

Investigation of the Effects of the Coil Design on Electro-Magnetic Forming of a Thin-Walled Aluminum Tubular Material

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Abstract

*In this study, a thin-walled aluminum tube was expanded using the **electro-magnetic forming (EMF)** process. Two different designs of coil were developed using EMF simulations with LS-DYNA's electromagnetic module in version 980. The initial thickness of the aluminum tube was 0.254 mm (0.01 in.) and the material of the tube was Aluminum 3000 (Al-3000). This aluminum material is known to be difficult to expand more than a 9% expansion ratio at a given thickness. To evaluate the performance of the coil to expand the tube without failures, two different coils were designed and manufactured to have two different gaps between the coil and the workpiece. Preliminary simulations were conducted to determine the baseline design of the coil and after some preliminary EMF tests, the coil design was changed. Tubular samples were tested with two different coils and two different die sets (e.g., 10 and 12% expansion ratios). The EMF process was numerically modeled with LS-DYNA and the simulation results were compared with experiments.*

1- Introduction

Electro-magnetic forming (EMF) is a high-speed forming process using the magnetic repulsion between two opposing magnetic fields to form sheet metal. The energy stored in a capacitor bank is discharged very rapidly, normally within 20 ms, through a magnetic coil. The magnetic field produced by the coil crosses the workpiece, generating eddy currents in the workpiece. This current produces its own magnetic field. These two opposing magnetic fields at the coil and workpiece induce a repulsion force between the coil and the workpiece. The theory behind this repulsion is well explained by Lenz's law.

The higher the electrical conductivity of the workpiece, the higher the magnetic force. No special magnetic properties are required for the metal workpiece. EMF does not need any forming press and only the capacitor bank and the tooling are needed. The conventional forming punch is replaced by a magnetic coil and the workpiece is driven into the die by its own inertia. The tooling consists of the coil and the solid die as shown in Figure 1. In EMF, die wear is expected to be minimal due to a minimal contact interface between the part and die during EMF process.

The EMF can be applied for swaging of thin-walled tubes over rods, cables, plugs, and bulging and flaring tubes. Flat pancake-type coils are also used for forming or embossing shallow drawing of thin sheet metal parts such as heat exchanger or fuel cell components.

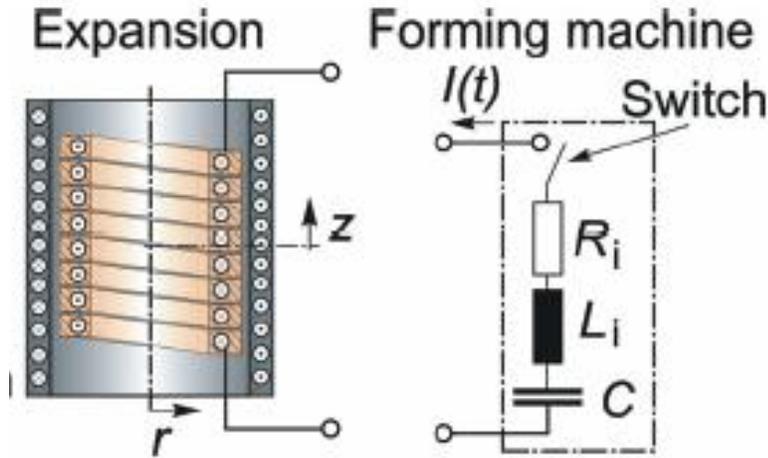


Figure 1 Basic Concept of EMF for Tube expansion.

2- State of the Art

Electromagnetic forming of tubular parts can be achieved in two configurations, compression or expansion. Electromagnetic tube compression is frequently used for joining of tubular workpiece. Electromagnetic tube expansion is usually applied to expand hollow workpiece to a mold [2]. Some researchers also leverage electromagnetic tube expansion to study material characteristics in high strain rate. The forming limits of aluminum alloys at high velocity and high strain rate have been investigated by [3], using electromagnetic tube expansion. Johnson identified the high-strain-rate constitutive properties for ductile materials with electromagnetic ring expansion [4].

To investigate the effects of working conditions, Zhang et al. carried out analytical and experimental studies on electromagnetic tube expansion [5]. They found that the system capacitance should not be too small or too large to get the maximum expansion. Gourdin used the principle of virtual work to estimate the electromagnetic forces with measured electrical currents to analyze electromagnetic tube expansion process [6] while Al-Hassani developed an analytical approach to calculate the workpiece current [7]. Recently, an electromagnetism module has been developed in LS-DYNA [8],[9] in order to accurately simulate electromagnetic forming. Henchi et al. applied this module to simulate electromagnetic ring expansions [10]. The numerical results agreed well with the experimental ones.

