

# Comparison Between Experimental and Numerical Results of Electromagnetic Forming Processes

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## Abstract

*Electromagnetic Forming (EMF) is a high speed metal forming process that is being studied with interest in both academia and industry as a way of improving existing sheet metal forming. The main thrust of the published research has been increasing the formability of aluminum alloys. Observing and measuring EMF process is made very difficult by the high speeds involved and the tooling used to obtain the final shapes. As with many other processes, numerical simulations can potentially be used to study the details of EMF; however, one limiting factor is the difficulty in modeling the process, since accurate models of both the structural and electromagnetic phenomena must be solved. Researchers have relied on simplifications that use analytical magnetic force distributions, on separate electromagnetic (EM) and structural codes or on in-house codes that can solve both problems simultaneously. In this paper, the predictive ability of the EM module of LS-DYNA<sup>®</sup> is assessed through a comparison between experimental and numerical results for samples formed by EMF. V-Channel and conical shaped samples were formed using two different EMF apparatuses. For the V-Channel samples a double rectangular coil was used and for the conical samples a spiral coil was used. Both processes were modeled using LS-DYNA<sup>®</sup>'s EM module. A comparison of the final experimental and numerical final shape and current profiles is presented. It was found that the models provide good qualitative results and are able to predict the major features of the samples studied. Good quantitative agreement between the predicted and measured current profiles was found. The discrepancies observed are the result of numerical issues and the simplifications used in the creation of the specific models. It was found that the software can accurately predict the trends of the forming processes studied.*

## Introduction

Academic and industrial researchers have shown interest in electromagnetic forming (EMF) of sheet metal for automotive applications, because it could be used to form aluminum and other low formability materials. Forming of aluminum has been the main focus, due to its potential as a means of reducing automobile weight is limited due to its inferior forming characteristics relative to mild steel [1,2,3].

Despite having been in use since the early 1960's [4], there is not yet a complete understanding of EMF. The process not only involves electromagnetically induced forces, but also materials deforming at very high rates and a complex tool sheet interaction when the material impacts the die [5,6,7]. One significant challenge of studying these processes is observing them and acquiring data due to the very short period of time in which the process takes place. One way of obtaining information about these processes is to simulate them using numerical analysis.

To numerically simulate EMF both structural and electromagnetic processes must be modeled, ideally simultaneously. This presents a challenge for software designers. A review of the methods that have been used to simulate EMF processes is presented in [8]. These methods can

be divided into three approaches: i) a structural code where the induced forces are obtained from an analytical solution or from a separate electromagnetic (EM) code and applied as a load; ii) the use of separate structural and EM codes that are made to communicate with each other during the simulation and iii) a code that simultaneously solves the structural and electromagnetic problem. The last method is referred to as a “coupled” or “fully coupled” code and is the ideal approach. Unfortunately, fully coupled codes are not readily available and are usually developed by investigators for their own use.

Recently a commercially available fully coupled code has been made available by LS-DYNA<sup>®</sup>. To provide an evaluation of the software experimental samples and data were compared to the results of the same processes modeled with the software. First, experiments were performed on a EMF apparatus with no work piece present, to obtain a current pulse. This was done to evaluate the electromagnetic part of the software without the effects of moving material. Then, open channel parts were formed from AA 5754 sheet and the final shapes were compared to those predicted by the code. The currents generated were measured and compared to the predicted ones. In addition, the final shapes of samples formed into a conical die were also compared with the predicted results

## Experimental Procedure

### Open Channel Samples and No Sheet Experiments

The no work piece and the open channel sample experiments were formed using a double rectangular coil (Figure 1) connected to a Pulsar MPW 20 – Research Edition magnetic pulse generator, which consists of a capacitor bank and a power supply to deliver the current to the capacitors at the required specifications. The pulse generator has a nominal maximum energy capacity of 20 kJ and charging voltage of 9 kV. For the experiments with no work piece a current was passed through the coil with no sheet present. The current was generated by charging the pulse generator to a voltage of 5000 V.

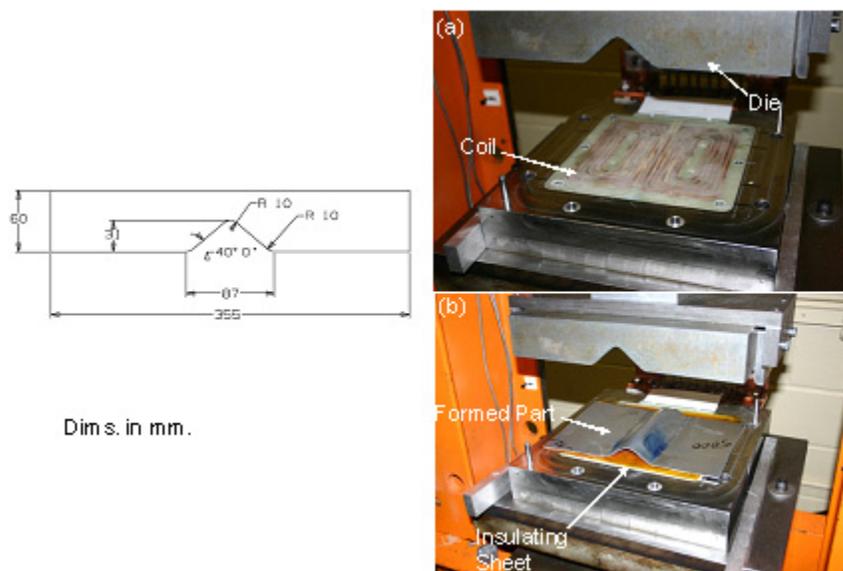


Figure 1: Experimental apparatus for the v-channel samples.

