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Analyzing the electromagnetic forming process of SS304 sheet using AA6061-T6 driver through a fully coupled numerical model and experimentally validation

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Abstract. Driver-based electromagnetic forming (EMF) is a process that uses electromagnetic forces to form metal components into a desired shape. The process involves the use of a conducting driver metal, which is driven by an electromagnetic coil that generates a high-frequency, high-amplitude current. The driver sheet pushes the nonmagnetic sheet metal workpiece against a die causing it to be deformed into the desired shapes. EMF is particularly useful for forming complex shapes and for creating precise forms with minimal material loss. Applications of EMF include the formation of aerospace and automotive components, medical devices, and other products that require precise shaping and minimal material waste. This research focuses on the driver-based electromagnetic forming of Austenitic Stainless Steel (SS304) sheets using Aluminum alloy (AA6061-T6) as a driver. The analysis includes the numerical results of the magnetic field, Lorentz force, sheet deformation and velocity at four points on the sheet profile. The study also compares the numerical results to experimental measurements of the sheet profile. The study found that the numerical results were in good agreement with the experimental results.

Introduction

With development of sheet metal forming industries interest in the electromagnetic forming process is catching the interest of researchers due its unique qualities like reduced wrinkling, increased formability and reduction in tooling costs [1]. Electromagnetic forming process is high-speed sheet metal forming method which uses impulsive magnetic forces to deform the workpiece [2]**.** Due to high strain rate (10^{-3}-10^{-5}) the formability of metals increases in electromagnetic forming as compared to conventional forming process [3]. Based on coil and workpiece configuration the electromagnetic forming can broadly be divided into tube forming with a helical coil and sheet metal forming with a spiral pan cake coil. In the later configuration the electromagnetic force distribution is not even which is the biggest challenge in this kind of electromagnetic forming. [4, 5]. Several studies have been carried out in the past to accurately estimate the magnetic force and deformation in electromagnetic sheet metal forming such as Daehn et al [6], they focused on uniform force distribution of the coil on the workpiece by changing the coil geometry. A loosely coupled numerical method was developed by Oliveira et al [7] to validated free forming experimental data however due to loose coupling the excessive bounce back phenomena was observed in elliptical closed die analysis [8]. Localized uniform magnetic force technique was used by [9] to achieve uniform deformation in a workpiece. Parametric analysis was carried out by [10] to analysis the electromagnetic forming process and identify important process parameters of the process. [11, 12] introduced driver based electromagnetic forming for sheet materials with low electrical conductivity which can not directly be deformed using Lorentz force. Good results have been achieved so far using driver based sheet metal forming but the methods, shape of the driver and coil are not unique which is a major issue.[12–14]. A fully coupled numerical model for closed die electromagnetic forming was developed by [15]. The numerical model gave better results in comparison to uncoupled model at cost of slight increase in computational time.

This research study aims to develop a fully coupled numerical model using COMSOL Multiphysics to analyze the driver-based electromagnetic forming process. Stainless steel SS304 workpiece is being deformed using AA6061-T6 alloy driver. The numerical results are validated with experimental results.

Numerical Model

A 3D numerical model was developed in COMSOL Multiphysics to analysis driver based electromagnetic forming process. To calculate the transient current, the following input variables were used: input voltage (V), capacitance of the capacitor bank (C), the sum of system inductance and coil inductance (L), and resistance of the system (R). The values of these parameters are provided in Table 1. Equations 1-5 were used to calculate the transient current (I(t)), damping coefficient (β), frequency of the current (ω), magnetic flux, and current density. The Lorentz body force was determined using Eq. 6, which was then applied as a body load on AA6061-T6.The numerical model was simplified by modeling only 1/4 of the geometry to reduce mesh elements and computational time. The model consists of air domain, die domain, driver sheet domain, driven sheet domain and coil domain. Meshed model is presented in Fig. 1.