3- Objective

The coil design is crucial for a good coupling with the generator and forming the part at high speed without defects. The primary objective of this study is to design and build the coil for EMF to successfully expand tubular materials without failures. The following particular objectives should be accomplished:

- Develop EMF process modeling and simulation technique using a commercial FEM code (LS-DYNA) for industry uses.
- Develop reliable EMF test tools for tube expansion.
- Determine the EMF process parameters for expanding tubes without failures.
- Validate the EMF simulation model by comparisons with experiments.

4- Approach

In this study, different coil designs were studied to expand thin-walled aluminum tubes using EMF. The initial thickness of aluminum tube was 0.254 mm (0.01 in.) and the material of tube was Aluminum 3000 (Al-3000). This aluminum material is known to be difficult to expand more than a 9% expansion ratio at a given thickness. To evaluate the performance of coils to expand tubes without failures, two different coils were designed and manufactured in order to have two different gaps between the coil and the workpiece. Preliminary FEM simulations were conducted to determine the baseline design of the coils and after preliminary EMF tests, the coil design was changed. Tubular samples were tested with two different coils and two different die sets (e.g., 10 and 12% expansion ratios). The EMF process was numerically modeled using a commercial FEM code, LS-DYNA. A newly developed electromagnetism module, available in version 980 was used for process simulations and the simulation results were compared with experiments.

5- Experimental Results

The experimental setup was prepared with a 5-kJ capacitor bank machine. During the EMF testing, the inside cavity of tooling should be kept in a vacuum condition by using an air pump connected to the tooling through a hose as shown in Figure 2. Without proper vacuum, the EMF results in severe wrinkling and tearing in the workpiece. This is caused by pulsating the trapped air with high-pressure during EMF.

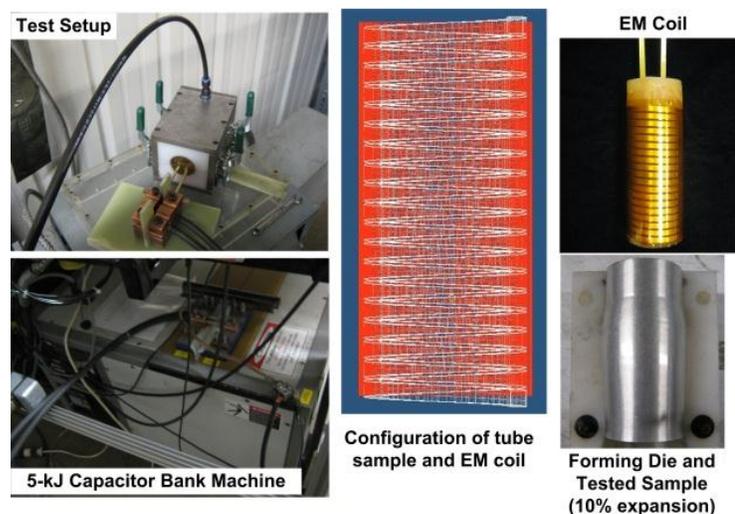


Figure 2 EMF Testing Setup and Configuration of the Tube and Coil

A spiral-type coil was designed with 19-turn windings that are 119.3-mm long to cover the 114.3-mm-long tube. Two coils were manufactured to have different gaps between the coil

and the workpiece. The coil designs are given in Figure 3. The original gap between coil and workpiece was determined as 0.18 mm to obtain the maximum expansion of the workpiece. A small gap reduces the mutual inductance between the coil and the workpiece, thus allowing a better coupling between the electrical generator and the EMF. However, from the preliminary testing, this tolerance turned out to be too tight and showed visible straining on the expanded tube surface, because of too intensive magnetic pulse pressure on the thin-walled tube. Reducing the applied voltage reduced the surface straining of workpiece, while the full expansion was not obtained. Therefore, a 0.38-mm gap coil was designed through FEM simulations and iterative EMF testing workpieces without a die by gradually increasing the voltage. This allowed finding the desirable gap between the coil and the workpiece to obtain the full 10% expansion without surface straining. Detailed dimensions of both coils are given in Figure 3. In EMF testing with the second coil, no straining was found on the surface of the fully expanded tube at 10%.

