# Numerical Simulation and Experimental Study of Electromagnetic Forming

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## Abstract

*Compared to traditional sheet metal forming, electromagnetic forming (EMF) has several advantages, such as increased formability, cost savings and improved flexibility. There are many EMF applications in sheet meal forming, especially for aluminum alloys, because aluminum alloys have relatively low formability and high conductivity when compared to steel. The EMF process uses magnetic field generated by a conductive actuator upon large capacitor discharge to accelerate workpiece to high velocity. It is a complex coupled mechanical-thermal-electromagnetic phenomenon, which makes it difficult to numerically simulate. However, to save time and cost, numerical simulation is needed to accurately predict results of EMF.*

*The Electromagnetism (EM) module of LS-DYNA® has been developed by LSTC, which can be used for numerical simulation of EMF. American Trim has applied this module to assist in its EMF designs. In this paper, to access the capability of EM module, the numerical and experimental results of sheet metal formed with EMF were compared. The experiment was to apply EMF for straight-edge flanging of Al 6061-T6 sheet. Then this flanging process was modeled using both SMP and MPP version of LS-DYNA EM module. The comparison between the final shapes of flanged samples and the numerical simulation showed the good correlation between experimental and numerical results, which indicates the good predictive ability of the LS-DYNA EM module for EMF.*

## Introduction

Electromagnetic forming (EMF) is characterized by very high forming velocity and deformation strain rates, which makes it fundamentally different from traditional sheet metal forming. At sufficiently high velocities and/or strain rates, stretching limits are not bounded by the restrictions of a traditional Forming Limit Diagram (FLD). Instead, ductility far beyond typical quasi-static forming limits can be achieved [1-3]. Therefore, EMF has the potential to improve material formability, and thus also to expand the range of candidate materials for a particular application. In addition, only single-sided tooling is required in EMF, as opposed to a precisely machined matched punch and die set in conventional stamping. Single-sided tooling reduces tooling cost and complexity of forming systems, and also eliminates tedious alignment requirement in conventional stamping.

Above advantages of EMF makes it attractive to form metal sheets, especially aluminum alloys due to their low formability and high electrical conductivity. But it is difficult to design and predict EMF process due to its complexity. During EMF, a large electric current pulse passes through a conductive coil by discharging a capacitor bank. The current pulse produces a transient magnetic field around the coil that induces eddy currents in a nearby metal workpiece. The mutually repulsive force between the stationary coil and the metal workpiece causes the metal workpiece to be accelerated toward, and to impact upon, a nearby die surface at very high velocity. Figure 1 is a schematic diagram of the basic EMF. It is impossible to accurately predict this complex process by analytical calculations due to the transient electromagnetic forces, large deformation and high strain rate.