The open channel samples were given a triangular or “V” shape and formed using the die shown in Figure 1, these samples will be referred to as v-channel samples. The side angle of 40° was chosen since it was the maximum safe angle reached with the conical samples studied in [5]. The material used was AA 5754 in 1 mm sheets in samples of 197 x 305 mm. The metal samples were placed over the coil with sheets of an insulating material (Kapton©) separating the coil from the sample for additional insulation. The sheet was then clamped using a hydraulic press. Two sets of samples were formed, one where the samples did not make impact with the die and the other where the material impacted the die. These samples were formed using 3000 V and 5000 V respectively.

### Conical Samples

The conical samples were formed as part of the work described in [5,9,10] where details of the experimental procedures can be found. Conical samples of 40° side angle were analyzed for this study. The die used for the conical samples is shown in Figure 2. A seven-turn spiral coil with a nominal diameter of 100mm and a maximum diameter of 115 mm at the end was used. An IAP Magnepress magnetic pulse generator with a storage capacity of 22.5 kJ at 15kV was used to form the samples. The currents used to form these samples were unfortunately not measured. The charge voltage was the recorded input parameter and for the samples in question it was 8000 V.

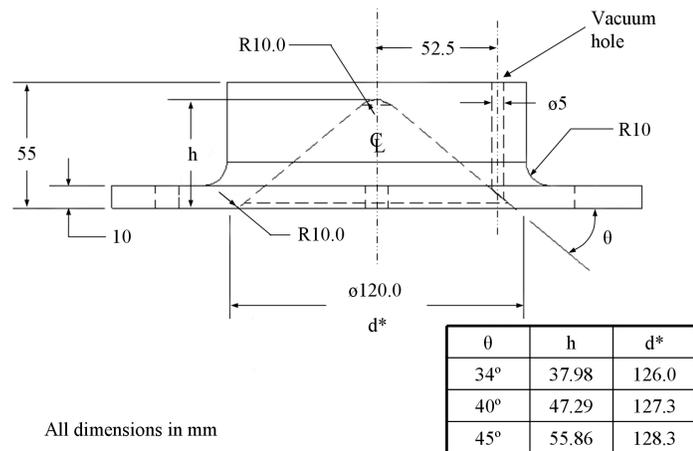


Figure 2: Die used to form the conical samples.

### Numerical Methods

The numerical effort for this work was undertaken with a version of LS-DYNA 980 that has an EM solver that combines Finite Element Analysis (FEA) with the Boundary Element Method (BEM) to perform the electromagnetic analysis by solving Maxwell's equations in the eddy-current approximation [11]. The BEM is used to model the air, so that it does not have to be meshed, while the coil and work piece are solved using FEA. Eliminating the mesh for the air many small elements that distort as the work piece deforms are eliminated; however, a high price is paid in computation time and memory requirements. A detailed description of the software is provided in [11,12].

The coils and work pieces were modeled using eight node hexagonal solid elements. Solid elements are required for both electromagnetic and structural reasons. They are needed to solve the induced currents and they are required due to the presence of through thickness and shear stresses on the sheet during forming when the sheet impacts the die [5,6,7]. The sheet was modeled with an elastic-plastic piecewise linear plasticity model. An isotropic quasi-static model was deemed acceptable since AA 5754 has shown little strain rate sensitivity [13]; however, the material has not been tested under the conditions encountered during EMF. The coils were modeled as elastic materials with a Young's Modulus of 97 GPa. The binders and dies were modeled as rigid bodies using shell elements, and were ignored for the electromagnetic calculation. The mesh used for the v-channel models is shown in Figure 4 and for the ones used for the conical models are in Figure 6. For the conical simulations, the sheet meshes were composed of 258,560 elements, while the sheet mesh for the v-channel simulations had 28,800 elements. The much larger number of elements for the cone mesh was needed to accurately capture the features found in the experimental results and to avoid erroneous predictions due to element distortion.