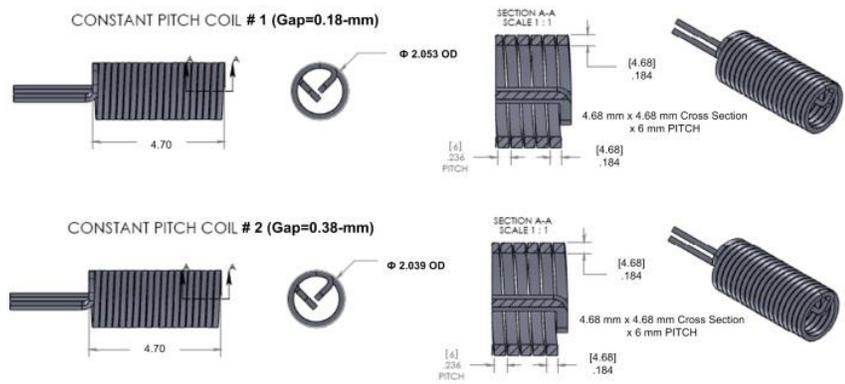


Figure 3 Coil designs

The test conditions with the two different coils are summarized in Table 1. Most of the tests were conducted with a 10% expansion die at various voltage inputs. Several experiments showed improper vacuum conditions and electric arcing occurred three times due to the damaged dielectric insulation Kapton tape between the coil and the workpiece.

The AT 1 coil showed only one successful result while the other trials resulted in failures of vacuum or die-underfill of workpiece. Because this design has very tight gap between the coil and the workpiece, it was difficult to obtain the consistent test results due to the excessive magnetic field pressure at the coil-workpiece interface. With AT 2 coil at both 5.028 and 5.308 kV, the full expansions were obtained without any failure in 10% expansion. However, both coils were not successful to expand the workpiece with a 12% expansion die. At 5.028 kV, the workpiece showed the material underfill with 12% expansion die, while the workpiece showed cracking as the voltage was increased up to 5.308 kV.

Table 1 Testing Conditions of EMF

Coil Type	Tube Material	Exp. Ratios (%)	Voltages (kV)
AT 1 (0.18-mm gap)	Al-3000 ($t_0=0.2$ -mm)	10 and 12	4.577 / 4.735 / 5.028 / 5.308
AT 2 (0.38-mm gap)			

6- EMF Simulation Results

A new Electromagnetism (EM) module has been introduced in LS-DYNA [8], [9]. This module allows solving the Maxwell equations in the eddy current (induction-diffusion) approximation. This is suitable for cases where the propagation of the electromagnetic waves in the air (or vacuum) can be considered as instantaneous, like in EMF cases. The EM fields are solved using a finite-element method (FEM) in the conductors and a boundary-element method (BEM) for the surrounding air/insulators. Therefore, no mesh is necessary for the air and the motion of the conductors can be easily handled. The EM module allows the introduction of a source electrical current into solid conductors and to compute the associated magnetic field, electric field as well as induced currents.

It is coupled with the mechanical solver, the Lorentz forces being added to the mechanics equations of motion as well as with the thermal one, the ohmic heating being added to the thermal solver as an extra source of heat.

The EM solver can be coupled to different current or voltage sources and in particular to an external (R,L,C) circuit where the user provides the resistance (R), inductance (L), and capacitance (C), and initial charging voltage (V0) of the capacitor bank. The electrical parameters (e.g. resistance, inductance, mutual inductances) for the coil and workpiece are concurrently calculated during the simulations taking into account the electrical properties and geometry of the coil and deforming workpiece. Figure 4 illustrates the simulation zone for the EMF process.