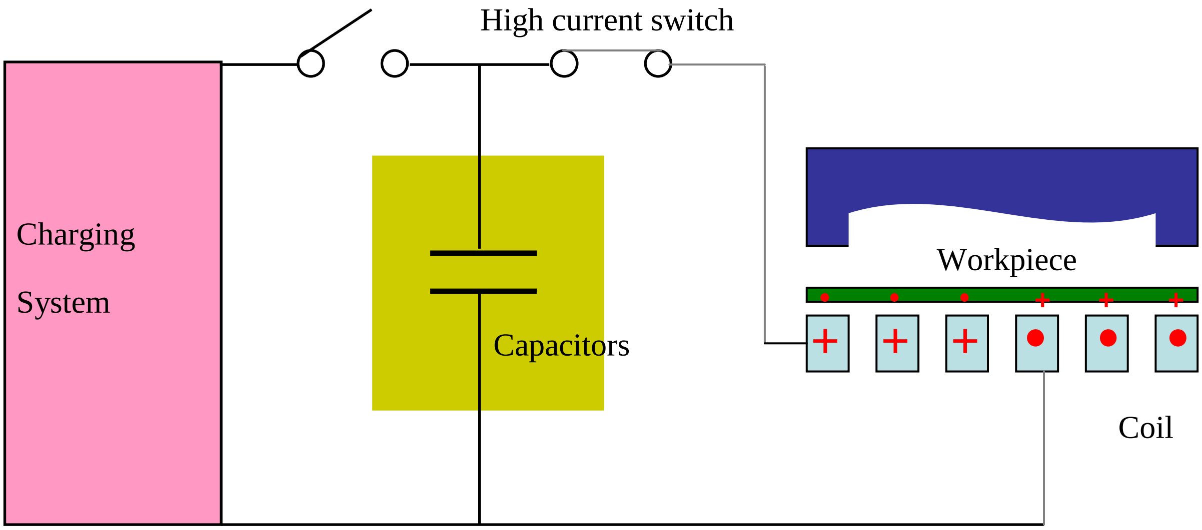


Figure 1. Basic layout of electromagnetic forming

To save time and cost, numerical simulation is highly needed to accurately predict the results of EMF and help the design of the process. EMF is a coupled mechanical-thermal-electromagnetic phenomenon, which means the electromagnetic, thermal and mechanical fields should be solved simultaneously. This is difficult to achieve for the commercially available codes.

Recently Livermore Software Technology Corporation (LSTC) has developed LS-DYNA® electromagnetism module, which can be applied to solve the 3D coupled mechanical-thermal-electromagnetic process. To evaluate the capability of this electromagnetism module, a simple experiment was carried out to use EMF to flange Al 6061-T6 sheet. And the LS-DYNA electromagnetism module was applied to simulate the flanging process. This paper will present the experimental procedure, numerical simulation and the comparison between the experimental and numerical simulation results.

## Experimental Procedure and Results

Flanging is a forming operation to bend a narrow strip at the edge of a metal sheet along a straight or curve line. It is relatively simple to carry out and simulate, comparing to other sheet metal forming processes. And the coupled mechanical-thermal-electromagnetic phenomenon still occurs in this process, when EMF is applied to bend metal sheets. In this paper, a straight-edge flanging of aluminum alloy sheet was carried out for experimental and numerical simulation study.

The capacitor bank used in this study was 18 kJ Elmag machine. And the single-turn coil was made of Cu and connected to the capacitor bank to generate electromagnetic forces for flanging, shown in Figure 2. The coil was covered with Kapton tape for insulation purpose. The material used was Al 6061-T6 with 0.8mm thickness. The size of the Al samples was 50mm x 50mm. During the flanging, the Al sheet was positioned between the coil and a solid block made of G10 Garolite. The G10 block was clamped by a hydraulic press to hold the rest area of the Al sheet. The flanging height was 10mm. Figure 3 shows the experiment setup.

