Influence of the Coupling Strategy in the Numerical Simulation of Electromagnetic Sheet Metal Forming

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Abstract

In this paper the Electromagnetic Forming process is numerically analyzed using a novel method that is being implemented into the commercial LS-DYNA® code. The method consists on a combination of a Boundary Element Method (BEM) and a Finite Element Method (FEM) formulations to compute the electromagnetic analysis. The main advantage of using BEM is that the air is not meshed avoiding the related problems and making it easier to couple the interacting fields involved in the EMF process. Sequential coupling and uncoupled strategies for the simulation of the related fields (i.e. electromagnetic, thermal and mechanical fields) are compared. Sequential coupling takes into account the deformation of the work piece are compared with the uncoupled strategy dismisses the deformation of the sample. The importance of the simulation method used is evaluated and compared with experimental results.

Introduction

Electromagnetic Forming (EMF) is a high speed material forming technology where conductor materials are formed by means of large magnetic pressures. Recently, EMF has aroused interest due to the fact that new materials with low conventional formability are being used. It has been reported by many researchers [1-5] that the high strain rates achieved in the EMF process (i.e. in the order of $10^3 s^{-1}$) allow material's to increase formability in comparison with conventional forming methods. Traditionally EMF has been used to form aluminum alloys [1-3], mainly due to their good electrical conductivity, although it is has also been employed to study the formability of other materials such as steels [4] and magnesium alloys [5].

The numerical simulation of manufacturing processes is a very useful tool for designing and changing process parameters, in the case of EMF parameters such as coil geometry or discharged energies could be changed at a fraction of the time and cost of an actual trial. However, in the EMF analysis the related physic fields involved in the process must be coupled, that is the electromagnetic, mechanical and thermal fields must be solved simultaneously. The coupling is both physical and geometrical: Lorentz forces computed in the electromagnetic analysis lead to a geometrical deformation of the work piece in the mechanical analysis according to the constitutive material law. The heating of the work piece computed in the thermal analysis due to Joule effect and adiabatic heating, changes both electromagnetic and mechanical properties of

the material which depend on the temperature. These interactions will be explained in detail in section 2.

Historically, the Finite Element Method (FEM) has predominantly been used for modeling EMF [6]. In the present study a combination of a Boundary Element Method (BEM) for insulators and a FEM for conductor materials is employed for the analysis of the electromagnetic field propagation. This modeling approach is being implemented as an electromagnetic module into the commercial code LS-DYNA® [7], thus making it possible to employ other capabilities of the code. The use of the BEM for the air avoids the significant problems associated with the re-meshing of the air surrounding moving conductors between subsequent calculation steps that is necessary to be made in the FEM simulations. This hybrid method also has advantages in the case of very small air/insulator gaps between conductors that require very small element size with the FEM formulation. Furthermore, this formulation avoids the introduction of the artificial infinite boundary condition, indispensable in the electromagnetic analysis with the FEM formulation.

In the current contribution, sequentially coupled and uncoupled strategies have been studied. The influence of the temporal discretization of the discharged current in both coupling strategies was also considered in order to optimize the computational time. Finally, the results obtained with each method were compared with the results from EMF experiments.

Numerical model of Electromagnetic Forming - Coupling strategies

Numerical analysis of EMF processes must couple the electromagnetic, mechanic and thermal fields. In the present work, the equations describing the process and the solving method are not presented for briefness, the reader is referred to [7, 8] for a detailed description of the method.

In the electromagnetic analysis Lorentz forces acting in conductor regions are computed according to Maxwell equations for the electromagnetic field propagation. The so called low frequency or Eddy current approximation is used due to the frequency range used in conventional EMF processes [7]. The electromagnetic problem is solved in a transient manner using the magnetic vector potential [9]. In conductor regions the FEM is used to compute the electromagnetic variables such as current density and Lorentz forces ($\vec{F} = \vec{j} \times \vec{B}$). In the non-conductor regions, including the surrounding air, the BEM is employed. In order to solve the electromagnetic problem a surface current is defined on the boundary of the conductors such that produces the same magnetic flux density $\vec{B}$ as the one produced by the current flowing through the conductor [10].

