Numerical and experimental investigation of fully-coupled and uncoupled finite element model for electromagnetic forming of Aluminium Alloy Al 3014

Z Khan¹, M Khan¹, S H I Jaffery¹, M Younas², A Khan³

¹Department of Design and Manufacturing Engineering (DME), School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), Sector H-12, 44000, Islamabad, Pakistan.
²Department of Mechanical Engineering, HITEC University, Taxila, 47080, Pakistan
³Department of Mechanical Engineering, Royal exchange building, University of Sheffield, UK
Email: zarak.khandme2015@smme.nust.edu.pk; mkhan@smm.nust.edu.pk; imran@smme.nust.edu.pk; Muhammad.younas@hitecuni.edu.pk; ashfaq.khan@sheffield.ac.uk

Abstract. Electromagnetic forming is a high-velocity forming process in which repulsive forces between conducting coil and workpiece are generated by mutual inductance, thus, creating opposite magnetic fields and Lorentz forces on conducting bodies. In such processes, the formability can be enhanced owing to the high-speed deformation of the material. This paper presents a fully-coupled numerical model and experimental study of the deformation behaviour of aluminium alloy (AL3014) using closed die magnetic pulse forming. The current density, magnetic flux density and Lorentz force of 1mm thick sheet were estimated numerically. The effect of deforming sheet on magnetic flux and induction was considered. As a result of which the percentage error in sheet deformation reduced from 10% for the existing uncoupled model to 5% for the fully coupled proposed model.

Keywords. Electromagnetic forming, Finite Element Model, Lorentz forces

1. Introduction
Electromagnetic forming involves the deformation of metal sheet under the influence of magnetic pressure. Due to high-speed deformation, the formability of material can be increased also the phenomena of wrinkling and spring back can be minimized as summarized by Psyk [1]. Experiments on free bulging of an annealed aluminium disk and its numerical simulation were first carried out by Takatsu et al [2]. Fenton and Daehn also worked on 2-D Arbitrary langrangian-Eulerian (ALE) to develop finite difference code (CALE) to predict the deformation of sheet metal [3] but two different time steps were used to maintain numerical stability of magnetic physics and material motion. A loose coupling method was used by Oliveira et al [4] to analyse the dynamic behaviour of sheet. ANSYS/EMAG and LS DYNA were used but the effect of change in geometry on the magnetic field wasn’t considered. Corriea et al [5] used commercial finite element code ABAQUS/Explicit to study the deformation of sheet and influence of viscoplastic material behaviour in free bulge electroforming process neglecting the effect of velocity. Y.U Haiping et al[6] studied the effect of change in geometry on the magnetic force. The changing inductance of workpiece and hence circuit was ignored. Xiaohui et al [7] worked on adaptive remeshing technique in air mesh to change regularly as the sheet deforms.
Li et al[8] used a conducting material as a driver to deform a 0.5mm non-conducting titanium sheet. The model for the driver and the driven sheet was uncoupled. A fully coupled model for axisymmetric free bulging of aluminium alloy was developed by Quanliang Cao et al [9]. The effect of velocity on the current applied to the coil was considered. Simulated deformation of Cao gave much better results than previous uncoupled models. The model was for free bulging. Haiping Yu et al [10] discussed the comparison of conventional forming and electromagnetic forming. Circular hole flanging by electromagnetic forming showed better formability compared to conventional forming. The uncoupled numerical model was in good agreement with experimental results. Hak-Gon Noh[11] performed experiments and 3-D numerical simulations for sheet metal forming with unsymmetrical die. The uncoupled model showed satisfactory results.

The numerical model consists of an RLC circuit coupled with the electromagnetic and structural mechanics module. The proposed numerical model was used to validate the current densities, magnetic flux densities and Lorentz force during the forming process. Sheets were deformed experimentally and then validated numerically using the proposed numerical model. The morphology of experimentally deformed sheets was compared with numerically estimated results.

