

# NUMERICAL SIMULATION OF ELECTROMAGNETIC FORMING PROCESS USING A COMBINATION OF BEM AND FEM

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**ABSTRACT:** Electromagnetic forming (EMF) is a high speed metal forming method where materials with good electrical conductivity are formed by means of large magnetic pressures. It is a very fast process where materials can achieve strain rates higher than  $10^3 \text{ s}^{-1}$ . This is a suitable method for forming metallic materials that are hard to form by conventional methods, such as aluminium alloys.

In this paper an alternative method is used for computing electromagnetic fields in the EMF process simulation, a combination of Finite Element Method (FEM) for conductor parts and Boundary Element Method (BEM) for the surrounding air (or more generally insulators) that is being implemented in the general purpose transient dynamic finite element code LS-DYNA<sup>®</sup>.

Finally, forming experiments for two different geometries were performed and compared with the results from the numerical simulation using the previously explained method. Advantages and drawbacks of the employed simulating method are outlined.

**KEYWORDS:** Electromagnetic forming, Numerical simulation, Boundary Element Method

## 1 INTRODUCTION

Due to the use of new materials in automotive industry, new forming processes are arousing interest [1]. Electromagnetic forming is one of the new manufacturing techniques where materials with good electrical conductivity are formed by means of large magnetic pressures. It is reported by many researchers [2–4], that high strain rates achieved in EMF process allow materials to increase formability in comparison with conventional forming methods. Furthermore, there are other significant advantages associated to the process:

- Application of the electromagnetic pressure to the part without physical contact between the tool and the workpiece.
- High repeatability as a result of the process being controlled by electrical parameters.
- Reduction of wrinkles and springback in the final part due to the high speed deformation.
- Accuracy on the obtained geometry.

On the other hand, the electrical conductivity of the workpiece has a great influence in process efficiency and non-conductive materials cannot be directly formed by EMF.

This technology consists in a sudden discharge of large amount of energy stored in capacitors banks through the forming coil. When an alternative current flows through the coil, a time variable magnetic field is created that will give rise to induced currents (Eddy currents) in every nearby conductor material. Bodies carrying currents will experience a repulsive force that will finally deform the specimen.

Although EMF process is considered to be an innovative manufacturing technique, it was coincidentally discovered by P. Kapitza in the 1920s [5]. However, the development of this forming method began later, in the 1960s, mainly due to the intensive development of aeronautical engineering. The EMF process has been used since then primarily in aeronautical industry, although very little research was performed in those early years. Recently, EMF has aroused interest due to the fact that new materials with low conventional formability are being used.

Numerical simulation of manufacturing processes is a very useful tool for designing and changing pro-

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cess parameters. The simulation of EMF is more complicated due to the different physics that are involved, electromagnetic, mechanical and thermal. Consequently numerical simulations of the process must couple these related fields. Historically, Finite Element Method modelling has been predominantly used for EMF simulating [6, 7], while other methods such as Smooth Particle Hydrodynamics [8] have not succeeded.

In the current paper an alternative method is used for computing the electromagnetic fields in the EMF process simulation, a combination of Finite Element Method (FEM) for conductor parts and Boundary Element Method (BEM) for the surrounding air (or more generally insulators) that is being implemented in the commercial code LS-DYNA [9].

## 2 ELECTROMAGNETIC FORMING PROCESS PHYSICS

The EMF analysis involves the combined study of electromagnetic, mechanical and thermal fields.

### 2.1 ELECTROMAGNETIC ANALYSIS

The transient electromagnetic field generated by the current being discharged from the coil fills the surrounding space and induces Eddy currents in any nearby conductor area, i.e. the specimen. In this way, Lorentz forces are generated, which will deform the specimen:

$$\vec{F}_{EM} = \vec{j} \times \vec{B} \quad (1)$$

where  $\vec{j}$  is the induced current density vector and  $\vec{B}$  is the magnetic flux density vector.

The propagation of the magnetic field can be expressed by Maxwell's equations. In the range of frequencies of EMF process, displacement currents are neglected (Eddy current approximation), therefore, equations are reduced to:

$$\nabla \times \vec{H} = \vec{j} \quad (2)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\nabla \cdot \vec{B} = 0 \quad (4)$$

$$\vec{j} = \sigma_e \vec{E} + \vec{j}_s \quad (5)$$

$$\vec{B} = \mu \vec{H} \quad (6)$$

where  $\vec{H}$  is the magnetic field intensity vector,  $\vec{E}$  is the electric field intensity vector,  $\sigma_e$  is the electric conductivity which depends on temperature,  $\vec{j}_s$  is the source current density and  $\mu$  is the magnetic permeability, which in a general case is dependant of the magnetic field and the temperature.