$$I(t) = \frac{U0}{\omega L} e^{-\beta t} sin\,(\omega t) \qquad \textit{(Eq. 1)}$$

$$\beta = \frac{R}{2L} \qquad \textit{(Eq. 2)}$$

$$\omega = \sqrt{\frac{1}{LC} - \beta^2} \qquad \textit{(Eq. 3)}$$

$$\nabla \mathrm{x} \vec{E} = \frac{-d\vec{B}}{dt} \qquad \textit{(Eq. 4)}$$

$$\vec{J} = \frac{\vec{I_c}}{s} = \sigma_e \vec{E} \qquad \textit{(Eq. 5)}$$

$$\rho \frac{d^2\overline{u}}{dt^2} - \Delta . \sigma s = \overline{fm} \qquad \textit{(Eq. 6)}$$

Cowper-Symond model was used for high-speed nonlinear deformation of both SS304 and AA6061-T6 sheets. The constants were taken from the work of [16]. The material properties are given in table 2.

$$\bar{\sigma} = \sigma_y \left[1 + \left(\frac{\dot{\varepsilon}}{p}\right)^m\right] \qquad \text{(Eq. 7)}$$

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Table 1 Input parameters of numerical model

Serial	Input parameters	Value (Unit)
1	Input Voltage (V)	2800 V
2	Capacitance (C)	0.006 F
3	Inductance (L)	0.5e-6 H
4	Resistance (R)	0.02 Ω

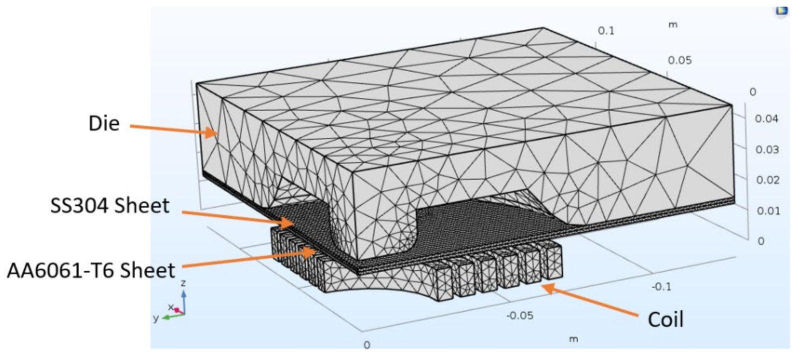


Figure 1. 3D Mesh of driver based closed die electromagnetic forming.

Table 2 Material properties of Coil, SS304 sheet and AA6061-T6 sheet

Sr	**Item/material**	**Properties**	**Parameter**	**Values**
1	Forming Coil / Copper	Resistivity	ρ	1.72e-8 m
2	Sheet / AA6061-T6	Resistivity	ρ	2.65e-8 m
		Poison's ratio	*v*	0.35
		Density	D	2980 kg/m^3
		Elastic Modulus	E	69.0 GPa
		Yield strength	σ	276MPa
3	Sheet/ SS304	Resistivity	ρ	0.72e-6 Ω.m
		Poison's ratio	*v*	0.29
		Density	D	8000 kg/m^3
		Elastic Modulus	E	200 GPa
		Yield strength	σ	300 MPa

Experimental Details

The basic experimental setup is shown in Fig. 2. The experimental setup consists of a capacitor bank the specifications are discussed in table 1. Furthermore, the setup includes power cables, spiral pan cake type copper coil with cross section of 10mm height and 5mm thickness having total diameter of 140mm and 6 number of turns, stainless steel die (SS304), 200mm x 200mm SS304 sheet blank of 0.71mm thickness and 200mm x 200mm AA6061-T6 driver sheet of 1.4mm thickness. The experiment was performed at 2800V and total energy of 23.530KJ.