2. Numerical model
A Finite Element (FE) model was used to numerically solve the 2-Dimensional problem. In the simulation, the discharge current flowing through the coil was calculated by solving Eq.1. Magnetic flux and current density were calculated using Eq. (1 & 2). The magnetic force was then calculated using Eq. 4. The deformation of the workpiece was calculated in solid mechanics which use magnetic force as body load on the sheet. 2D geometry consisted of five domains as shown in Figure 1.

\[ I(t) = \frac{U_0}{\omega L} e^{-\beta t} \sin(\omega t) \]  
\[ \nabla \times \vec{E} = -\frac{dB}{dt} \]  
\[ \vec{J} = \frac{\vec{E}}{s} = \sigma_e \vec{E} \]

Where \( \vec{H} \) is magnetic intensity, \( \vec{J} \): is current density, \( s \): is a sectional area of one-turn of the coil, \( \vec{B} \): magnetic flux density, \( \vec{E} \): electric intensity, \( \sigma_e \): electrical conductivity.

\[ \rho \frac{\partial \vec{v}}{\partial t} - \nabla \cdot \vec{s} = \vec{f} \]
Where \( \rho \) is density, \( \vec{u} \) is the displacement vector, \( \sigma \) is stress tensor and \( \vec{f_m} \) is the electromagnetic force density.

The electrical and mechanical properties of the sheet and constants for the model were taken from the work of [11], where the constants used were \( \rho = 6500 \text{s}^{-1} \) & \( m = 0.25 \). For simulation of Sheet / AL3014, Cowper-Symonds model Eq.5 was used. Properties are given below in the Table 1.

\[
\bar{\sigma} = \sigma_y \left[ 1 + \left( \frac{\bar{\epsilon}}{\rho} \right)^m \right]
\]

**Table 1.** Electrical and mechanical properties of the sheet and coil [11]

| Serial | Component/material       | Properties | Parameter | Values  |
|--------|--------------------------|------------|-----------|---------|
| 1      | Forming Coil / Copper    | Resistivity| \( \rho \) | 1.72e-8 m |
| 2      | Sheet / AL3014           | Resistivity| \( \rho \) | 2.65e-8 m |
|        |                          | Poison’s ratio| \( \nu \) | 0.35    |
|        |                          | Density     | \( \rho \) | 2980 kg/m³ |
|        |                          | Elastic Modulus| \( E \) | 69.0 GPa |

3. Experimental details

After validation of the proposed model experiments were performed to compare the results of the model with experimental results. A schematic of the experimental setup is shown in Figure 2. The parameters for the comparison were taken from the work of Noh at el., [11]. The input voltage used was 11kV, capacitance used was 333e-6 F and inductance was 5.8e-6H. Resistance and frequency were taken as 0.03[ohm] & 23876.10414[rad/s] respectively. The coil had an inner diameter of 50mm and an outer diameter of 140mm, its cross-sectional width was 5mm x 10mm with a spacing of 2.5mm. Sheet blank was 260mm x 260mm with a thickness of 1mm. Experiments were performed at 20.146KJ energy.

![Electromagnetic forming configuration](image)

**Figure 2.** Electromagnetic forming configuration

4. Results

**4.1. Comparison of current densities, magnetic flux densities and Lorentz force**

The current densities, magnetic flux densities and Lorentz force at each time step were calculated numerically and plotted. The dotted curves represent the proposed fully coupled model while the solid curves are taken from reference article [11]. A comparison of the current densities at three known time steps is shown in Figure 3. The current density of the proposed model was observed to be conservative as compared to the uncoupled model. It was due to the effect of sheet deformation on the induction of the system and Lorentz force which was considered in the proposed fully coupled model and ignored.
in the uncoupled model developed by [11]. Similar results were observed for magnetic flux densities and Lorentz force as shown in Figure 4 and Figure 5 respectively.

The main reason was the effect of change in geometry on the current density & magnetic flux density in a fully coupled model which was ignored in the uncoupled model. The changing geometry changes the inductance of the workpiece and hence the circuit current which in turn changes the current density, magnetic flux density and Lorentz force [5]. The effect of temperature was ignored in the proposed model because the process takes place very quickly and the effect of temperature is always negligible [6]. From Table 2 it can be observed that the maximum value of current density at all time steps is lower for the proposed model as compared to the un-coupled model. The magnetic flux density estimated by the proposed model has lower peak value at 75μs as shown in Table 2, but has a slightly higher value at time step 170μs and 330μs. The Lorentz force at 75μs and 170μs has a lower value for the proposed model and slightly higher value at time step 330μs.