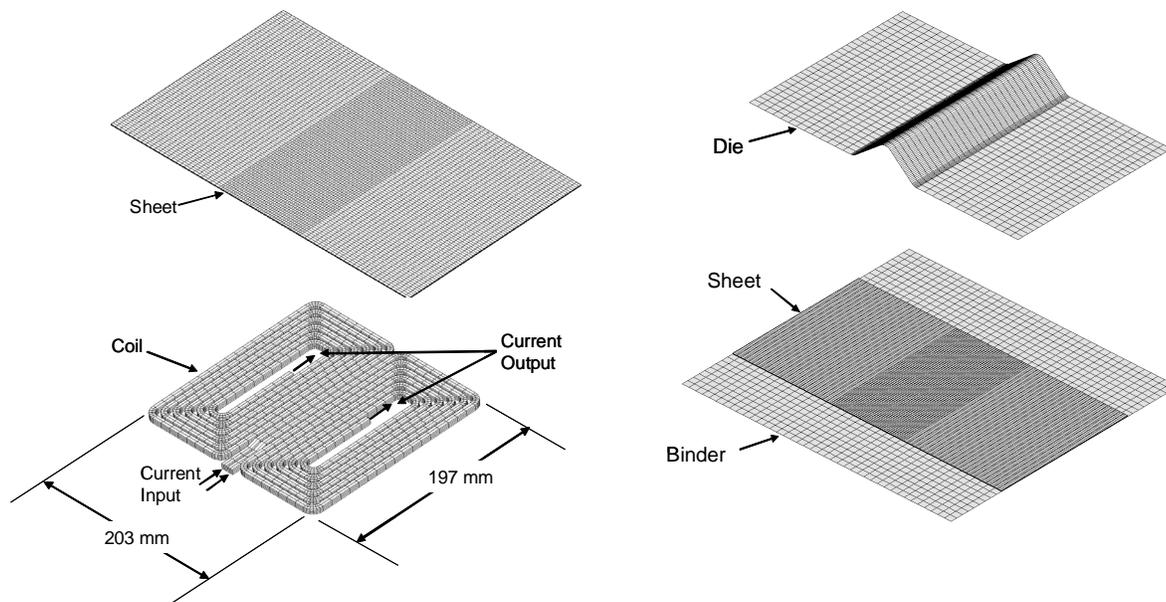
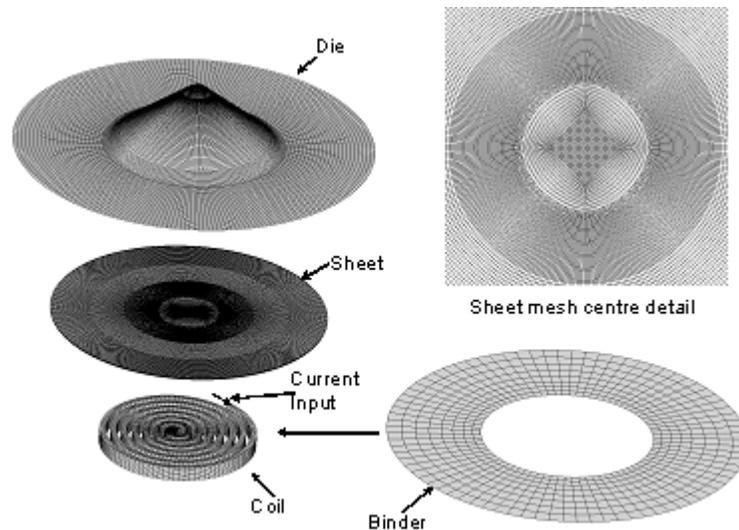


Figure 3: Mesh used for the v-channel model. The binder and die were not included in the EM calculation.



**Figure 4:** Mesh used for the v-channel model. The binder and die were not included in the EM calculation. The inset shows the centre of the sheet.

The process was modeled as an RLC circuit with the resistance, inductance and capacitance of the system being provided as inputs and the software calculated the current. This allowed for evaluation of the predicted current profile by comparing it with the experimentally measured ones. The values used for the v-channel simulations were;  $R = 5.96 \times 10^{-3}$  Ohms,  $L = 48.0 \times 10^{-6}$  mH and  $C = 2.7 \times 10^{-7}$  F. For the conical simulations the values used were;  $R = 2.98 \times 10^{-3}$  Ohms,  $L = 230.0 \times 10^{-6}$  mH and  $C = 2.0 \times 10^{-7}$  F. A conductivity of  $25 \times 10^6 \text{ Ohm}^{-1}\text{m}^{-1}$  was used for the coil and sheet. This simplification results in some inaccuracies; however, for the purposes of this study it was considered acceptable.

All the simulations were carried out using a computer with two Opteron 270 dual core 64-bit 2 GHz processors with 2 Mbytes of L2 Cache. The machine was equipped with 16 gigabytes of RAM. Each simulation was performed on a single processor.

## Results and Discussion

### Current Pulsed through Double Pancake Coil with No Work Piece

The experimental and numerical results for a current pulse through the coil with a 5000 V charging voltage are shown in Figure 5. The models over predict the peak positive current by approximately 7%. The negative peak is over predicted by approximately 50%, which is believed to be due to the lack of inclusion in the model of the temperature rise in the coil which can have a significant impact on the electrical conductivity. The mesh density through the cross section of the coil may also be too coarse to correctly model the diffusion of the electromagnetic fields. Since the deformation occurs while the current is still positive, the over predictions of the current on the negative side were not a grave concern for the forming part of the study.