The Lorentz forces evaluated at the nodes in the electromagnetic analysis are added to the mechanical model and the equations of motion are solved with an explicit dynamic Lagrangian formulation [11]. The dynamic response of the deformed materials can be modeled using different constitutive models implemented in LS-DYNA. In this particular case, it is important for the models to take into account strain rate effects. In this study, the flow stress of the sheet material was modeled using a simplified Johnson and Cook material model [12], where the influence of the temperature was neglected:

$$\sigma = \left(A + B \cdot \varepsilon_{eps}^{n}\right) \cdot \left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \tag{1}$$

where ε_{eps} is the effective plastic strain, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate. A, B, C and n are the four material constants.

In the thermal analysis the Joule heating term is added to the temperature rise from the plastic work converted into heat due to adiabatic nature of the process:

$$\Delta T = \frac{1}{\rho C_p}\left(\beta \int_0^{\varepsilon_p} \sigma d\varepsilon_p + \frac{j^2}{\sigma_e \rho}\right) \tag{2}$$

where ρ is the density of the material, C_p is the specific heat capacity, β is the is the fraction of plastic energy converted into heat, σ is the true stress, ε_p is the plastic strain, j is the current density and σ_e is the electric conductivity.

In this work the electromagnetic material properties dependant of the temperature are neglected since the forming is performed at room temperature and the temperature rise was not very significant.

The computational time step is independent between the mechanical, thermal and electromagnetic solvers. It is obvious that the sequential coupling approach is closer to the real physical problem when $\Delta t \to 0$. However decreasing this time step (Δt) will cause an important increase on computational time. Therefore a compromise must be made between the most accurate representation of the real problem and the required computational time. In this work the time step for the electromagnetic analysis was varied while the thermo-mechanical ones were kept constant. Consequently, the discharged current was discretized in different time steps, 0.1μs; 0.5μs; 1μs; and 5μs, as it can be seen in Figure 1. In all the cases, only the first pulse of the discharged current was considered and the electromagnetic analysis was performed up to 60μs, with a recomputation of BEM and FEM matrices every 10 steps in the sequential coupling approach, while the thermo-mechanical computation was held up to 200μs, with Δt =2μs and Δt =5ns respectively.

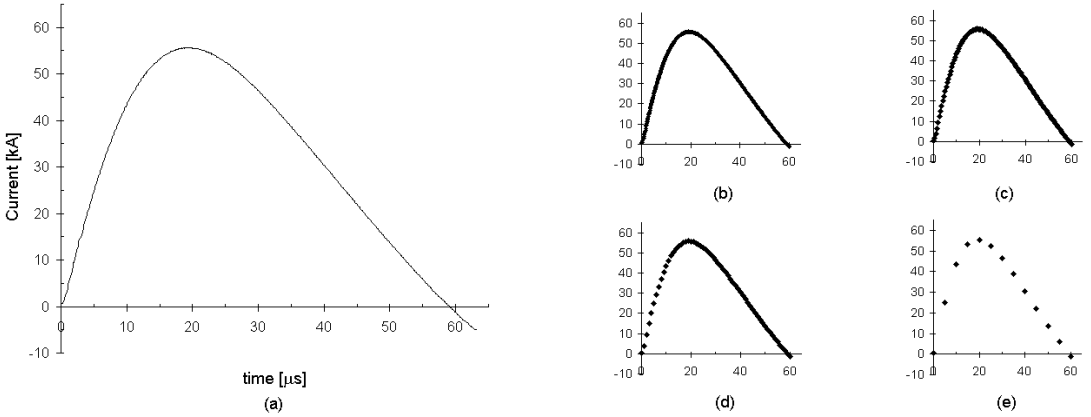


Figure 1: Discharged current profiles: measured (a) and discretized for Δ*t*=0.1μs (b), Δ*t*=0.5μs (c), Δ*t*=1μs (d) and Δ*t*=5μs (e)

The BEM and FEM matrices depend on the position of the nodes, and should in theory be recomputed at each time step when the conductors are moving. Unfortunately, the assembly of these matrices, and in particular the BEM ones is time consuming. LSTC is working on new methods to reduce this assembly time, but in the meanwhile, for practical cases, they are reassembled only every so often. In the uncoupled simulations, they are only assembled once at the beginning of the simulation.

As it was outlined in the introduction, sequentially coupled strategy was compared with the uncoupled simulations. In the uncoupled simulations, the deformation of the work piece is not taken into account in the electromagnetic analysis, so that the transient electromagnetic analysis is performed considering the initial shape of the sheet. The time variant Lorentz forces computed for the undeformed sheet at each node are stored and introduced in the mechanical analysis during the deformation of the work piece. Obviously, this strategy does not accurately reproduce the real problem for large deformation conditions, although from the point of view of the computational time, this simplification could be appropriate for some cases.