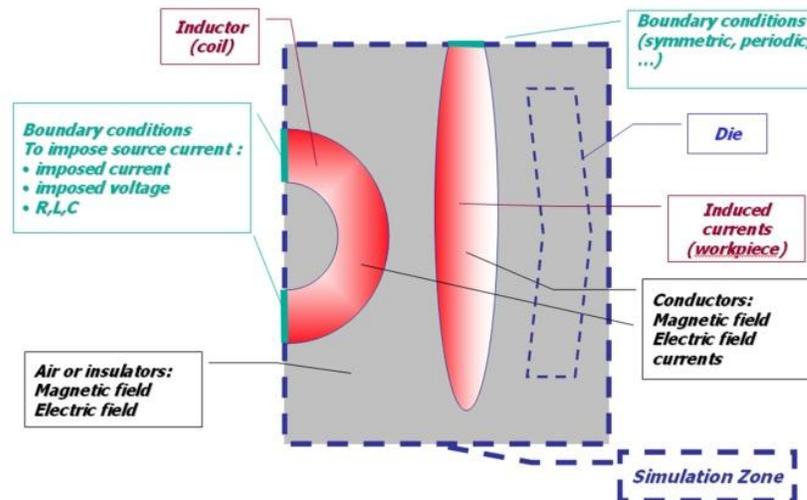


Figure 4 Schematic of the LS-DYNA Simulation Zone for the EMF

Due to the presence of full systems in the BEM part of the EM solver, the cost of an EMF simulation is relatively expensive compared to conventional forming simulation only based on FEM. A full-coupled EMF simulation for this project-mattered geometry requires about 16-18 hr using four CPUs while the mechanical forming simulation with the pressure boundary condition requires less than 10 min using one CPU. These simulations with multi-turn coils are particularly CPU expensive since the BEM mesh (the surface of the conductors) is very large. A new option

allowing uniform currents in a cylindrical geometry [9],[11], could be used instead to minimize the CPU.

Any heat generation from plasticity and friction was not considered for calculation in the simulation, assuming that the thermal effect of deformation on flow stress is negligible.

The material constitutive model for Al-3000 workpiece was defined as the elasto-plastic object for simulations by using the Hollomon model as described in ($\bar{\sigma} = K \cdot \bar{\epsilon}^n$), while the die and coil were defined the elastic object. The detailed material parameters for Al-3000 workpiece are given in Table 2.

The strain-rate hardening effect was not considered in the simulations, because this material is known to be less sensitive to strain-rate hardening from literature. The RLC-circuit parameters of the 5-kJ capacitor machine at American Trim are summarized in Table 3. All the EMF simulations were conducted at EWI using LS-DYNA.

Table 2 Material Parameters of Al-3000

	Elastic Modulus (GPa)	Poisson Ratio	Strength Coefficient (K) (MPa)	Hardening Exponent (n)	Yield Strength (MPa)
Values	70	0.33	370	0.1	200

Table 3 RLC Circuit Parameters of 5-kJ Capacitor Bank Machine at American Trim

	Resistance (R) (mΩ)	Inductance (L) (μH)	Capacitance (C) (μF)	Input Voltave (V ₀) (kV)
Values	11	0.211	138	4.57, 4.73, 5.02, 5.30

Figure 5 illustrates the configuration of tooling and workpiece in EMF process. As shown in this figure, the coil was inserted to the tube and a uniform clearance was kept between the coil and the tube, because a dielectric coating was applied on the coil and machined for uniform thickness in the radial direction.

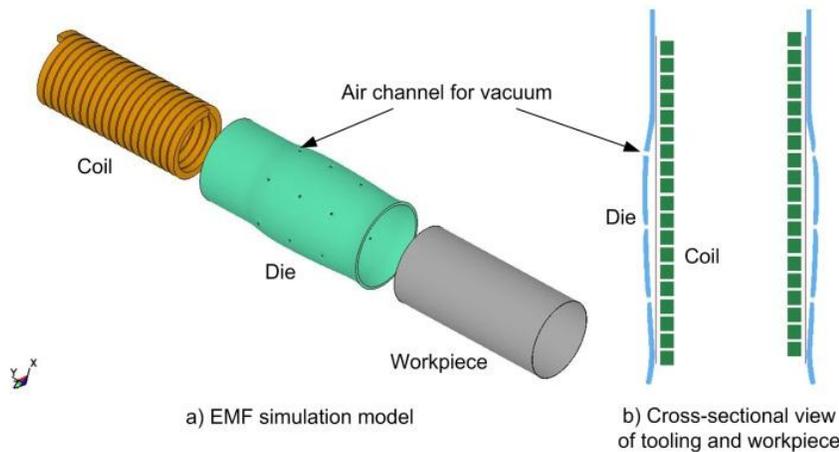


Figure 5 LS-DYNA Simulation Model and the Configuration of Tooling and Workpiece for EMF

The initial voltage V_0 measured in experiments were input to EMF simulations as well as the (R,LC) parameters of the generator. The numerical current in the coil was then compared to the experimental one and Figure 6 shows the good agreement. As the voltage increased, the magnetic pressure increased. Slightly larger workpiece expansion was predicted by the simulation models than observed in the experiments. **Fehler! Verweisquelle konnte nicht gefunden werden.** Figure 6 compares the expansion ratio of the finally formed workpiece at different voltage inputs. The simulation model predicted the full expansion of the workpiece as the maximum expansion ratio to be 10.32% at 5.308 kV.