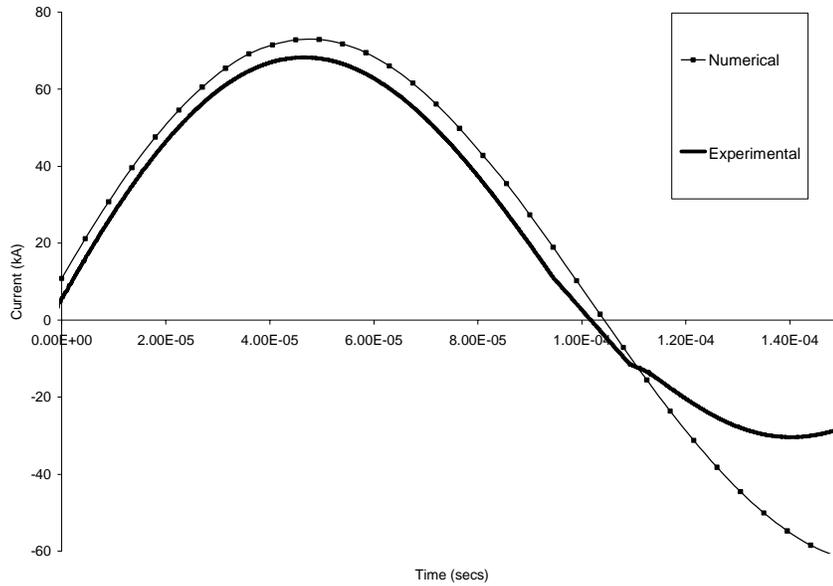


Figure 5: Experimental and numerical currents for a discharge through the coil with no work piece.

### V-channel comparisons

Pictures of a sample formed using 3000 V charging voltage where no impact with the die occurred are shown in Figure 6. It can be seen the parts are not formed uniformly, which is an indication that the force distribution is uneven. Figure 7 shows the predicted final shape for the same case. The numerical models predict the major features of the part. The experimental samples do not have a symmetric height distribution (Figure 6-c), which is not captured by the models.

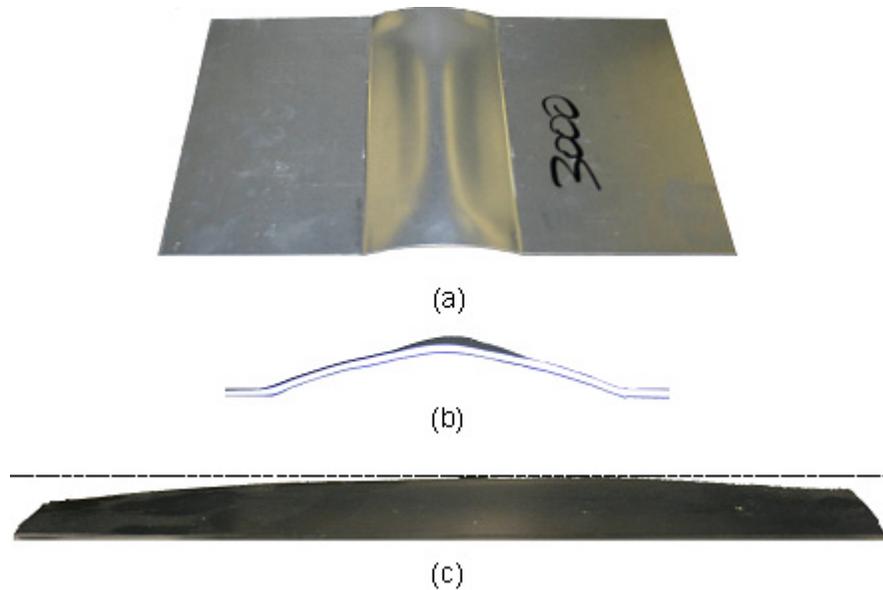


Figure 6: V-channel sample formed with a 3000 V charging voltage. The sample did not make contact with the die.