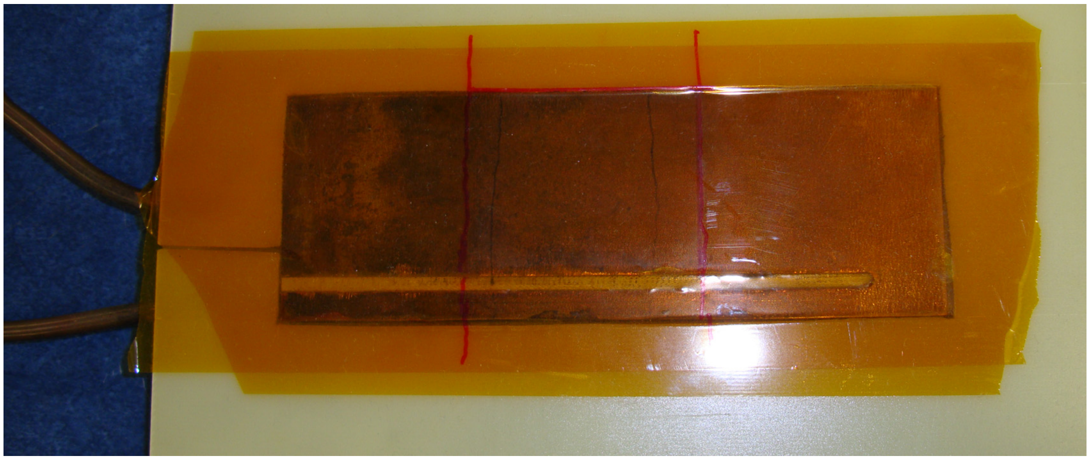

Figure 2. Photo of the single-turn coil used in experiments

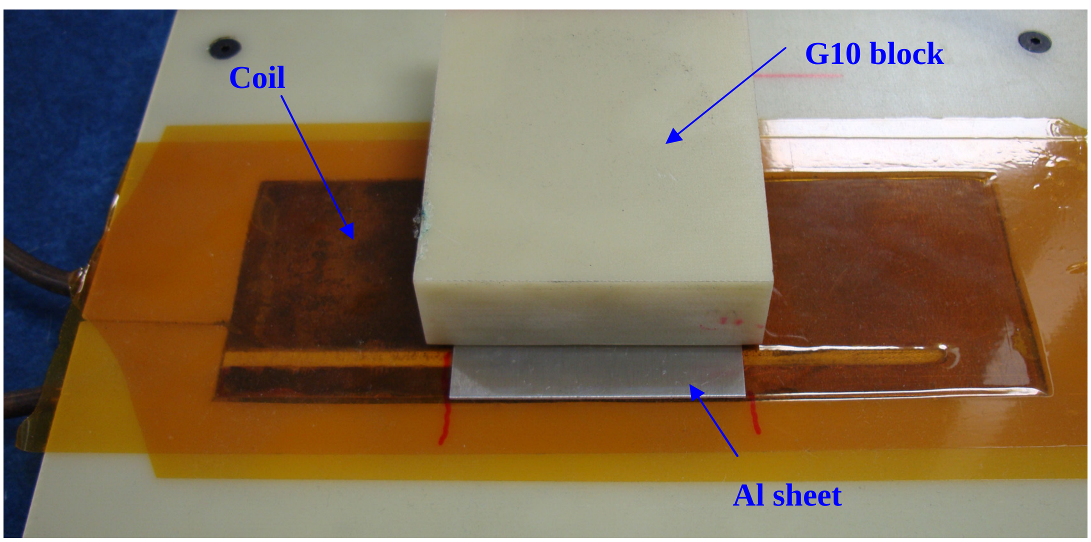


Figure 3. Photo of experiment setup

In this study, different energy inputs were applied to bend the Al sheets. It was found that the Al sheet was bent to 90 degree by 3.6 kJ energy input and 64.5 degree by 2.7 kJ energy input. In the 2.7 kJ case, a Rogowski coil was used to measure the electric current in the single-turn coil. Figure 4 shows the flanged Al sheet in 2.7 kJ case and Figure 5 shows the measured current trace in the coil.

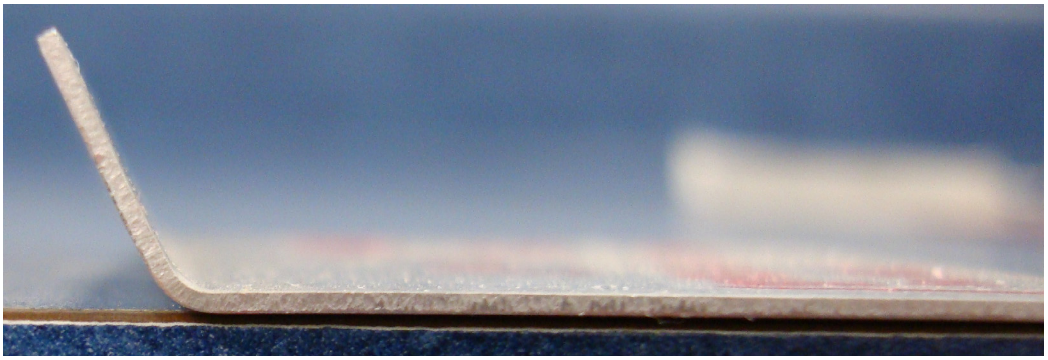

Figure 4. Photo of flanged Al sheet in 2.7 kJ case (the bent angle: 64.5 degree)