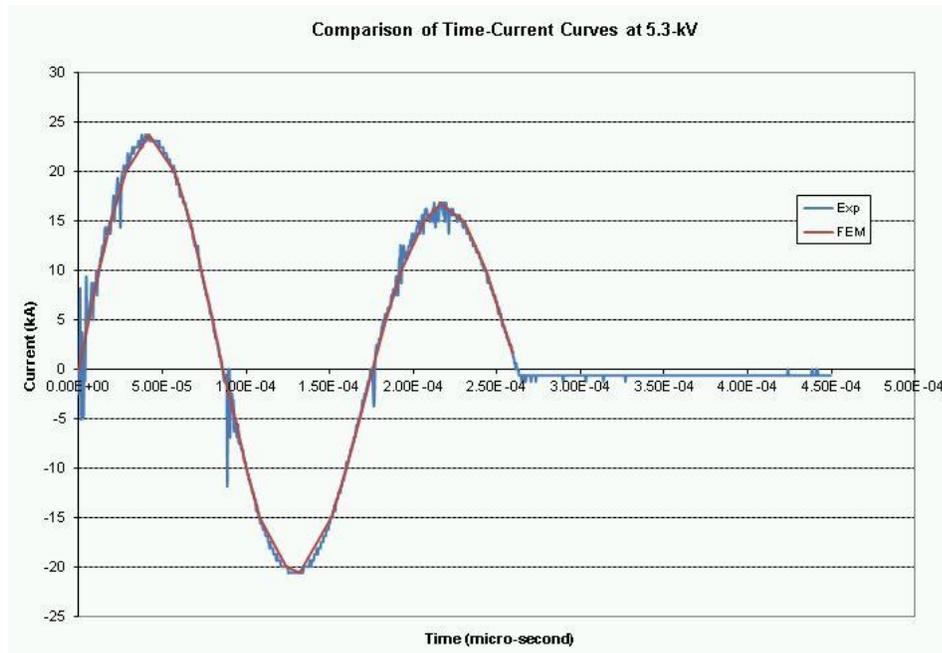


Figure 6 Comparison for the current in the coil between the numerical results (in Red) and the experimental results (in Blue)

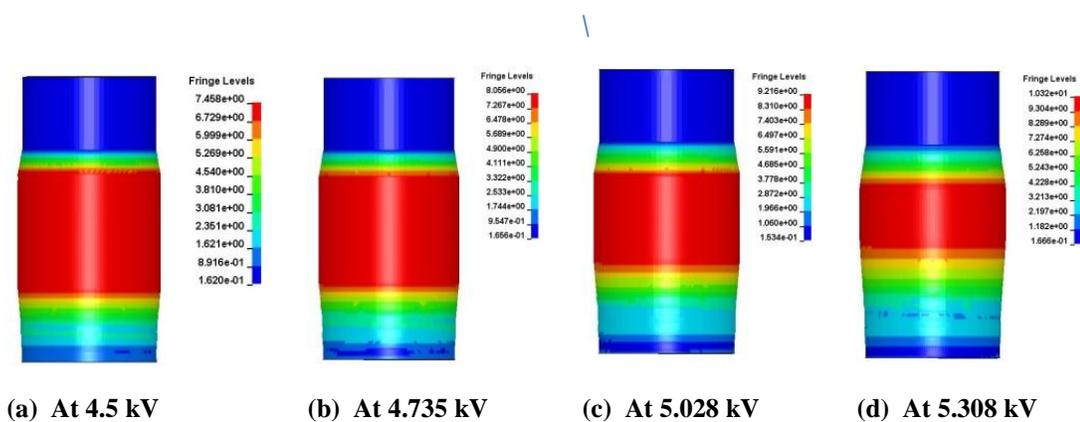


Figure 7 LS-DYNA Predictions of Final Expansion Ratios for Different Values of Applied Voltage (in percentages)

The experimental and simulation results of the maximum expansion ratio are compared for different voltage inputs in Figure 8. The measurement of the maximum diameter for the

tested tubes was manually conducted by using a digital caliper. The error between two data sets is in a range of 0.19~0.82%. Simulation results showed reasonable correlations with the experiments.

