters [7].

| Materials       | A (MPa) | B(MPa) | n   | C     | $T_m$ (K) | m   |
|------------------|---------|--------|-----|-------|-----------|-----|
| 1050A-H24        | 110     | 150    | 0.36| 0.014 | 918       | 1   |

Material properties of Al 1050 used for the simulation in the EM module of the finite element software LS-DYNA is listed in table 2.

**Table 2.** Material properties for tube Al 1050 [8].

| Density ($\rho$)         | Modulus of rigidity (G) | Modulus of Elasticity (E) | Poisson’s Ratio ($\gamma$) | Heat Capacity (C) | Thermal Conductivity (k) | Electrical resistivity ($\rho$) |
|--------------------------|-------------------------|---------------------------|---------------------------|------------------|-------------------------|-------------------------------|
| 2705 Kg m$^{-3}$         | 26 GPa                  | 69 GPa                    | 0.33                      | 896 J Kg$^{-1}$K$^{-1}$ | 227 W m$^{-1}$K$^{-1}$     | 2.9×10$^8$ Ω m               |
2. Results and Discussion

The deformation patterns obtained during the experiment at various energy levels are shown in figure 2. In the experiment the discharge voltages were varied from 3 kV to 5.4 kV and it was found that at 5.4 kV of discharge voltage the compression obtained in the tube was maximized because further increase in voltage leads to penetration of tube edges between them.

![Figure 2. Experimental result of EM compression of tubes at different voltages.](image)

Deformation patterns obtained during the experiment at different discharge voltages and from simulation at same discharge voltages are shown in figure 3. It was observed that the deformation patterns obtained from the simulation have a good agreement with that of the experimental deformation pattern at the same discharge voltages.

![Figure 3. Deformation pattern of tubes obtained in experiment and simulations at different voltages](image)

(a) 5.4 kV, (b) 5.2 kV, (c) 5.0 kV, (d) 4.8 kV, (e) 4.2 kV, (f) 3.5 kV, (g) 3.0 kV.

After an experimental validation of the model based on the deformation patterns, obtained at different levels of discharge voltages the frequency of the model were varied by changing the capacitance value, and keeping constant inductance equal to 1.2 µH. The values of the capacitance used for variation in the frequency are listed in table 3.
### Table 3. Values of capacitance and frequency at different voltages.

| Voltage (kV) | 3   | 3.5 | 3.7 | 4   | 4.2 | 4.8 | 5   | 5.2 | 5.4 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Frequency (kHz) | 1   | 5   | 10  | 15  | 20  | 25  | 30  | 35  | 40  |
| Capacitance (μ F) | 21108 | 844 | 211 | 93  | 52  | 33  | 23  | 17  | 13  |

#### 2.1. Variation in velocity with frequency and discharge voltage

The velocity of the tube was found to be increasing as the frequency was increased from 1 kHz to 15 kHz, and further increase in frequency from 15 kHz to 35 kHz leads to decrease in velocity. The optimum value of frequency was found to be 15 kHz. The effect of frequency on velocity vs time of tube is shown in figure 4. The velocity of the tube was increasing as the discharge voltage was increased, and the corresponding variation is shown in figure 5. At the maximum voltage of 5.4 kV for the given configuration the maximum velocity was found 158 m/s.

![Figure 4](image1.png)  
**Figure 4.** Variation in the velocity with time at different frequencies at 5.4 kV.

![Figure 5](image2.png)  
**Figure 5.** Variation in velocity with time at different discharge voltages at 15 kHz.

#### 2.2. Variation in stress with frequency and discharge voltage

The stress developed in the tube was found to be increasing as the frequency was increased from 1 kHz to 15 kHz, and further increase in frequency from 15 kHz to 35 kHz leads to decrease in stress. The optimum value of frequency was found to be 15 kHz. The effect of frequency of stress vs time is shown in figure 6. Stress developed in the tube was increasing as the discharge voltage was increased, and the corresponding variation is shown in figure 7. At the maximum voltage of 5.4 kV for the given configuration the maximum stress was 125 MPa.

![Figure 6](image3.png)  
**Figure 6.** Variation in the stress with time at different frequencies at 5.4 kV.

![Figure 7](image4.png)  
**Figure 7.** Variation in stress with time at different discharge voltages at 15 kHz.
2.3. Variation in plastic strain with frequency and discharge voltage
The plastic strain developed in the tube was found to be increasing as the frequency was increased, and further increase in frequency leads to decrease in plastic strain. The optimum value of frequency was found to be 15 kHz. The effect of frequency of plastic strain is shown in figure 8. Plastic strain value was increasing as the discharge voltage was increased, and the corresponding variation is shown in figure 9. At the maximum voltage of 5.4 kV for the given configuration the maximum plastic strain was 1.3.

![Figure 8. Variation in the effective plastic strain with time at different frequencies at 5.4 kV.](image)

![Figure 9. Variation in effective plastic strain with time at different discharge voltages at 15 kHz.](image)

2.4. Effect of frequency on skin depth
Due to primary discharge current in the circuit, an eddy current is induced in flyer tube which is alternating in nature and alternating electric current flow mainly at the skin of the conductor, at an average depth called the skin depth [9] and it is measured as by equation (2). For different values of frequency and discharge voltage the values of skin depth are listed in table 4.

| Voltage (kV) | 3.0 | 3.5 | 3.7 | 4.0 | 4.2 | 4.8 | 5.0 | 5.2 | 5.4 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Frequency (kHz) | 1   | 5   | 10  | 15  | 20  | 25  | 30  | 35  | 40  |
| Skin depth (mm) | 2.670 | 1.190 | 0.845 | 0.690 | 0.598 | 0.534 | 0.488 | 0.452 | 0.422 |

\[
\delta = \left( \frac{\rho}{\pi \mu_0 \mu_r f} \right)^{1/2}
\]  

(2)

Where \( \rho \) is the electrical resistivity of the workpiece, \( \mu_0 \) is the permeability of the free space (\( \mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1} \)), \( \mu_r \) is the relative permeability of the material and \( f \) is the frequency of the discharge current and it is given by equation (3). The variation in the skin depth with frequency is shown in figure 10.

\[
f = \frac{1}{2\pi \sqrt{LC}}
\]  

(3)
3. Conclusions

Comparison between the numerical and experimental results were carried out based on the deformation patterns and showed good agreement between them. Increase in frequency first increases the velocity, strain and stress and then decrease. Strain rate hardening has the largest effect on EM compression. In the simulation result, the optimum frequency value was found 15 kHz for Al 1050 alloy. In the simulation maximum resultant velocity of the tube was found 258 m/s, the maximum stress was 125 MPa and the maximum plastic strain was 1.3 at 5.4 kV discharge voltage and 15 kHz frequency.

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