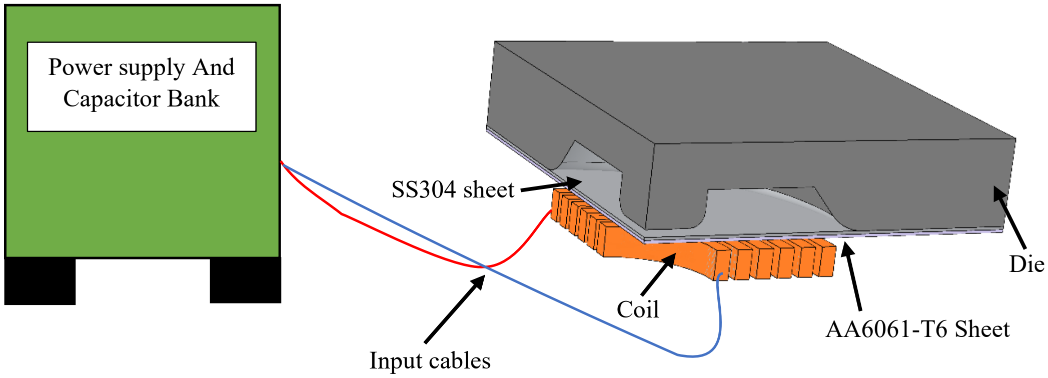


Figure 2. Electromagnetic forming setup

Results

Magnetic field :

Fig. 3 illustrates the magnetic flux density on AA6061-T6 at various time steps throughout the electroforming process. While the magnetic flux density is present until 1000 microseconds, the highest value of magnetic flux density was 4.8 T, which was observed between 50 and 100 microseconds. This suggests that the rise time of the impulse is much shorter than the fall time, which is advantageous for the electromagnetic forming process. At 200 µs the magnetic field lines and the deformation of both driver (AA6061-T6) and driven sheet can be seen in Fig. 4. It was observed that the magnetic flux due to induced current is very prominent on driver sheet which is due to its very high conductivity, however the magnetic flux in driven sheet (SS304) is almost negligible, that is because of its lower conductivity and austenitic non-magnetic characteristic. At 200 µs as evident from Fig. 4 the driver and driven sheets are still in contact while the driver sheet is forcing the driven sheet against the die.

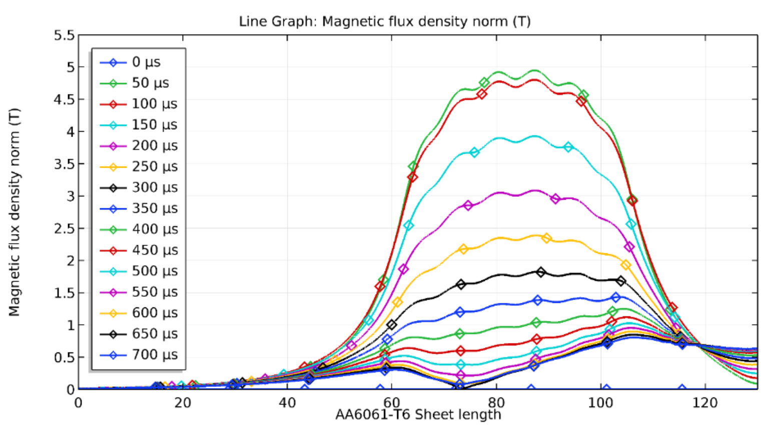


Figure 3. Magnetic flux density in AA6061-T6 sheet at various time steps during electromagnetic forming