The magnetic vector potential ( $\vec{A}$ ) is introduced for the numerical solution of the electromagnetic equations:

$$\nabla \times \vec{A} = \vec{B} \quad (7)$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla V \quad (8)$$

where  $V$  is defined as the electric scalar potential. The continuity equation is formulated taking the divergence of eq.(2), in order to satisfy the conservation of the current density:

$$\nabla \cdot \vec{j} = 0 \quad (9)$$

Consequently, combining eq.(2) and eq.(5) and introducing in eq.(6) with the recently defined eq.(7) and eq.(8), Maxwell's equations in terms of magnetic vector potential become:

$$\nabla \times (\nabla \times \vec{A}) = \mu \sigma_e \left( -\frac{\partial \vec{A}}{\partial t} - \nabla V \right) + \mu \vec{j}_s \quad (10)$$

### 2.2 MECHANICAL ANALYSIS

The approach for the continuum mechanics problem comes from solving displacement field for the known force field. Material behaviour, the relation between stress and deformation for a solid body, will condition the equation of motion:

$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} = \nabla \cdot \vec{\sigma} + \vec{F} \quad (11)$$

where  $\rho$  is the density of the material,  $\vec{u}$  is the displacement vector,  $\nabla \cdot \vec{\sigma}$  represents material's constitutive law (stress-strain relation) and  $\vec{F}$  is the force vector where magnetic forces from eq.(1) are also considered.

### 2.3 THERMAL ANALYSIS

In the thermal analysis, the temperature variation due to the heat generated in the EMF process is accounted for. The heat sources in EMF processes can be from: i) the plastic work during the deformation of the material and ii) the Joule heating produced by induced currents. Therefore, the temperature increment can be calculated as follows:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_p} \left( \beta \int_0^\epsilon \sigma \partial \epsilon + \frac{j^2}{\sigma_e} \right) \quad (12)$$

where  $T$  is the temperature,  $c_p$  is the thermal conductivity of the material,  $\sigma$  and  $\epsilon$  are respectively the stress and the strain of the material and  $\beta$  is the percentage of plastic work converted into heat. Note that since the deformation is assumed to be faster than the heat conduction rate for an EMF process, approximately 90% of the plastic work is considered to be transformed into heat ( $\beta = 0.9$ ).

## 3 NUMERICAL MODEL

With the current numerical method, equations governing the EMF process are solved in different ways for each domain. A Finite Element formulation is used to compute the electromagnetic solution

of conductor regions. In non-conductive bodies a Boundary Element Method is employed. More specifically, eq.(10) is projected against basis functions to get a Finite Element representation. Considering  $\Omega$  the conducting regions,  $\Gamma$  the exterior surface of insulating regions and  $\vec{n}$  the outward normal to surface  $\Gamma$ , it gives eq.(14) after a standard integration by part:

$$\begin{aligned} & \int_{\Omega} (\nabla \times \vec{A}) (\nabla \times \vec{W}_j) \partial\Omega + \\ & \int_{\Omega} \mu\sigma_e \left( \frac{\partial \vec{A}}{\partial t} + \nabla V \right) \vec{W}_j \partial\Omega = \\ & \int_{\Omega} \mu \vec{j}_s \vec{W}_j \partial\Omega - \frac{1}{\mu} \int_{\Gamma} (\vec{n} \times (\nabla \times \vec{A})) \vec{W}_j \partial\Gamma \end{aligned} \quad (13)$$

The last surface integral on the right hand side is computed using a Galerkin Boundary Element method. To do so, an intermediate variable, surface current  $\vec{k}$  is introduced, solution of:

$$\vec{A}(x) = \frac{\mu}{4\pi} \int_{\Gamma} \frac{1}{|x-y|} \vec{k}(y) \partial y \quad (14)$$