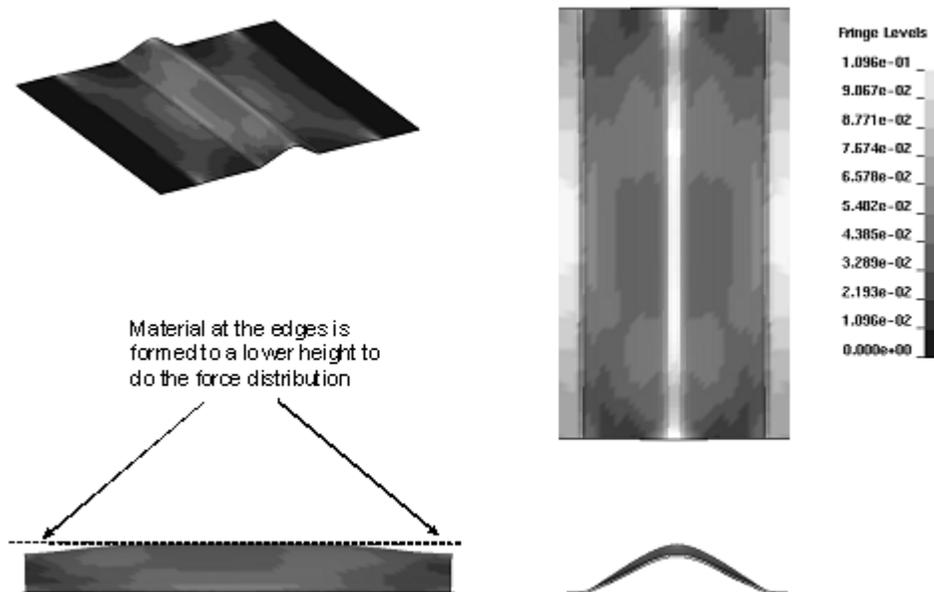


Figure 7: Predicted final shape for a v-channel forming process with a 3000 V charging voltage. Contours are of effective plastic strain.

Samples that made contact with the die were formed using a charge voltage of 5000 V. Figure 8 shows one of these samples. The shaded areas indicate the places where the sheet made impact with the die. It is apparent that the final part does not correspond to the shape of the v-channel die. The predicted final shape is shown in Figure 9. The model captures the general trend, but not the difference in height observed in the experimental samples (Figure 8-c) which are more pronounced than in the no impact samples. This discrepancy is likely due, in part, to the difference between the actual coil and the model of it. The coil has geometric imperfections,

such as uneven height of the coil, which are not accurately reproduced in the mesh for the numerical model. Also, the quasi-static material model used may not be capturing the actual behavior of the material in the forming conditions in question.

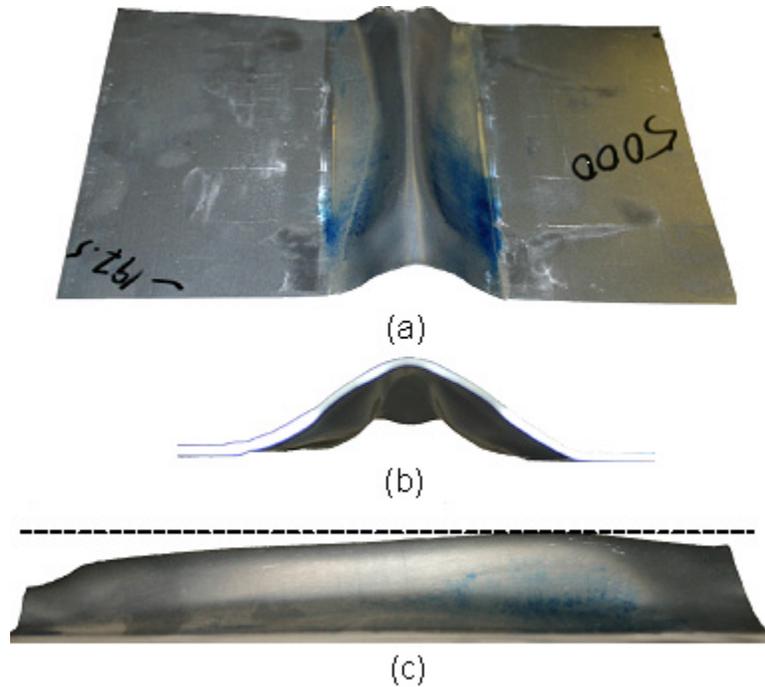


Figure 8: V-channel sample formed with a 5000 V charging voltage. The shaded areas indicate where the sample made contact with the die. The uneven forming is attributed to coil imperfections which result in an uneven force distribution.