Experimental work and validation of the numerical results

The EMF experiments were performed in the laboratories of the University of Waterloo, Ontario, Canada employing a commercial Pulsar 20 kJ capacitor bank. The coil utilized in the experiments was a double spiral flat coil with 6 turns each, made from copper wire of a square cross section of 5 mm (Figure 2), a detailed description is presented in [13]. In order to avoid the dead spot regions of the coil, a V shape channel die with 67.3 mm width, 240 mm long and 30.5 mm height was used in the experiments in the fashion shown in Figure 2. A closing force of 75 Tn was completed by means of a hydraulic press. The material employed in this study was 1 mm thick sheet commercial available AZ31B-O magnesium alloy.

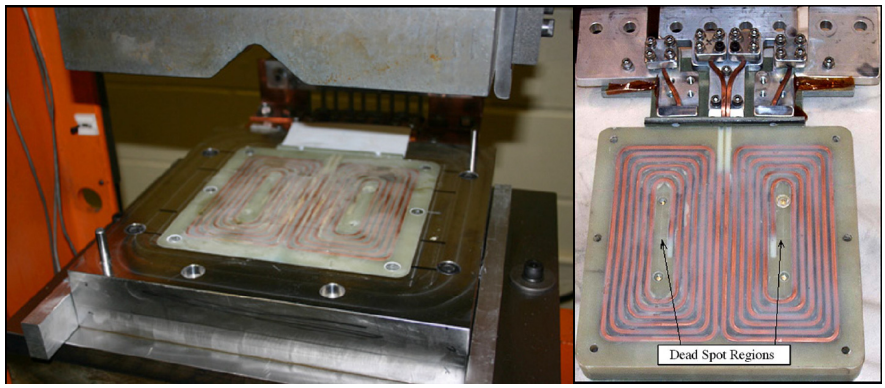


Figure 2: Experimental set up and the coil used in the experiments

The 3D numerical model (Figure 3) is composed of eight-node hexahedral solid elements for the double coil - 5952 elements - and for the sheet - 11200 elements -. In the case of the sheet the thickness is discretized with 4 elements in order to consider the skin depth effects. Four-node shell elements are used for modeling the die - 2850 elements - and the binder - 1600 elements - with the purpose of saving computational time.

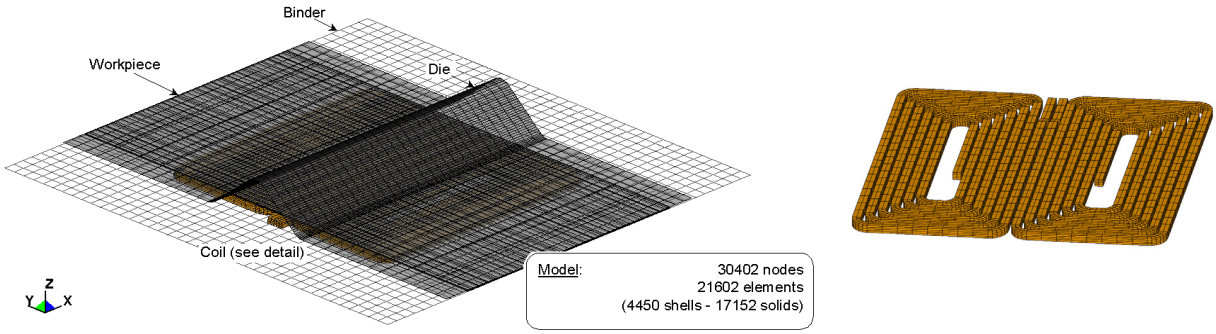


Figure 3: Finite Element model and detail of the coil.

In the electromagnetic analysis the discharged current measured in the experiments (Figure 1) is imposed as a global constraint. The die and the binder are considered as insulators assuming that they are electrically isolated, so there is not current calculation in these bodies. The electrical conductivity of the magnesium alloy sheet was assumed to have a constant value of approximately 11MS/m at room temperature [14].