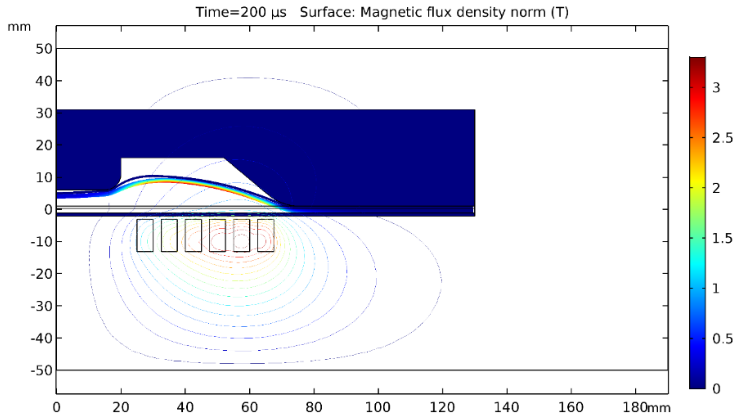


Figure 4. Magnetic flux density at 200 µs time step

Lorentz force:
Lorentz force is the repulsive magnetic force between two conducting maetrials, in this case the force was generated between the coil and driver (AA6061-T6) sheet. The Lorentz force reaches its maximum value at time step 75 µs as can be seen in Fig. 5. The Lorentz force than diminishes after 300 µs but the deformation continues till 1000 µs. The deformation after the first 300 µs is purely due to inertial forces and the duration of inertial motion is greater than the duration of motion due to impulsive magnetic force. Therefore, inertia has major contribution in electromagnetic forming. The Lorentz force originates from the area on the driver sheet which is directly above the coil. Fig. 6 presents the location where Lorentz force originates from and also gives the maximum Lorentz force value of $1.6 x 10^{10}$ N/m^3 at time step 75 µs.

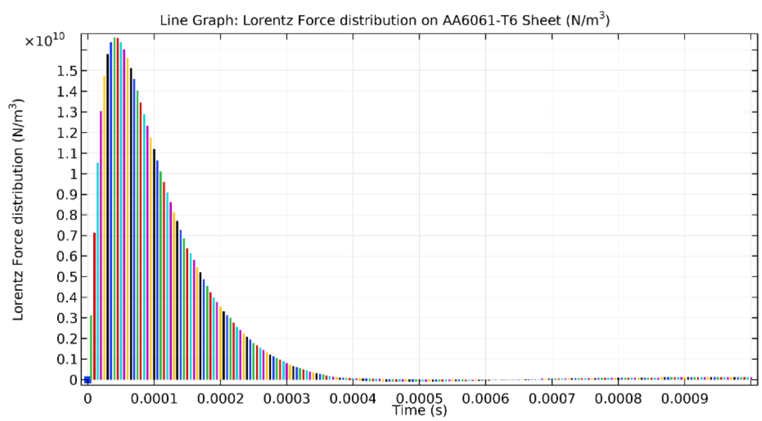


Figure 5. Lorentz force applied on AA6061-T6 on all time steps

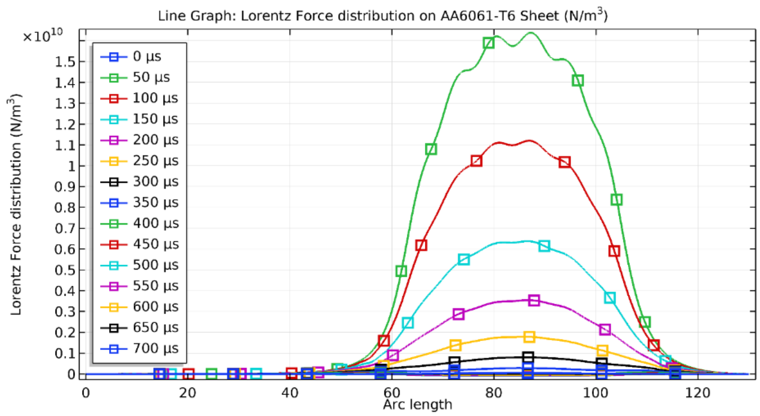


Figure 6. Lorentz force applied on length of AA6061-T6 on various time steps

Deformation:

The final deformation of the driven sheet (SS304) can be observed in Fig. 7. The highest deformation that was achieved by this sheet was 9.3 mm.The driver sheet being pushed by Lorentz force drives the driven sheet impacting it against the die. The experimental sample is shown in Fig. 8. The maximum numerical deformation and experimental deformation are compared and plotted in Fig. 9. The maximum deformation calculated numerically at peaks was 9.3 mm while the experimental results was 8.9mm which is in close approximation. The maximum error in deformation values is 4.49% which is acceptable.

