Computational modelling for electromagnetic forming processes

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Abstract

Electromagnetic Forming (EMF) is a very promising high-speed forming process. However, designing these processes remains quite intricate as it leads to deal with strongly coupled multiphysics process and thus requires the use of computational models. We present here the main features of the numerical model which we are currently developing to model this process.

1. Introduction

Electromagnetic Forming (EMF) is a very promising high-speed forming process. It consists – as shown in Figure 1 - in submitting the workpiece to a transient electromagnetic field that will transform into body forces and ultimately cause the workpiece to deform.

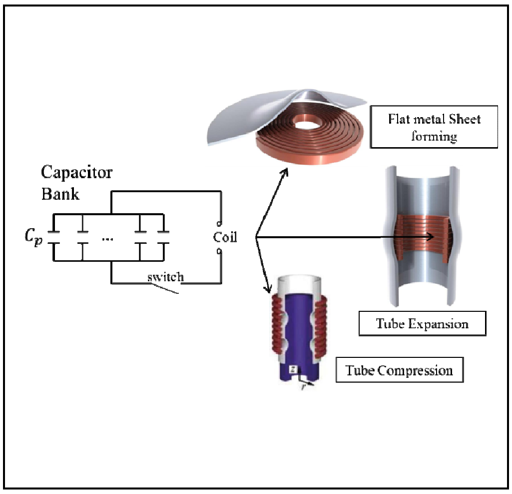


Fig. 1. General Scheme of electromagnetic forming & typical forming configurations.

This process has many advantages: improved formability for the materials involved, reduced elastic springback after forming, no punch and thus contactless application of pressure… Joining of dissimilar materials is possible. The process enables high controllability and repeatability of the outcomes. Besides, it is also an environment-friendly process since no lubricants are used

However, designing these processes remains quite intricate as it leads to deal with strongly coupled multiphysics. The design stage can therefore be greatly helped through the support of a computational mechanical model.

Some models already exist, as the one based on ANSYS/EMAG [Ansys], or the one based on LS-DYNA described in [L'Epplattenier], based on a coupling between finite elements and boundary elements for modelling the electromagnetic problem, as well as an explicit approach for modelling the mechanical problem. We present here the main features of the numerical model which we are currently developing to simulate this process. The model is based on a coupling between the MATELEC tool for modelling the electromagnetic problem and FORGE for modelling the mechanical problem.

Another specificity of EMF forming processes lies in the modelling of the material behaviour. EMF forming processes typically lead to strain rates which range roughly from 10^2 to 10^4 s^{-1}. Many constitutive models have been proposed to take into account dynamic effects in material behavior, and can be basically sorted in three classes: the phenomenological models such as the [Cowper-Symonds] or the [Johnson-Cook] models; the models derived from thermal activation analysis, some of them using microstructural internal variables in addition to the classical ones (i.e. strain, strain-rate and temperature); and the models that are more specific to shock regimes and viscous drag.We have selected for the time being a Johnson-Cook's model (Eq. 1.1) to model the material behaviour.

$$\sigma = (A + B\dot{\bar{\varepsilon}}_{pl}{}^{n}).(1 + C\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0})).(1 - (\frac{T - T_0}{T_m - T_0})^m) \text{ .} \tag{1.1}$$

where σ denotes the effective Von Mises stress, $\bar{\varepsilon}_{pl}$ the effective plastic strain, $\dot{\bar{\varepsilon}}$ the effective strain-rate, $\dot{\bar{\varepsilon}}_0$ a reference strain-rate, T the material temperature, T_0 the room temperature, and T_m the melt temperature. A, B, n, C and m are the material constitutive parameters.

2. Modelling the electromagnetic problem

Computation of coupled multiphysics problems involving electromagnetic fields can be quite consuming in terms of computational time and resources. Moreover, design stage which may involve both direct modelling and optimisation techniques are even more demanding in terms of computer power requirements.

Reducing the resources needed for solving the electromagnetic problem is one way to enable solving these problems within reasonable time and memory needs. It is therefore important to select the most appropriate numerical methods and parameters in order to save computational time and memory requirements for solving the electromagnetic problem.