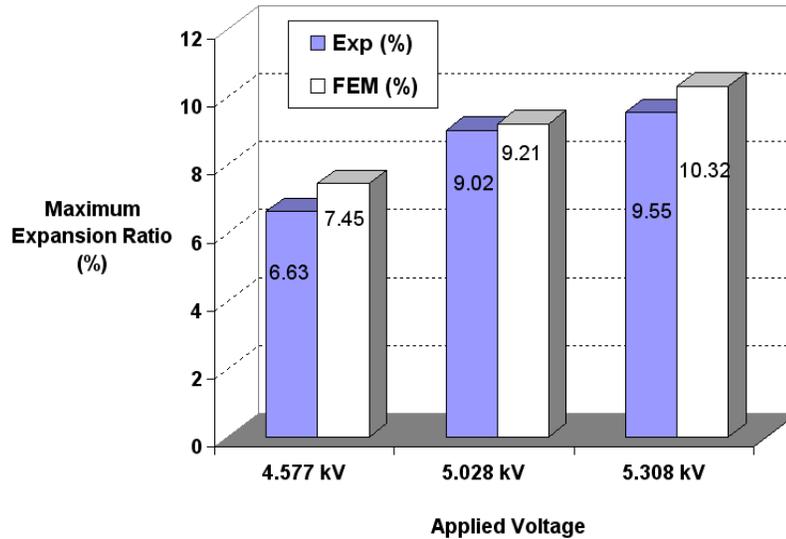


Figure 8 Comparison of the Maximum Expansion Ratio (%) between Experiments and Simulation

The von Mises stress of the workpiece was predicted by the simulation model. As shown in Figure 9, the maximum stress was predicted at the maximum expansion area and the value was predicted to reach 310 MPa at 5.30 kV.

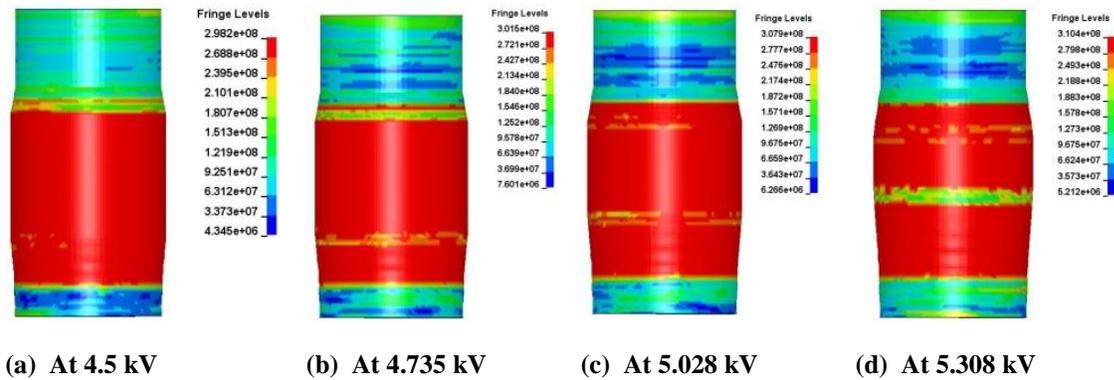


Figure 9 LS-DYNA Predictions of Stress Contours for Different Values of Applied Voltage

From simulation results at 5.30 kV, an interesting result of a stress drop at the middle of the workpiece was predicted. This might be caused by the bouncing back of the material after its impact on the die surface. This phenomenon is more clearly shown in Figure 10. As the voltage increases from 5.02 to 5.30 kV, the lower section of the thin-walled tube at 5.3 kV showed more bouncing back after the mid-section of workpiece impacted the die surface.