![Figure 3. Comparison of Current densities results fully coupled proposed model vs Noh et al [11]](image)

![Figure 4. Comparison of Magnetic flux densities results fully coupled proposed model vs Noh et al [11]](image)

![Figure 5. Comparison of Lorentz force results fully coupled proposed model vs Noh et al [11]](image)

### Table 2. Comparison of Peak values of all parameters at different time steps

| Serial | Parameters      | Time in [μs] | Uncoupled Model         | Proposed Model         | Difference % |
|--------|-----------------|--------------|-------------------------|------------------------|--------------|
| 1      | Current Density | 75           | 11.5x10⁹ A/m²           | 10.5x10⁹ A/m²          | 9%           |
|        |                 | 170          | 10x10⁹ A/m²             | 9.4x10⁹ A/m²           | 6.1%         |
|        |                 | 330          | 4x10⁹ A/m²              | 3.8x10⁹ A/m²           | 5%           |
| 2      | Magnetic Flux Density | 75 | 5T | 4.8T | 4.08% |
|        |                 | 170          | 1.6T                    | 1.8T                   | 11%          |
|        |                 | 330          | 0.7T                    | 1.1T                   | 44%          |
| 3      | Lorentz Force   | 75           | 4.8x10¹⁰ N/m³           | 4.65x10¹⁰ N/m³         | 3%           |
|        |                 | 170          | 1.4x10¹⁰ N/m³           | 1.3x10¹⁰ N/m³          | 7%           |
|        |                 | 330          | 0.3x10¹⁰ N/m³           | 0.4x10¹⁰ N/m³          | 28%          |

### 4.2. Z-Displacement of Deformed Sheet
From Figure 6 it can be observed that the numerical model used in the article [11] shows exaggerated results as compared to experimental values. On the other hand, with the proposed model much better results can be obtained by including the effect of changing geometry at each time step which results in a change in inductance and hence Lorentz force acting on the workpiece as it deforms. The maximum values of z displacement at three points were measured. The maximum z-displacement at point A for experimental, proposed model and uncoupled model was 12mm, 12.6mm and 13.3mm respectively. At point B the maximum values were 2mm, 2.2mm and 2.4mm respectively. Similarly the maximum z-displacement at point C for experimental, proposed model and uncoupled model was 12.3mm, 12.8mm and 13.2mm respectively. The percentage error between the proposed model and experimental results at point A,B and C was 5%, 10% and 4.06% respectively. while The percentage error between the uncoupled model and experimental results at point A,B and C was 10.83%, 20% and 7.31%. The percentage error of the uncoupled model is approximately twice as that of the proposed model. The proposed fully coupled model will be used for further analysis.

4.3 Comparison of experimental and numerical deformation

The energy of 20.146KJ was used to deform the sheet. After deforming the experimental profile for 1mm sheet was measured using FARO Arm CMM machine [12] and plotted against the numerically estimated curves as shown in Figure 7. A comparison of numerical and experimental curves at three points A,B and C was carried out. From Figure 7 it can be observed that the maximum displacement in z-direction on the numerical curve at point A\textsubscript{N}, B\textsubscript{N} and C\textsubscript{N} are 12.6mm, 2.2mm and 12.7mm respectively. The maximum values in z-direction on experimental curves at A\textsubscript{E}, B\textsubscript{E} and C\textsubscript{E} are 12mm, 2mm and 12.1mm respectively. The percentage error between the experimental and numerical values was 4.7%, 10% and 5.7% respectively.

![Figure 7](image7.png)

**Figure 7.** Comparison of Experimental results with the simulated result

![Figure 8](image8.png)

**Figure 8.** Deformed sheet experiment at 20.146 KJ
It can be observed that numerical results are in close agreement with the experimental sheet deformation. The reason for the error is attributed to the minimal variation in the coil and sheet gap during experimentation, which is a critical factor in defining magnetic pressure [13]. Figure 8 shows the experimentally deformed sheet.

5. Conclusion
- The effect of sheet deformation on induced current and Lorentz force can result in deviation of numerical analysis from actual results during electromagnetic forming. From the results, it can be seen that the current densities estimated by the uncoupled model differ from the results obtained from the fully-coupled model with a maximum and minimum difference of 9% and 5% respectively.
- The magnetic flux densities estimated by the proposed model have a minimum difference of 4.08% at 75 μs. The difference then grows bigger till 330 μs.
- The peak Lorentz force estimated by the proposed model and uncoupled model are nearly the same with only 3% difference. The maximum difference is at the time step 330 of about 28%.
- The maximum percentage error between the uncoupled model and experimental values was 10.83% at point A and 20% at point B. Whereas the percentage error between experimental values and the proposed model was 5% at point A and 10% at point B. Although both the model gives exaggerated values, the proposed fully coupled model is closer to the experimental curve hence more accurate.
- The experimental validation shows the proposed model gives improved results as compared with the uncoupled model.

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