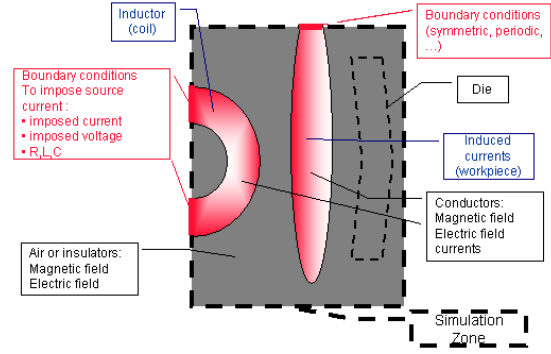
which allows to compute the surface term using:

$$\begin{aligned} \vec{n} \times (\nabla \times \vec{A})(x) &= \frac{\mu}{2} \vec{k}(x_0) - \\ & \frac{\mu}{4\pi} \int_{\Gamma} \frac{1}{|x-y|^3} \vec{n} \times [(\vec{x}-\vec{y}) \times \vec{k}(y) \partial y] \\ x &\rightarrow x_0 \in \Gamma \end{aligned} \quad (15)$$

The principal advantage of using the BEM for the air analysis is that it does not need an air mesh. It thus avoids the meshing problems associated with the air, which can be significant for complicated conductor geometries. These problems include, very small gaps between conductors, which lead to a large number of very small and distorted elements and the remeshing which is needed when using an air mesh around moving conductors. Another advantage of the BEM is that it does not need the introduction of somewhat artificial infinite boundary condition. On the other hand, the main disadvantage of the BEM is that it generates full dense matrices in place of the sparse FEM matrices. This causes an a priori high memory requirement as well as longer CPU time to solve the linear systems. In order to improve these requirements, a domain decomposition coupled with low rank approximations of the non diagonal sub-blocks of the BEM matrices has been introduced. Other methods to improve the computational time are also being studied.

In Figure 1, different regions and boundaries for a typical EMF process are shown. It can be seen that different boundary conditions can be applied for each domain, i.e. imposed current profile for a coil and induced currents for the workpiece.

A FEM formulation was used for the numerical simulation of the thermo-mechanical problem. The



**Figure 1:** Different simulation zones in a common EMF process

equation of motion is solved in an explicit mode as it is explained in [10].

## 4 VALIDATION OF THE MODELLING PROCEDURE

### 4.1 ELECTROMAGNETIC FORMING EXPERIMENTS

Two different experiments were carried out with the purpose of validating the explained simulation strategy. The same material was chosen for both forming experiments, 1 mm thick AA5754 aluminium alloy sheet.

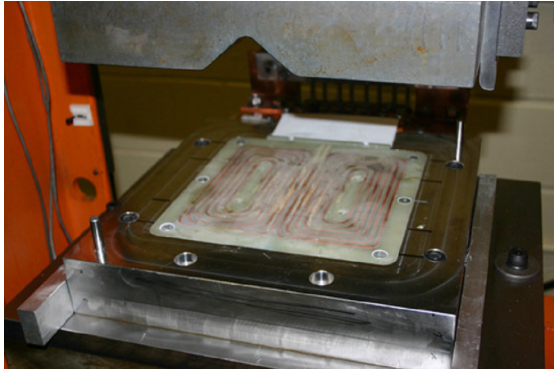
#### 4.1.1 V channel experiments

Experimental work for this geometry has been done in the laboratories of the University of Waterloo. The equipment employed is a commercial Pulsar 20 kJ capacitor bank. The experimental set up can be seen in Figure 2.



**Figure 2:** EMF equipment in the laboratories of the University of Waterloo

A die with V shape was used with 67.3 mm width, 240 mm long and 30.5 mm height, the coil is described in [7]. A closing force of 75 Tn was achieved by means of a hydraulic press. Figure 3 shows the geometries for the coil and die.



**Figure 3:** Forming coil and die geometry in UW

#### 4.1.2 Cone forming experiments

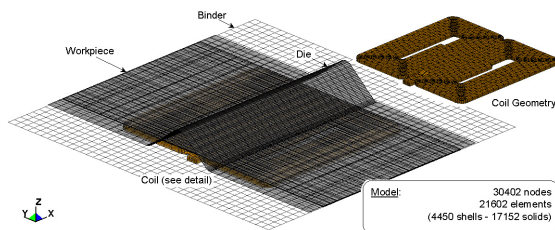
Experimental work for this geometry was carried out in the laboratories of Labein-Tecnalia. A 22 turn spiral flat coil was employed to form sheet specimen into a 45° conical die with 100 mm diameter base. A clamping force of 100 Tn was used in these experiments. Further information about these experiments could be found in [4].

### 4.2 NUMERICAL MODELS

Previously defined experiments were modelled with the strategy explained in the current work. The particularities for each model will be explained in the next sections.