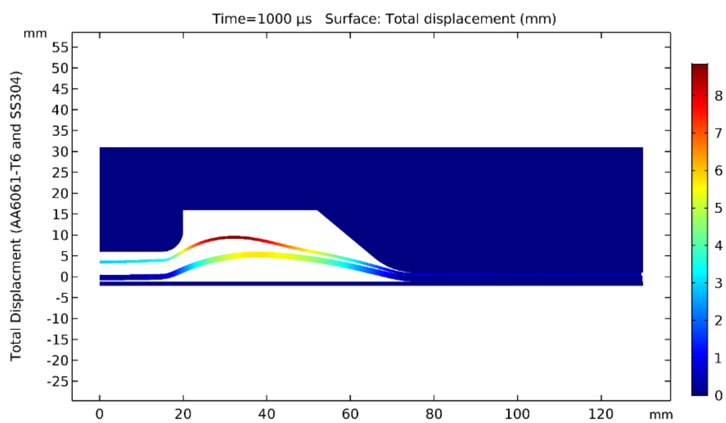
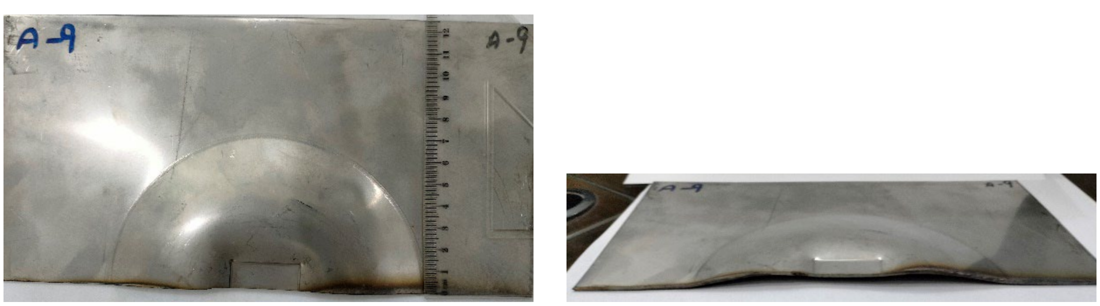


Figure 7. Numerically simulated final deformation of SS304 sheet and AA6061-T6 driver sheet



(a) (b)

Figure 8. (a) Experimentally deformed driver sheet (SS304) (b) Cross section of driver sheet

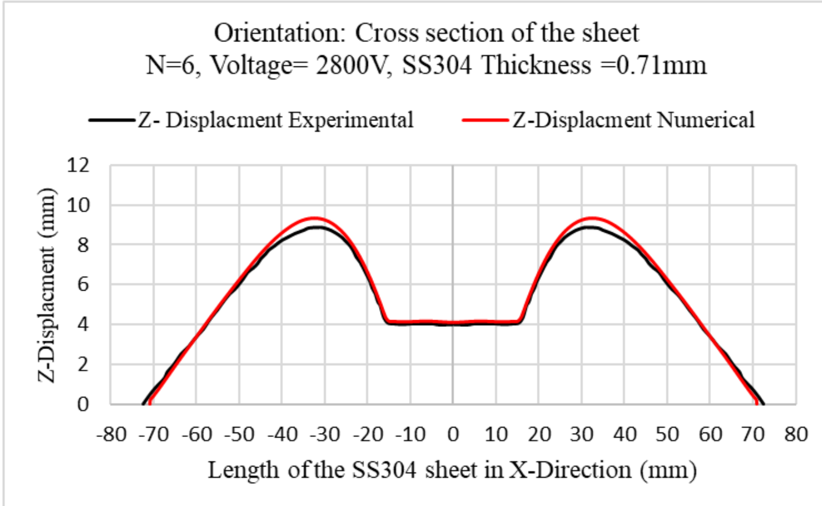


Figure 9. Comparison of numerically estimated deformation and experimental deformation of SS304 in Z-direction

Conclusion

- Driver based electromagnetic forming of material with low conductivity can be approximated and best initial conditions can be achieved using the numerical model instead of iterative experimentation saving time and resources.
- Magnetic flux density and magnetic field lines estimated by the numerical model clearly illustrates the current being induced in the driver sheet.
- The research found that the Lorentz force only plays a role in one-third of the electromagnetic forming process, while the remaining two-thirds of the deformation is caused by the inertial forces generated by the impulsive force.
- The numerical simulations were found to closely match the experimental results, with an error of only 4.49%. The error can be reduced by careful measurement and reducing approximations in the model.
- The driven sheet deformation can be enhanced if the driver sheet remains free between the driven sheet and the coil instead of fixing it at ends.

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