In the mechanical analysis, the die and the binder are considered as rigid bodies and a clamping force is defined between them. The coil is modeled as a very high strength elastic material to avoid any deformation. This assumption is valid when the resin in which the coil is embedded resists the reaction forces produced in the EMF discharges. The sheet it is modeled using the simplified Johnson and Cook material model (*MAT_098) and the constitutive parameters are taken from [5]:

Table 1: Values of the simplified Johnson-Cook coefficients [5]

Coefficients	A (MPa)	B (MPa)	C (MPa)	n
	180.002	344.548	0.554	0.012

Numerical results

First of all, the effect of the discretization on the vertical component of the Lorentz forces (F_z) is studied. In Figure 4 values of the vertical Lorentz forces (F_z) achieved with both coupling strategies are plotted for an element from the deformed area.

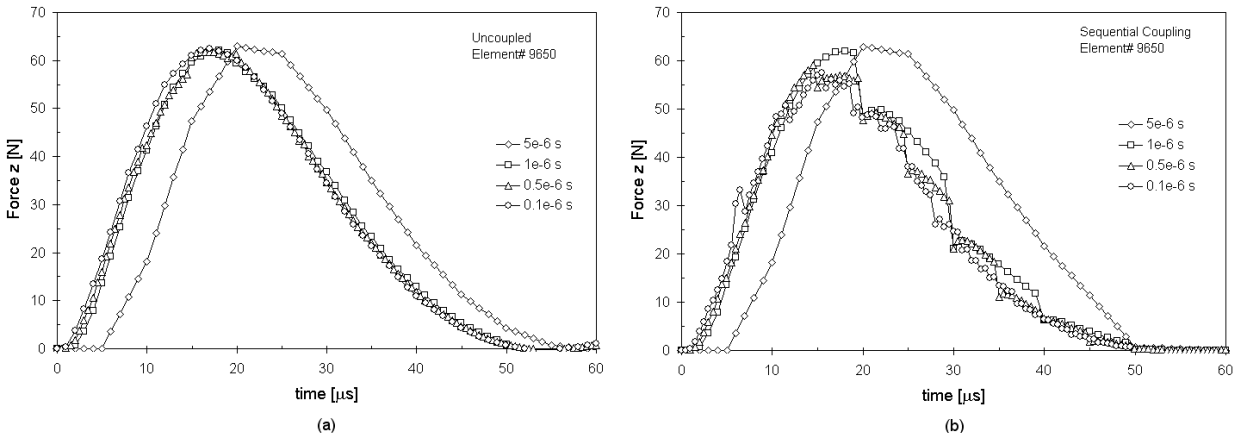


Figure 4: Effect of the discretization on the Lorentz force. (a) Uncoupled (b) Sequentially Coupled

It can be seen that decreasing the time step the peak value of the force is reached faster in both cases. In the results of the sequentially coupled strategy it can be clearly noticed when the Increasing the frequency of this recomputation gives a clear difference in the results and increases the simulation run-time. Therefore, it can be seen that the time step is a very important value in the sequential coupling strategy. However, in the uncoupled strategy the time step does not need to be decreased significantly, results are very similar for time steps lower than 1μs.

In Figure 5 the values of the forces for both strategies are compared for each time step studied. It can be seen that the difference of the forces between the uncoupled and the sequentially coupled strategies is increasing while the time step decreases, as expected, since the sequential approach comes closer to the real problem.