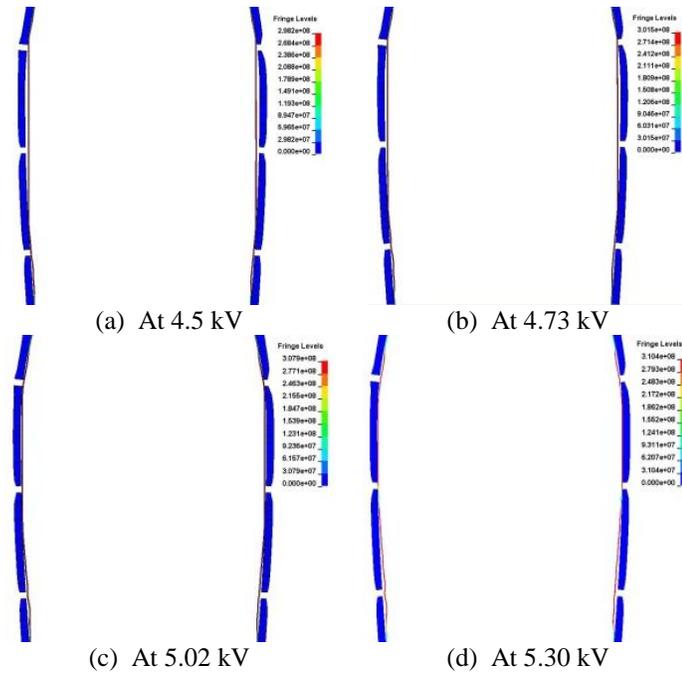


Figure 10 LS-DYNA Predictions of the Die-Filling of Tubular Material for Different Voltages

The velocity of the deforming material was difficult to measure in the experiments because the workpiece was entirely encapsulated by the die. However, considering the expected velocities of the deforming tube in EMF in a range of 100~300 m/s, the simulation predicted result of the maximum velocity as 256 m/s as shown in Figure 11 is reasonable.

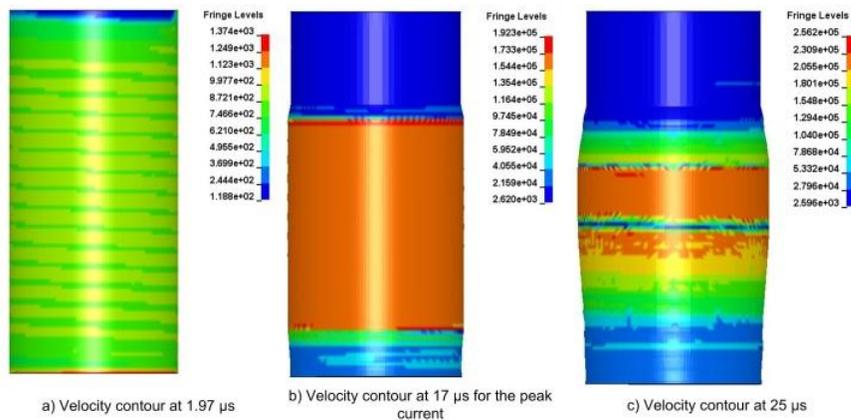


Figure 11 LS-DYNA Prediction of the Change of Deformation Speed of the Workpiece at 5.30 kV (Unit is mm/sec).

The final thinning distribution of the workpiece was compared between simulations and experiments. Eight different points were selected to compare the thinning as shown in Figure 12.

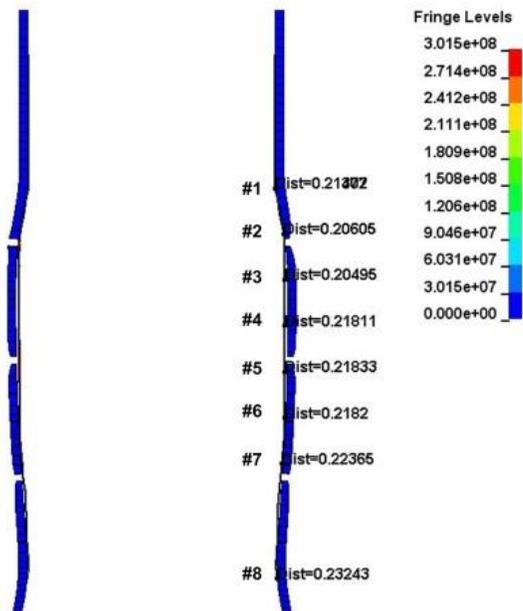


Figure 12 Locations of Thinning Comparison.

The thinning distribution was compared for different voltage levels in Figure 13. The simulation result at 4.577 kV showed a very good correlation with the experiment. However, as the voltage level increased, the EMF simulation model gave some under predictions of thinning up to 40 μm, although the overall trends of thinning are comparable between simulation and experimental results. This level of error would be reduced by increasing the number of elements through the wall thickness of the model. But this would significantly increase the computation cost.