2.1. The electromagnetic model

The model is classically based on the Maxwell equations (2.1)

$$curl\ (E) = -\frac{\partial B}{\partial t};\ curl\ (H) = j + \frac{\partial D}{\partial t};\ div\,(B) = 0 \text{ .} \tag{2.1}$$

where H denotes the magnetic field, B the magnetic induction, E the electric field, D the electric flux density, and J the electric current density.

We also have the following relations for the intrinsic material properties:

$$D = \varepsilon E;\ B = \mu(\|H\|, T)H;\ J = \sigma E \text{ .} \tag{2.2}$$

where ε denotes the material permittivity, μ the magnetic permeability, and σ the electrical conductivity.

Several authors in literature have chosen to neglect the displacement currents in the Maxwell-Ampere equation (magneto-quasi-static approximation). However, we have considered here the complete Maxwell equations.

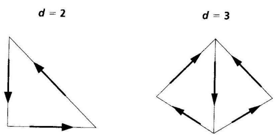
The (A,V) formulation (see for instance [Chari]) leads us to to the following equation for the vector potential A:

$$\varepsilon \frac{\partial^2 \mathbf{A}}{\partial t^2} + \sigma \frac{\partial \mathbf{A}}{\partial t} + \mathbf{rot}\,(\frac{1}{\mu}\mathbf{rot(A)}\ ) = -\sigma\ \mathbf{grad(}\ V\,\mathbf{)} - \varepsilon\ \mathbf{grad(}\ \frac{\partial V}{\partial t}\mathbf{)} \tag{2.3}$$

2.2. *The finite element approximation*

The two main numerical approaches for these problems are either based on mixed boundary elements/finite elements approaches – in which the coupling between the inductors and the workpiece is carried out through a boundary element approach, or on global finite element approaches.

We define a global domain which embeds all solid parts as well as a finite volume of air. It should be stressed here that the air domain needs to be wide enough in order to model accurately electromagnetic wave propagation. The domain is then discretised using tetrahedral edge finite elements for determining the magnetic vector potential field A. Edge elements have been introduced by [Nedelec]. Their main specificity is that the unknowns are the tangential components on the edges of the magnetic vector potential field (Figure 2a); shape functions for the finite element approximation are vectors with a specific shape as shown on Figure 2b.



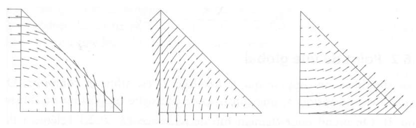


Fig. 2.a. 2D or 3D edge elements; Fig. 2.b. Edge element shape functions for 2D edge elements

We get the following differential system for the weak formulation after a semi-discretisation over space:

$$[M]\left\{\frac{\partial^2 A(t)}{\partial t^2}\right\} + [\mathbf{C}]\left\{\frac{\partial A(t)}{\partial t}\right\} + [\mathbf{K}]\{A(t)\} = \{\mathbf{B}(t)\}. \tag{2.4}$$

where C and K denote capacity and rigidity matrices and B the load vector.

Regarding the solving of the linear system, we use a conjugate gradient solver coupled with an SSOR preconditioning which has proven to be quite efficient.

3. Modelling the mechanical problem

3.1. The solid mechanics model

For a detailed account of the finite element modelling of metal forming processes, the reader is referred to [Wagoner].

We use a mixed formulation. In the domain of the part, this formulation is written for any virtual velocity v* and pressure p* fields:

$$\begin{aligned} &\int_\Omega \dot{\sigma}' : \dot{\varepsilon}^* dv - \int_\Omega \dot{p}\, div(v^*) dv = 0 \\ &- \int_\Omega (div(v) + \frac{\dot{p}}{\kappa}) p^* dv = 0 \end{aligned} \quad . \tag{3.1}$$

3.2. The finite element approximation

Many different finite element formulations were proposed, and developed at the laboratory level, but it is now realized that the discretization scheme must be compatible with other numerical and computational constraints, among which we can quote:

- Remeshing and adaptive remeshing ;
- Unilateral contact analysis,
- Iterative solving of non-linear and linear systems;
- Domain decomposition and parallel computing;

Today a satisfactory compromise is based on a mixed velocity and pressure formulation using tetrahedral elements, and a bubble function to stabilize the solution for incompressible or quasi incompressible materials.