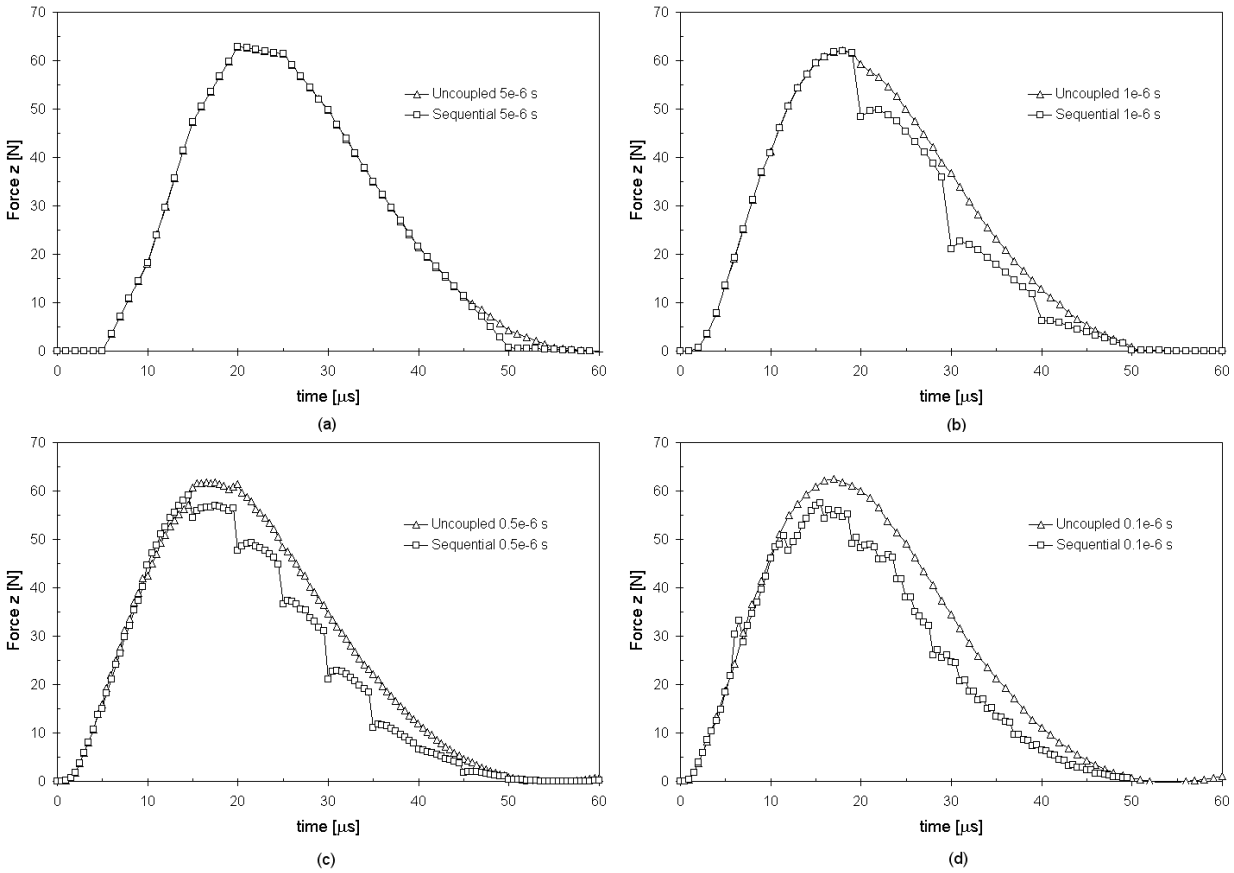


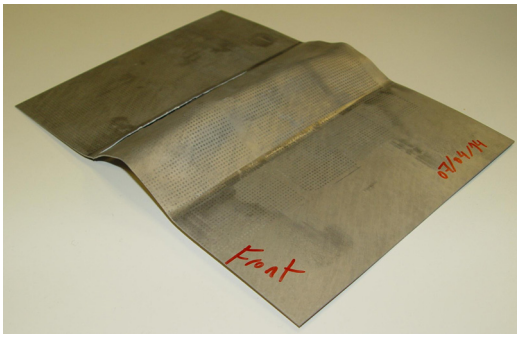
Figure 5: Comparison of the numerically obtained forces results for the Sequential Coupled and Uncoupled simulations with Δ*t*=5μs (a), Δ*t*=1μs (b), Δ*t*=0.5μs (c) and Δ*t*=0.1μs (d)

In order to compare the deformation results of both models, results from the time discretization of 1μs are chosen due to the insignificant variation of the predicted force for the uncoupled simulations. In Figure 6 final shape results for both coupling methods are compared for a discretization time of 1μs, it can be seen that the plastic strain values from the uncoupled simulations are significantly higher, although in both cases they are higher than the ones obtained experimentally (Figure 6(a)). The cause of this is on the one hand, that the profile of the discharged current used was not the measured one and, on the other hand, the limitations of the

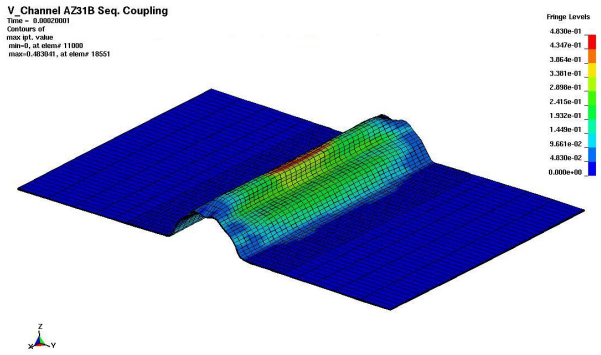
material model used. Also, the results for the plastic strain values decrease when reducing the time of the sequential coupling strategy.