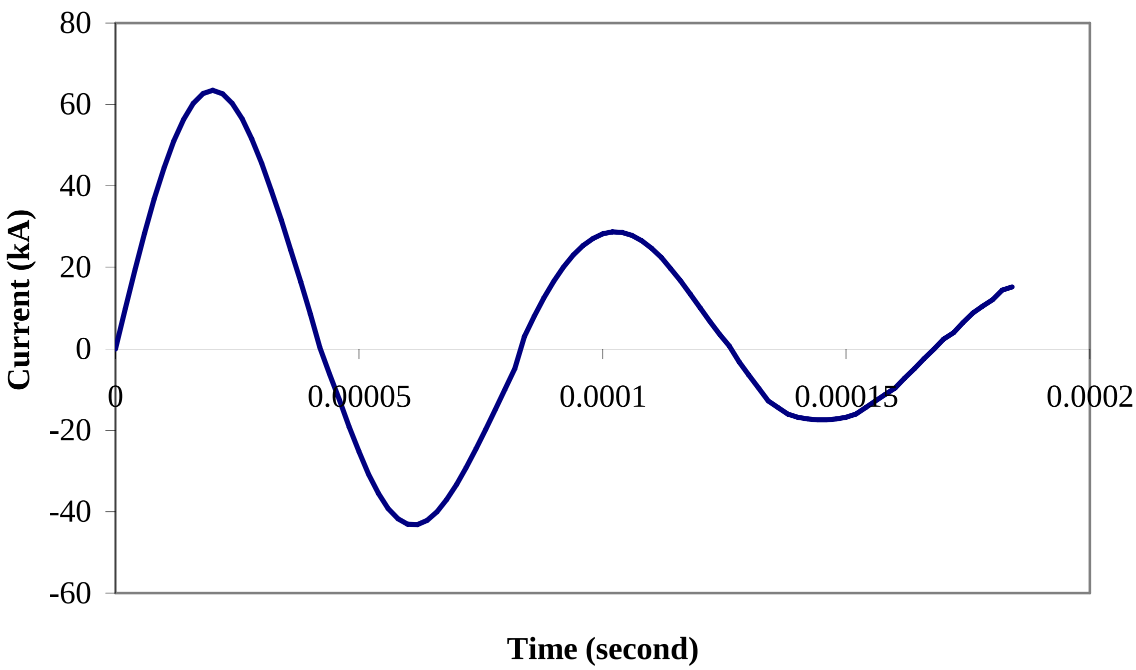


Figure 5. Current trace in the coil in 2.7 kJ case

## Numerical Simulation

The numerical simulation was performed using the LS-DYNA electromagnetism module available in the “beta” 980 version. In this module, Finite Element Method (FEM) is coupled with Boundary Element Method (BEM) to compute magnetic field, electric field and induced current by solving Maxwell equations in eddy-current approximation. FEM is applied to solve Maxwell equations for the solid conductors and BEM is used for the surrounding air. The detailed introduction of this module can be found in other paper [4].

The 3D simulation model of the flanging was built for LS-DYNA, shown in Figure 6. There are three parts: the Cu single-turn coil, the Al 6061-T6 sheet and the G10 holder. The coil and the Al sheet were modeled using eight node hexagonal solid elements, which are required for the solid conductors in electromagnetism module. The area of the Al sheet under the G10 holder had the coarser meshing than the flanging area, since this area didn't have plastic deformation at all during the flanging and coarser meshing could save computing time. The G10 holder was modeled as rigid body with shell elements since G10 Garolite didn't have plastic deformation during the flanging and is nonconductive material.