#### 4.2.1 V channel experiments

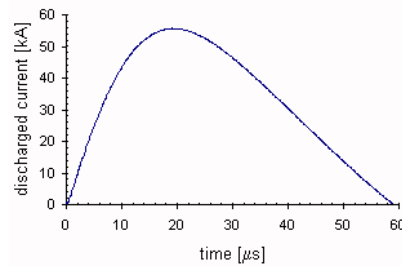
The geometry for the finite element model is shown in Figure 4. Die and binder are modelled with shell elements and are considered as rigid bodies in order to save computational time. Both are considered as insulators so there is not current calculation in these bodies. The clamping force is defined between them in the mechanical analysis.



**Figure 4:** Finite Element model for the "V channel" geometry

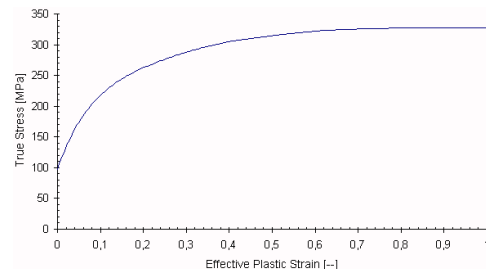
Two symmetrical coils made of copper and the workpiece are modelled with solid elements. The experimentally measured currents vs time flowing through each coil were imposed as global constraints. The spatial repartition of the current in the coils and the workpiece were computed by solving Eddy current problem. The current profile loaded in the EM analyses is shown in Figure 5. Only the first

pulse of the discharged current is taken into account since it is considered to be the pulse responsible for the main deformation of the workpiece [7].



**Figure 5:** Discharged current profile for the EM analysis

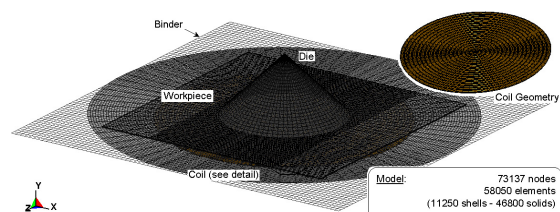
The coil is modelled as an elastic material of very high strength to avoid any deformation, while the specimen is modelled as a plastic material. The assumption of the coil to work in elastic domain is faithful when the resin in which is embedded resists the reaction forces produced in EMF discharges. The plastic behaviour of the workpiece is modelled with the quasi-static flow stress curve of the AA5754 aluminium alloy (Figure 6), assuming that strain rate effects can be neglected since they are not significant according to experimental results from [11]. The workpiece thickness is discretized with 4 elements in order to consider the skin depth effects.



**Figure 6:** Stress vs strain curve for AA5754 alloy

#### 4.2.2 Cone forming experiments

In the same way as explained in "V channel" simulations, Figure 7 shows the model for the cone forming simulation.



**Figure 7:** Finite Element model for the cone forming

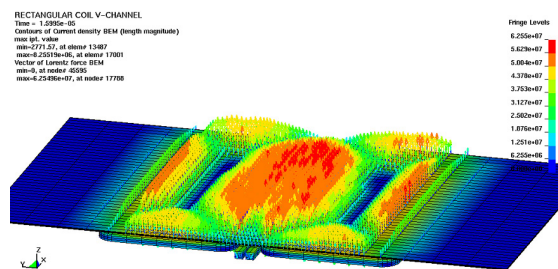
In the cone shape forming simulations, die and binder are also modelled with shell elements and are considered as rigid bodies. They are also considered as non-conductive materials assuming that their electrical conductivity is significantly lower than that of the coil and workpiece. One can also note that the workpiece acts as a shield for the magnetic field between the coil and the die, thus very little field reaches the surface of the die.

The geometry of the coil is simplified and instead of modelling the spiral winding, 22 concentric toroids are used to simulate the shape of the coil. Solid elements are used to discretize coil and sheet, with 3 elements through the thickness.

The loaded current and the mechanical behaviour of the coil and workpiece are modelled in the same way as the previously explained "V channel" simulation.

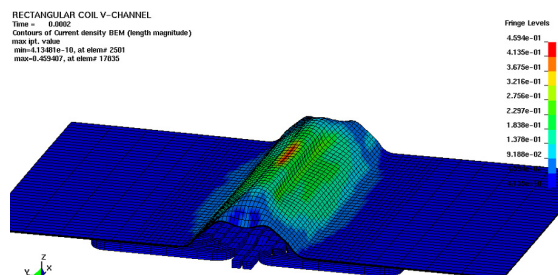
## 5 RESULTS AND DISCUSSION

Figure 8 shows the result for the "V channel" simulation. A vector plot of the Lorentz forces generated in the workpiece due to the induced currents is included. It is observed that the maximum values are achieved where both coils are closer, whereas minimum values of force appear in the centre of each coil. This was an expected result given the geometry of the coil.