The discretized mixed integral formulation for the mechanical problem is:

$$\begin{aligned} R_n^V &= \int_\Omega \rho\gamma N_n dV + \int_\Omega 2K(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1} \dot{\varepsilon} : B_n dV - \int_\Omega ptr(B_n) dV = 0 \\ R_m^P &= \int_\Omega M_m (div(v) + 3\alpha_d \dot{T}) dV = 0 \end{aligned} \quad . \tag{3.2}$$

3.3. Numerical issues

The non-linear equations resulting from the mechanical behaviour are linearized with the Newton-Raphson method. The resulting linear systems are often solved now with iterative methods, which appear faster and require much less CPU memory than the direct ones.

Automatic dynamic remeshing during the simulation of the whole forming process is almost always necessary, as elements undergo very high strain that could produce degeneracy. Before this catastrophic event, decrease of element quality must be evaluated and a remeshing module must be launched periodically to recover a satisfactory element quality. The global mesh can be completely regenerated, using a Delaunay or any front tracing method, but the method of iterative improvement of the mesh, with a possible local change of element structure and connectivity, seems to be much more effective.

Computing time can be decreased dramatically by using parallel computing techniques over several processors. This can be achieved here using the iterative solver and defining a partition of the domain, each sub-domain being associated with a processor. But the parallelization is made more complex due to remeshing and the remeshing process itself must be parallelized.

In order to avoid the necessity for the user to perform several computations, with different meshes to check the accuracy, error estimation can be developed using for example the generalization of the method proposed by [Zienkiewicz and Zhu]. Then, if the rate of convergence of the computation is known, the local mesh refinement necessary to achieve a prescribed tolerance can be computed, and the meshing modules are improved to be able to respect the refinement when generating the new mesh.

4. Results for magnetic forming modelling

In order to show the main features of the approach used in our numerical model, we present here an example of modelling for the case of a ring expansion. Figure 2 shows the global three-dimensional mesh encompassing both the coil and the workpiece. Figure 3 provides results at an intermediate stage regarding material velocities.

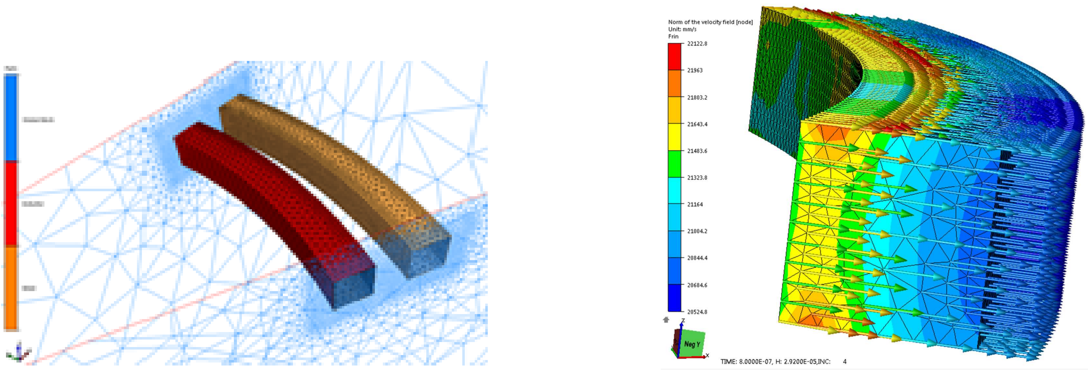


Fig. 3.a. Global 3-D mesh for a ring expansion case; Fig. 3.b. Mesh velocities

5. Conclusion

We have presented here the main features of a numerical model meant to model magnetic forming processes. The model is based on finite element approximation and couples the solving of a Maxwell electromagnetic model with a solid mechanics model.

Regarding the development of this model, the next stages of this work will deal with the development of numerical strategies aimed at reducing computation at times and based on an intensive use of parallel computations. Work will also be carried out on determining the most appropriate constitutive laws for modelling dynamic behaviour, as well as the development of identification strategies for determining the parameters of these constitutive models.

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