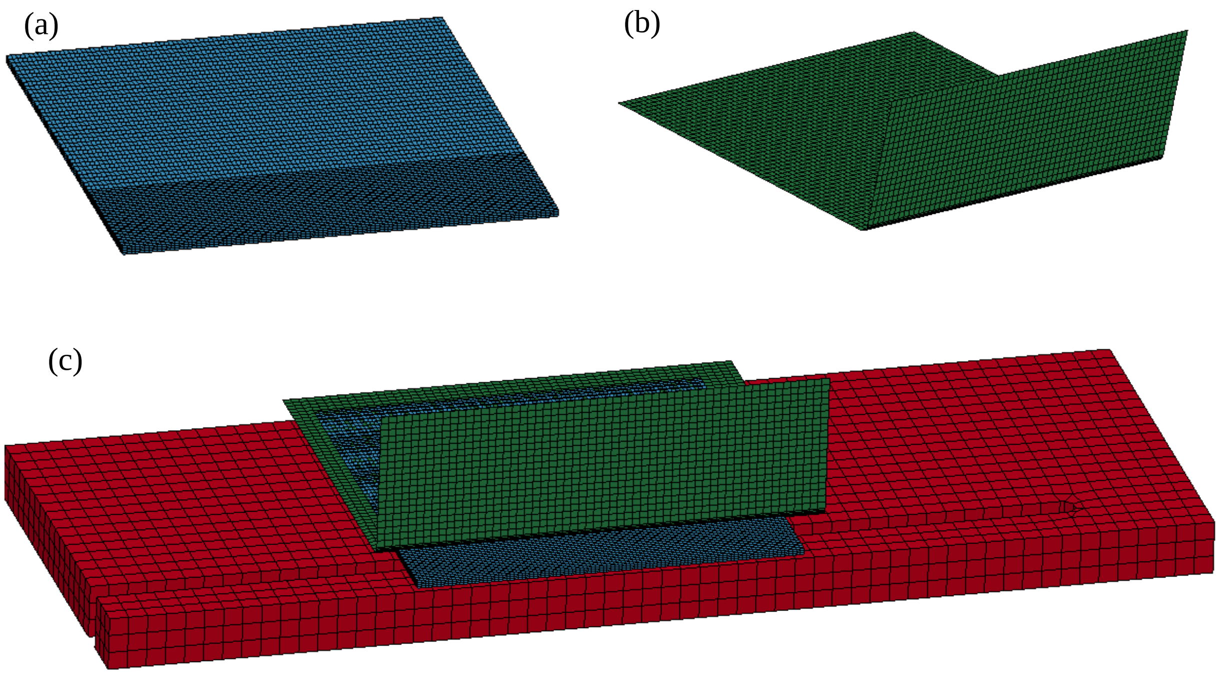


Figure 6. Meshed model of flanging (a) meshed Al sheet; (b) meshed G10 holder; (c) meshed assembly

Since this flanging process involves high strain rate and large deformation, Cu and Al 6061-T6 were modeled using Johnson-cook strength model, which has the following form [5]:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon})[1 - (\frac{T - T_{room}}{T_m - T_{room}})^m]$$

Table 1 shows the Johnson-cook strength model parameters for Al 6061-T6 and Cu. The G10 Garolite was modeled as elastic material. Table 2 lists the material properties of Al 6061-T6 and Cu. The measured current trace in Figure 5 was set as the input for the simulation. Due to the long computing time, the ending time of the simulation was set as 186μs to save time.

Table 1. Johnson-cook strength model parameters [6, 7]

| Material | A (MPa) | B (MPa) | C | n | m | $T_m$ (K) |
|---|---|---|---|---|---|---|
| Al 6061-T6 | 324 | 114 | 0.002 | 0.42 | 1.34 | 925 |
| Cu | 90 | 292 | 0.025 | 0.31 | 1.09 | 1356 |

Table 2. Material properties of Al 6061-T6 and Cu [8]

| Property | Al 6061-T6 | Cu |
|---|---|---|
| Electrical Conductivity ($10^6$ / Ω mm) | 0.025 | 0.058 |
| Mass Density (g/mm$^3$) | 0.0027 | 0.00894 |
| Young's Modulus (GPa) | 68.9 | 115 |
| Poisson's ratio | 0.33 | 0.31 |
| Heat Capacity (J/g °C) | 0.896 | 0.385 |
| Thermal Conductivity (W/m K) | 167 | 391 |

## Results and Discussion

The simulation results were interpreted by LS-PREPOST. Figure 7 shows the comparison between the final shapes of the flanged sample and the simulation result in the 2.7 kJ case. For the flanged sample, the Al sheet was bent to 64.5 degree. The simulation result showed that the Al sheet was bent to 69.4 degree. There is 7.6% difference between the simulation and the experiment, which indicates the good correlation between experimental and numerical simulation results.

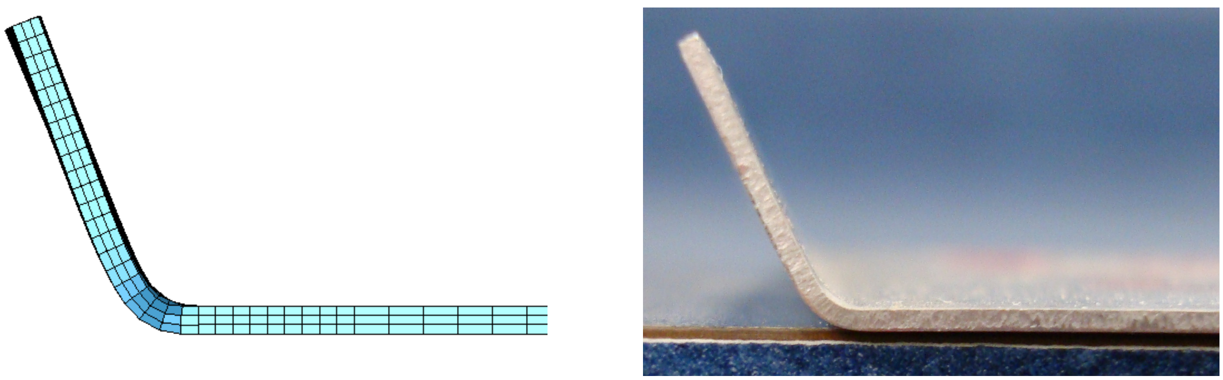

Figure 7. Comparison of the experimental and numerical simulation results for 2.7 kJ case (Left: simulation—bent angle: 69.4 degree; Right: experiment—bent angle: 64.5 degree)