There is also a considerable difference in the temporal displacement and temperature values, as shown in Figure 6(c). In this particular forming operation the final displacement of the part is defined by the geometry of the die, thus the difference could be less significant. In another kind of forming operation, such as free forming or flanging operations, the benefits of sequentially coupled strategy would be better appreciated. In the case of the thermal results, the values of the temperature rise achieved are clearly divided into two parts: i) the initial Joule heating up to the end of EM calculation and ii) the clearly observable adiabatic heating due to plastic work that is added to the Joule heating. In Figure 6(c) it can be seen that the values for the temperature rise in the uncoupled simulation are higher in the uncoupled strategy due to the influence of the deformation of the work piece.

It must be noted that the computational time for the coupled strategy is significantly higher than for the uncoupled strategy. For the model with the time step of 1μs, the sequentially coupled model required a total computational time of 10 hours, compared to 3 hours for the uncoupled strategy (the simulations run in a 6GB RAM Workstation).



(a)



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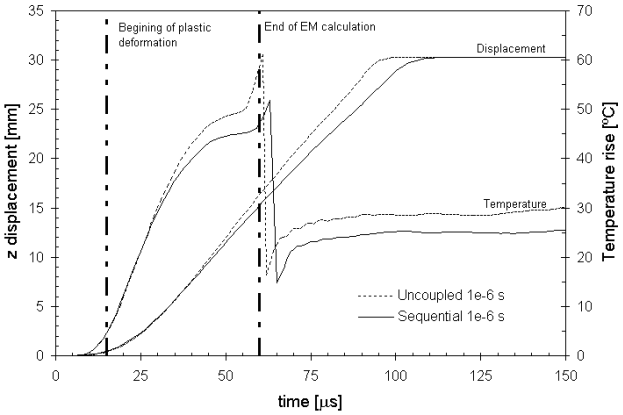
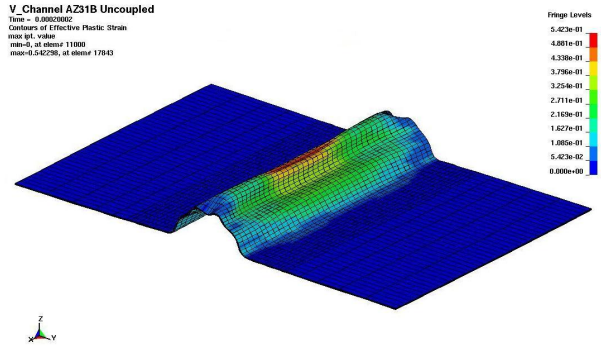


(c)



(d)

Figure 6: Comparison of the deformed experimental part (a) and numerical results for the Sequential Coupled (b) and Uncoupled (d) simulations for Δt=1μs (a). Temporal results of the z displacement and temperature rise (c)

Conclusions

The numerical results obtained employing the electromagnetic module implemented in LS-DYNA show good agreement with experimental data. In order to obtain more accurate results, the material model used for the work piece must be improved. An anisotropic yield function should be used since magnesium alloys show clear tension-compression anisotropy at quasi-static strain rates [15]. This issue was out of the scope of the present study. However, it was found that the new EM module could be a very useful tool for the design and optimization of the geometries and the energy discharging conditions.

The sequentially coupling strategy provides better results when large deformations are achieved, which is the case in most EMF operations. Although it has not been analyzed in the current study, when more than the first pulse of the discharged current is acting in the forming operations, the sequential coupling strategy is even more essential. In the future this type of experiments will be carried out and compared to the numerical results in order to determine the importance of the coupling strategy for large deformation operations.

From the results of this work it is apparent that the definition of the recomputation of the BEM and FEM matrices is crucial in the sequential coupling strategy. Initially it does not have a significant influence since the material remains practically undeformed up to 10-15μs (Figure6(d)), but once the material starts deforming, it is essential to re-compute the BEM and FEM matrices with a higher frequency. Therefore, a further development of the electromagnetic code that is being implemented in LS-DYNA should consider this possibility.

In the case of the computational time, the time step and the recomputation of the matrices is crucial. Faster BEM assembling methods are being implemented to decrease the CPU time and thereby result in more reasonable simulation times. This would also allow for reassembling the matrices more often leading to more accurate numerical results.

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