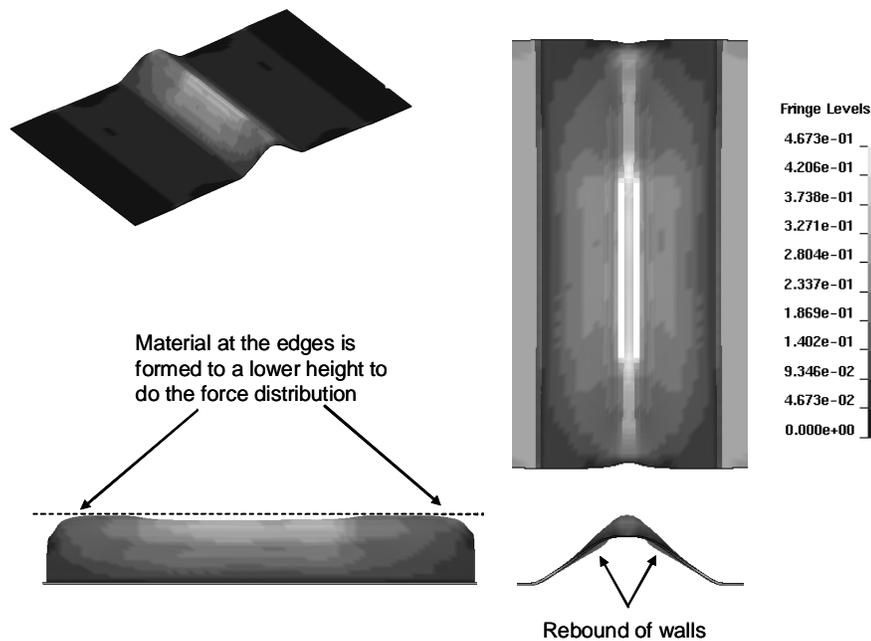
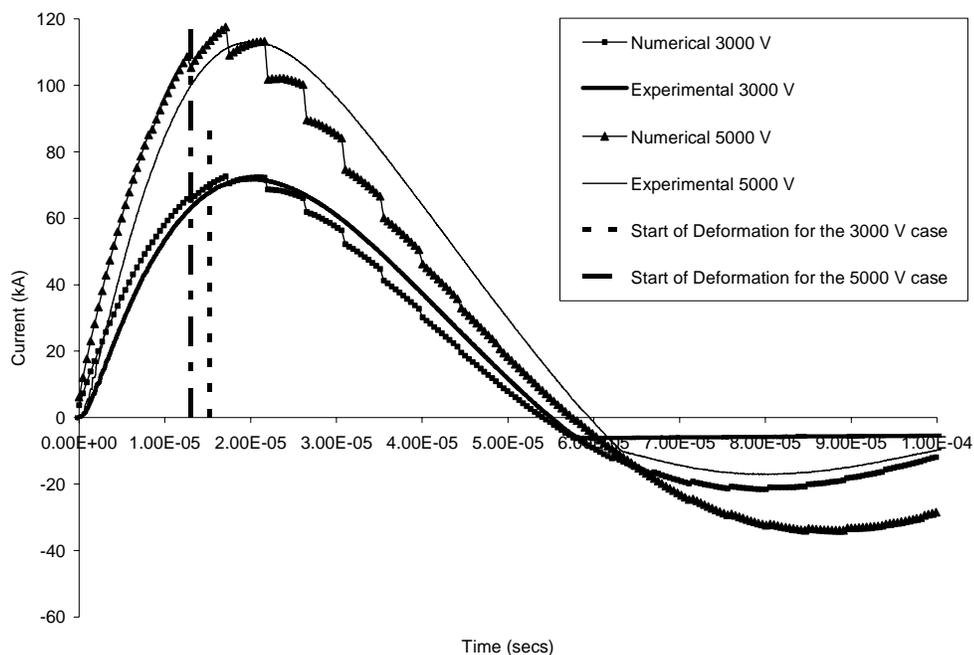


Figure 9: Predicted final shape for a v-channel forming process with a 5000 V charging voltage. Contours are of effective plastic strain.

The experimental (average of three samples) and predicted currents for both the no impact and impact cases are shown in Figure 10. The simulations were performed with ten EM solver time steps between the re-computation of the BEM and FEM matrices. The predictions agree well with the actual values during the rise of the current. As the current decays, the predictions show a lagged profile for both the 3000 and 5000 V charging voltage cases. The models over predict the peak current by approximately by 4% during the rise of the current pulse and then under predict the current by approximately 20% during the decay. As with the no work piece simulations the largest discrepancy was in the negative side, with approximately 50% difference for the 5000 V case. Due to equipment issues, the negative part of the 3000 V cases was not recorded.

Both the predicted current profiles show a series of steps after the sheet starts to deform. This behavior was not observed in the predictions with no sheet, and thus the presence of the sheet appears to be the cause. The peaks are the result of the time interval that exists between the re-computation of the matrices. Halving the time steps between re-computation to five reduces the discontinuities in the current output, but does not eliminate them, as can be seen in Figure 11. The final predicted shape and behavior of the sheet is virtually identical for both cases. Using half the time step results in a 2.5 times larger model run-time, increasing the run-time from approximately 7 to 18 days. At this time the reduction of the discontinuities in the output does not justify the increase in time.



**Figure 10: Experimental and numerical current profiles for 3000 and 5000 charging volt cases. The steps in the predicted values are a consequence of the time between matrix re-computation and the movement of the sheet.**