Figure 8 shows the left edge of the Al sheet at the different time steps in the simulation, which indicates that the straight strip of the Al sheet was not accelerated to move at the same time. At the early stage, the middle area of the straight strip moved first and the two edges followed the middle area. But at the late stage, the middle area rebounded back and the two edges continued to move forward. Because of the continuousness of the metal strip, the middle area and the two edges rebounded back and forth several times and then settled down at last. This phenomenon makes sense because the induced current densities were different at different areas of the Al sheet and then the resulted repulsive Lorenz forces were also different. Figure 9 is the vector of the induced current density in the Al sheet at the time of 23μs. Figure 10 is the vector of the Lorentz force in the Al sheet at the time of 23μs. These two figures clearly agree with the above statement.

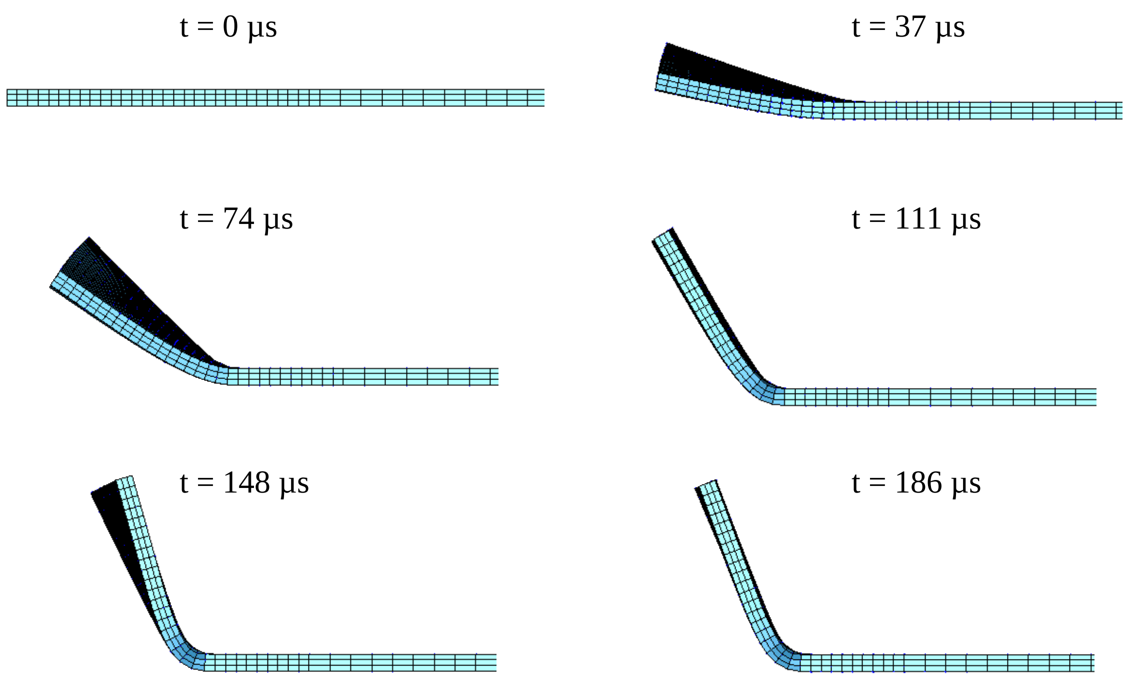


Figure 8. Left edge image of the Al sheet at the different time steps

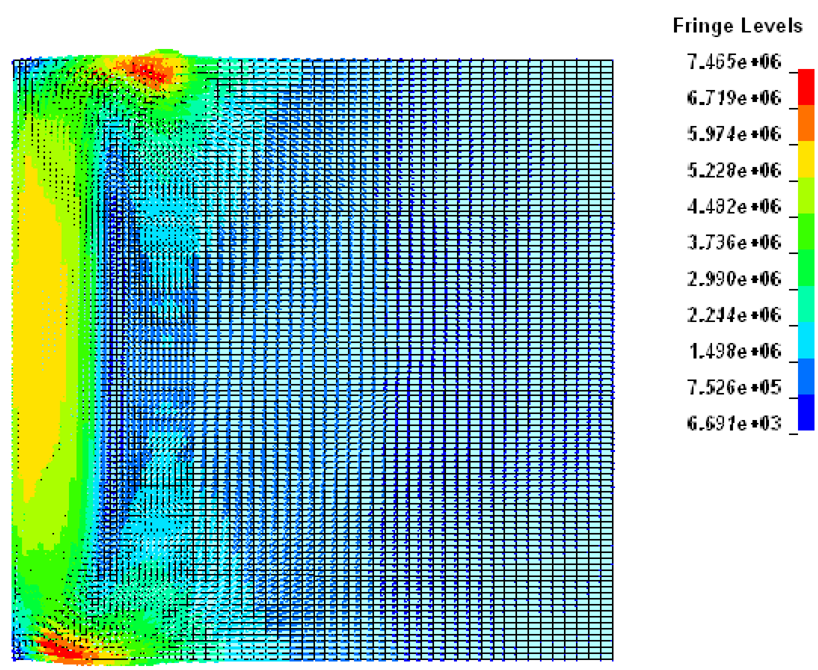


Figure 9. Vector of induced current density in Al sheet at the time of 23μs (top view)

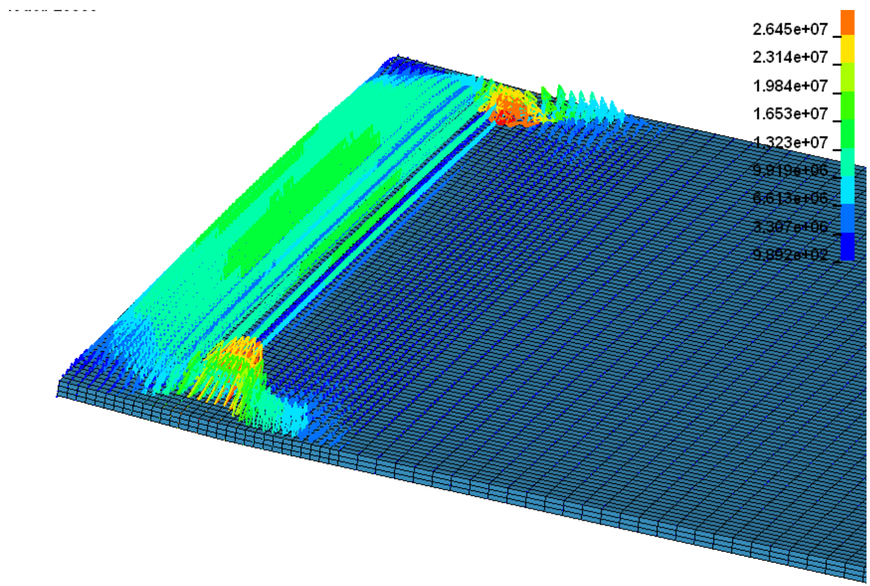


Figure 10. Vector of Lorentz force in Al sheet at the time of 23μs (top view)