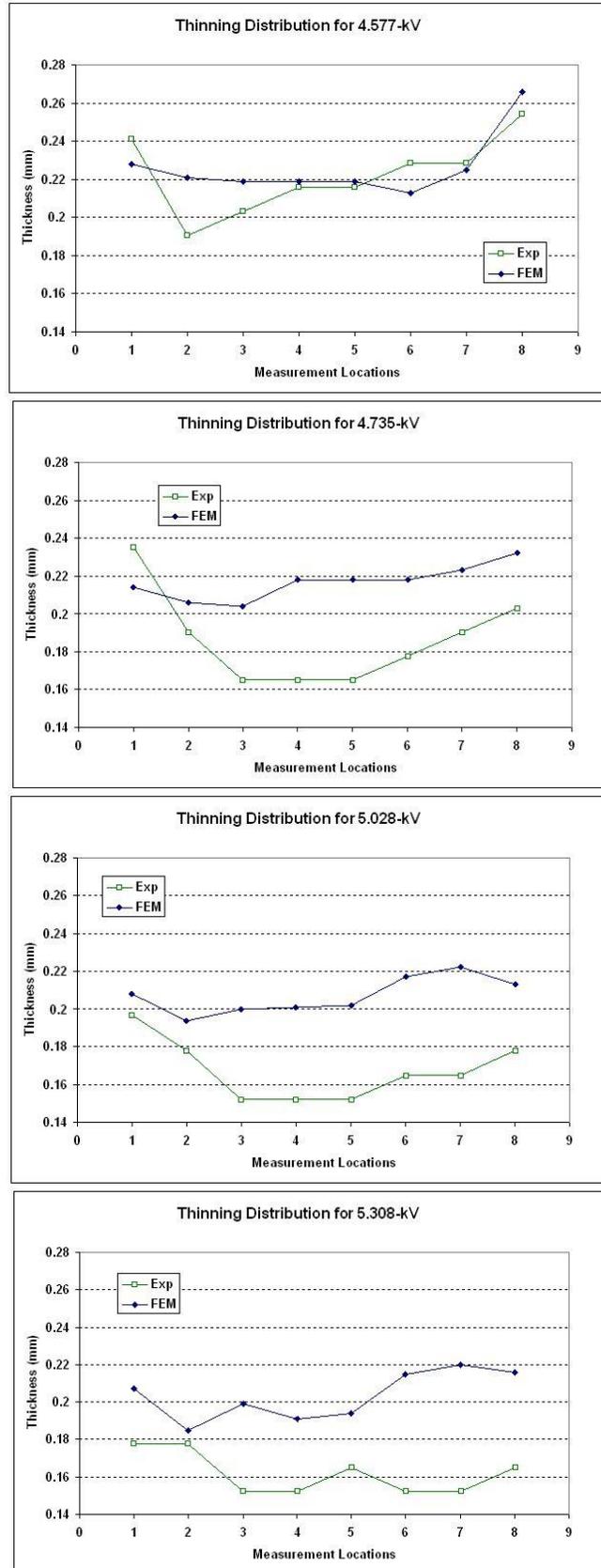


Figure 13 Comparison of Thinning Distributions between Experimental and Simulation Results

7- Findings

The following findings can be summarized from this study:

- The EMF process showed the improvement of formability of Al-3000 up to 10% expansion.
- Full expansion of the workpiece with the 10% expansion die was achieved at 5.307-kV input voltage.
- 12% expansion was not successful with both coils.
- The AT 2 coil (0.38-mm gap) showed better performance than the AT 1 coil (0.18-mm gap) in terms of the maximum expansion without failures.

8-Conclusion

The following conclusions can be drawn from this study:

- The EMF simulation model was developed and it turned out to be a very useful tool to design the coil and EMF process parameters. We expect to use the developed EMF simulation tool and knowhow for future applications of EMF and joining processes.
- It is important to understand and compensate the dynamic of the bouncing effect of the deforming material. Considering that the maximum forming speed is very high, up to 250 m/s, the impact energy of deforming thin aluminum material should be controlled not to exceed the critical level that results in more bouncing back and tearing in some cases.
- As a future project, it would be desirable to develop the database to relate the coil design parameters (i.e., material type, cross-sectional area/shape, the pitch between windings, and the gap between the coil and workpiece) and the performance of coil to form the workpiece.

9-Acknowledgement

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