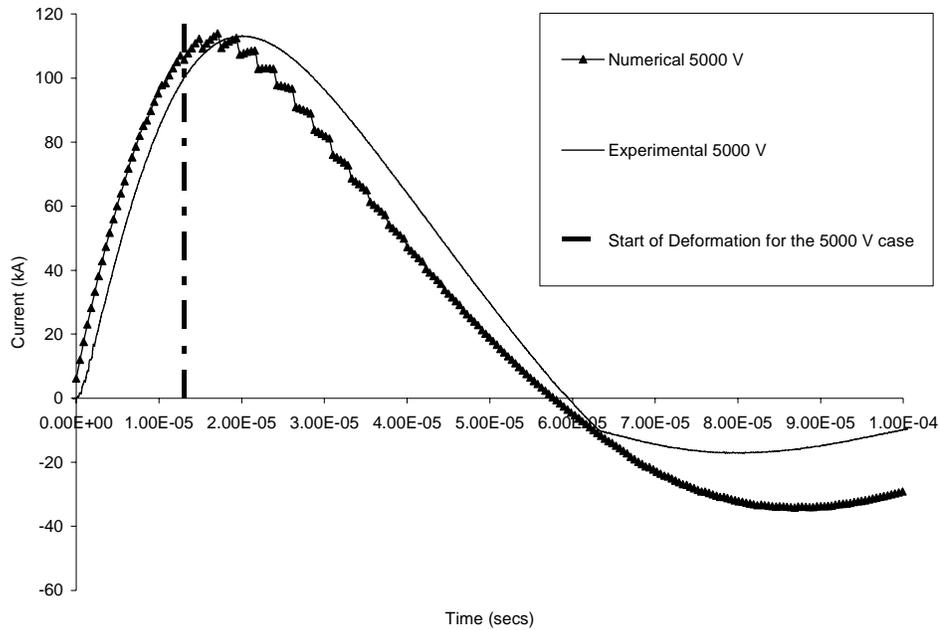


Figure 11: Experimental and numerical current profiles for a 5000 charging volt cases with double the time between matrix re-computation. The steps in the predicted values are reduced at a cost of a 2.5 increase in run time (from 7 to 18 days).

### Cone comparisons, final shapes

Comparisons are presented in this section of experimental and predicted conical sample final shapes. The experimental current profiles were not measured for these experiments. For the models the experimental charge voltage of 8000 V was used as input for the model. Figure 12 shows experimental and numerical conical samples. The models predicted all the general trends, including the step which is always present in the samples. The uneven forming is the result of a non-uniform induced force distribution, which is shown in Figure 13.

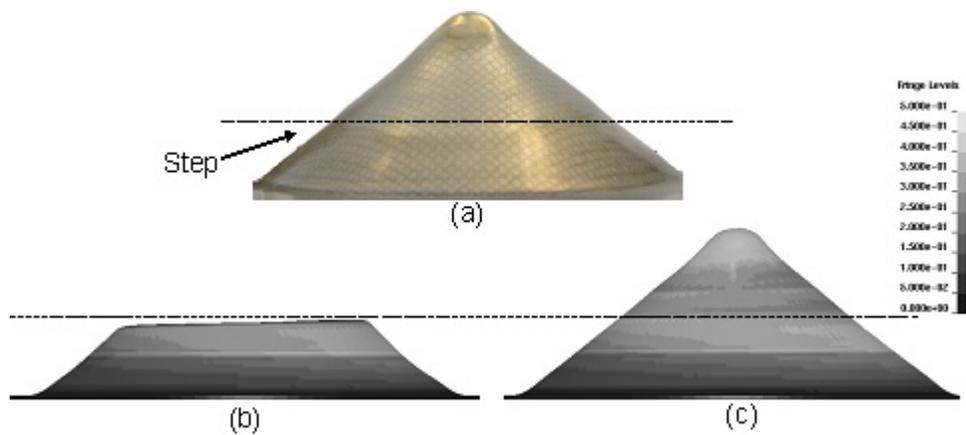
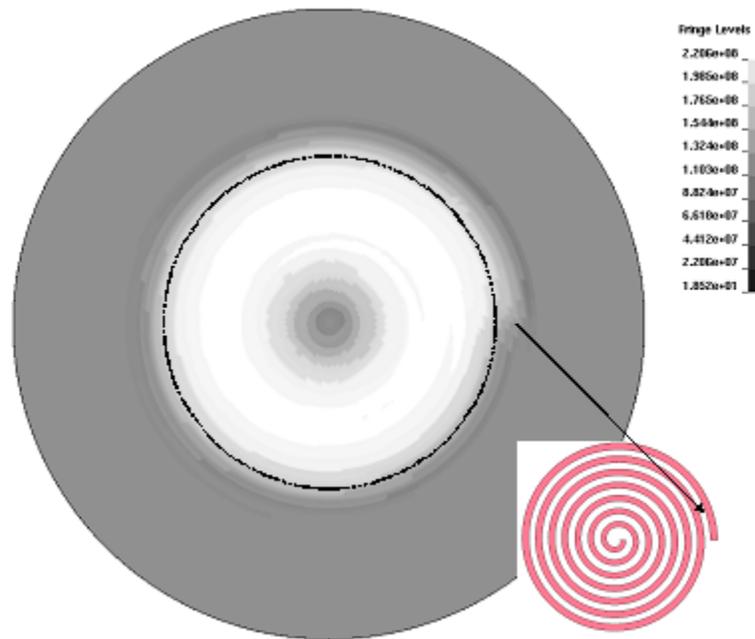


Figure 12: Comparison of experimental and predicted conical samples.