## SMP and MPP Version

The above simulation was carried out using the Shared Memory Parallelism (SMP) version of LS-DYNA electromagnetism module. Recently, a Massively Parallel Processing (MPP) version of the electromagnetism module was developed, allowing sharing the CPU and memory between different processors and thus faster computations on larger problems. To test the capability of the MPP version, the same simulation was run again using the MPP version. Both of the simulations were performed using a computer with two quad-core Intel Xeon processors (3.00 Ghz/1333MHz). And the computer has 16GB of RAM. The simulation using SMP version was carried out on a single CPU and the simulation using MPP version was performed on four CPUs. The simulation results show that the MPP version dramatically reduced the elapsed time by 63%, comparing to the SMP version. Table 3 is the comparison between these two versions for above simulation.

Table 3. Elapsed time for SMP and MPP version

| Version | CPU number | Elapsed time (second) |
|---|---|---|
| SMP | 1 | 367774 |
| MPP | 4 | 136040 |

## Conclusion

The straight-edge flanging of Al 6061-T6 sheet by EMF was studied by experiments and LS-DYNA numerical simulations in this paper. The comparison between the final shapes of the flanged sample and the numerical simulation shows the good prediction capability of the LS-DYNA electromagnetism module for EMF. It is a good tool to understand and design the EMF process.

Both SMP and MPP version of LS-DYNA electromagnetism module predicted EMF process reasonably well. And MPP version can reduce the elapsed time dramatically.

## Acknowledgement

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