**Figure 8:** Induced current density and Lorentz forces at 16ms during the deformation of AA5754 sheet

Final deformation results show good qualitative agreement with the deformation achieved in the experiments, as shown in Figures 9 and 10.



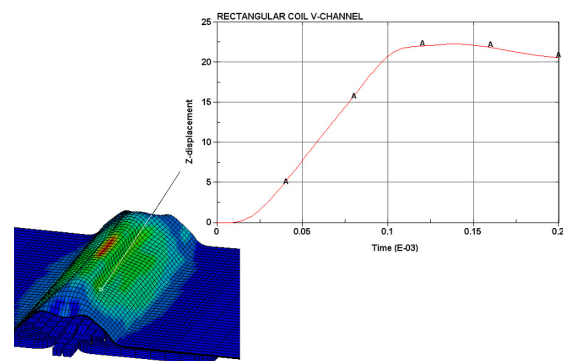
**Figure 9:** Plastic deformation for the final step

In Figure 10 the ink from the deformed workpiece



**Figure 10:** Electromagnetically formed experimental part

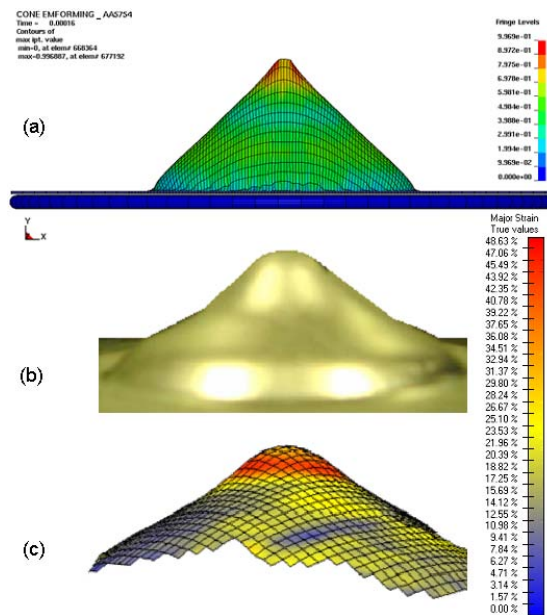
shows that the sheet has been formed until it contacts the die. However, the final part does not follow the die shape in the whole length because there is a rebound, since the contact is produced at high velocity. In the numerical simulation that fact is also observable, Figure 11 shows the displacement in Z direction of an element during the time and the rebound effect is observed.



**Figure 11:** Evolution of the z displacement of the remarked element

EMF simulation for the cone forming case is more complicated due to the fact that each winding is defined as a current carrying conductor and thus, the computational time is longer.

The agreement between final deformation results in the numerical simulation and experimental work is quite good. In Figure 12, it can be seen that although the quantitative approach is good, final values for the plastic deformation differ. The reason for this can be that several assumptions have been made, such as for the coil geometry and the tribological data. With the purpose of obtaining closer results contact at high strain rates should be better characterised. It is also remarkable that since strain rate effects have not been taken into account, higher deformation values are computed. If they would be considered, deformation values would probably be slightly lower for the since a mild increase in flow stress with strain rate was also reported in [11] for AA5754 alloy. Accordingly, numerical results would possibly be closer to experimental values.



**Figure 12:** Comparison of the numerical result and experimental part. (a) Plastic deformation result; (b) Experimental part; (c) Measured deformation

## 6 CONCLUSION

In this paper a combined FEM/BEM method has been employed for the numerical simulation of electromagnetic forming process. In general, results from the numerical analysis show that it is a good tool to better understand the process of EMF. With the explained method air meshing is avoided, hence, one of the major problems of the EMF coupled simulation is eluded. Another advantage of the BEM is that it does not need the introduction of somewhat artificial infinite boundary conditions, indispensable in FEM analyses.

It is interesting to remark the future tasks outlined from this work. It has been reported that 3D computational time is moderately long. Recently a 2D axis-symmetric option has been incorporated into LS-DYNA code, with the purpose of saving CPU time. It could be used for the cone forming case which has a rotational invariance. Finally, results from the FEM+BEM method employed in the current paper should be compared with the results from the problem solved with FEM.

## 7 ACKNOWLEDGEMENT

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