**Figure 13: Predicted force distribution on the side of the sheet that is facing the coil. The contours are of  $\mu\text{N}$ .**

### Computational Costs

The nature of the boundary element method results in large memory and time requirements. Memory usage was significant for all the models used in comparison to a standard FEM model. Fully accessible Random Access Memory (RAM) in the order of 4 Gigabytes was required for these simulations.. The biggest handicap for these simulations was the time taken for completion. The v-channel simulations with ten steps between matrix re-computation took seven days to complete. The time could be reduced through the use of a measured current profile and by determining the earliest possible point to turn off the EM solver.

### Conclusions

The software is able to predict the major features observed experimentally on the samples. The current profiles are predicted reasonably well. The predicted currents for the no workpiece case are over predicted, but agree well with the experiment while the current is positive. The over prediction worsens as the current becomes negative. The predicted current profiles for the v-channel samples agree quite well during the rise of the current and show larger discrepancies with experiments after the workpiece starts moving. After the sheet starts moving the currents are under predicted and present a series of steps, which are the result of the time between matrix re-computation. The steps can be reduced by reducing the time between matrix re-computation, at the cost of a significant increase in run time. The discrepancies that exist between the numerical and the experimental results can be attributed, in part, to mesh simplifications that do not capture all the features of the real coil, the coarseness of the mesh through the cross section of the coil, to inaccuracies in the material models and the lack of a thermal solution for the coil. The model run times and memory requirements pose a significant challenge that is being addressed by the developers.

## References

- 1 Wilson, D.V., “Aluminium versus steel in the family car-The formability factor”, *Journal of Mechanical. Working Technology*, v.16, 1988, pp. 257-277
- 2 Miller, W.S.; Zhuang L.; Bottema J.; Wittebrood A.J.; De Smet P.; Haszler A.; Vieregge A “Recent development in aluminium alloys for the automotive industry”, *Materials Science and Engineering A*, v.A280, 2000, pp. 37-49.
- 3 Mori, T.; Hino, M.; Iwaya, J. and Miyahara, M., “Press formability of aluminum alloy sheets for automobile parts”, *KOBELCO Technology Review*, n.14, July 1992, 49-53.
- 4 Wagner, H.J. and Boulger, F.W. “High velocity metalworking processes based on the sudden release of electrical of electrical energy” memorandum prepared by the Battle Memorial Institute for the Defense Metals Information Center, 1960.
- 5 Imbert, J. M. *Increased Formability and the Effects of the Tool/Sheet Interaction in Electromagnetic Forming of Aluminum Alloy Sheet*. Masters of Applied Science Thesis, University of Waterloo, 2005.
- 6 Imbert, J.M.; Worswick, M.J.; Winkler, S.L.; Golovashchenko, S and Dmitriev, V., “Analysis of the Increased Formability of Aluminum Alloy Sheet Formed Using Electromagnetic Forming SAE paper number 2005-01-0082. *SAE Transactions Journal of Materials. and Manufacturing*.
- 7 Imbert, J.M.; Winkler, S.L; Worswick, M.; Oliveira, D.A. and Golovashchenko, S., “The Effect of Tool/Sheet Interaction on Damage Evolution in Electromagnetic Forming of Aluminum Alloy Sheet”, *ASME-Journal of Engineering Materials and Technology*, v-127, n1, January 2005 pp. 145-152.
- 8 El-Azab, A.; Garnich, M. and Kapoor, A., “Modeling of the electromagnetic forming of sheet metals: state-of-the-art and future needs”, *Journal of Materials Processing Technology*, v.142, 2003, pp. 744-754.
- 9 Imbert, J.M.; Worswick, M.J.; Winkler, S.L.; Golovashchenko, S and Dmitriev, V., “Analysis of the Increased Formability of Aluminum Alloy Sheet Formed Using Electromagnetic Forming SAE paper number 2005-01-0082. *SAE Transactions Journal of Materials. and Manufacturing*.
- 10 Imbert, J.M.; Winkler, S.L; Worswick, M.; Oliveira, D.A. and Golovashchenko, S., “The Effect of Tool/Sheet Interaction on Damage Evolution in Electromagnetic Forming of Aluminum Alloy Sheet”, *ASME-Journal of Engineering Materials and Technology*, v-127, n1, January 2005 pp. 145-152.
- 11 L’Eplattenier, P., Cook, G., Ashcraft. Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical-Thermal-Electromagnetic Simulations. 3<sup>rd</sup> International Conference on High Speed Forming, Dortmund, Germany, March 11-12, 2008.
- 12 L’Eplattenier, P., Cook, G., Ashcraft, C., Burger, M., Shapiro, A., Daehn, G., Seth, M., 2006. Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical-Thermal-Electromagnetic Simulations. In: 9<sup>th</sup> International LS-DYNA Users Conference.
- 13 Smerd, R.; Winkler, S; Salisbury, C; Worswick, M.; Lloyd, D; and Finn, M., “High Strain Rate Tensile Testing Of Automotive Aluminum Alloy Sheet”, submitted for publication to the *International Journal of Impact Engineering*, November 2004.