Electromagnetic Forming Processes: Material Behaviour and Computational Modelling

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Abstract

Electromagnetic Forming 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. Accurate knowledge of constitutive law parameters for material at high strain rates remains quite difficult to access. We thus introduce here a procedure which has been developed in order to deal with identification of these parameters.

Keywords: High-speed forming; Material dynamic behaviour; Computational modelling

1. Introduction

Electromagnetic Forming 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. 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.

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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 electromagnetic forming processes lies in the knowledge of the material behaviour. Electromagnetic forming processes typically leads to strain rates that can be comprised between 10^2 and 10^4 s^{-1}. Identification of parameters for a constitutive law in that range can be quite difficult. We introduce here an identification procedure and a mechanical test based on tube expansion. It is meant to achieve material behaviour under mechanical loading close to the ones experienced in a real process.
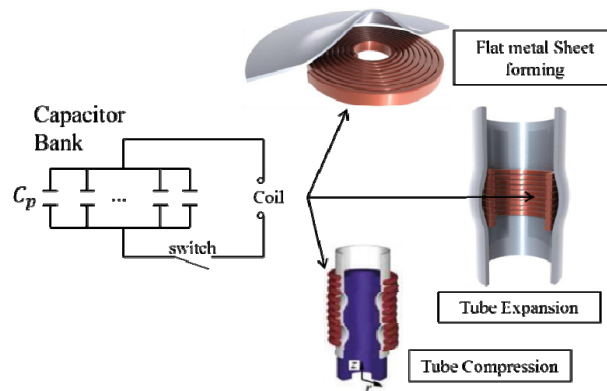

Fig.1. General scheme of electromagnetic forming & typical forming configurations.

Nomenclature

J	current density
E	electric field
D	electric induction field
H	magnetic field
B	magnetic induction field
T	temperature
μ	magnetic permeability
σ	electrical conductivity
A	magnetic potential vector field
V	electric potential scalar field
ε	strain tensor
$\dot{\varepsilon}$	strain rate tensor
$\underline{\underline{\sigma}}$	stress tensor

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

We shall first introduce Maxwell equations, which are needed for modelling the electromagnetic problem.

$$curl\,(E) = -\frac{\partial B}{\partial t}; \;\; curl\,(H) = j + \frac{\partial D}{\partial t}; \;\; div\,(B) = 0 \,, \tag{1}$$

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 associated with free charges.

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

$$D = \varepsilon E \,; \; B = \mu(\|H\|, T)H \,; \; J = \sigma E \,, \tag{2}$$

where ε denotes the material permittivity, μ the magnetic permeability, and σ the electrical conductivity. They all depend on temperature and the magnetic permeability μ and material permittivity ε depend also on H.

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 ([Chari]) is obtained by defining a vector potential A such that

$$\mathbf{B} = curl\,(\mathbf{A}) \,. \tag{3}$$

Using this expression leads us to:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \mathbf{grad}(\,V\,) \,, \tag{4}$$

where V denotes the electric scalar potential.

We then finally get to the following equation where the unknown is the vector potential A field:

$$\varepsilon\,\frac{\partial^2 \mathbf{A}}{\partial t^2} + \sigma\,\frac{\partial \mathbf{A}}{\partial t} + \mathbf{rot}\,(\frac{1}{\mu}\mathbf{rot(A)}\,) = -\sigma\,\mathbf{grad}(\,V\,) - \varepsilon\,\mathbf{grad}(\,\frac{\partial V}{\partial t}) \,, \tag{5}$$

with σ = σ (T), μ =μ (T, H) and ε =ε (T, H)

The right hand term will in fact stand for the input current.

In order to ensure solution uniqueness, we have to introduce an additional equation. The most usual condition is known as the Coulomb gauge and writes:

$$div\,(\mathbf{A}) = 0 \,. \tag{6}$$

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 finite element approach, or on global finite element approaches. The two main numerical approaches for these problems are: a mix of boundary elements/finite elements – in which the wave propagation phenomena on the domain surrounding the solids is computed using the boundary elements, or a global finite element approach.

The edge element, used here 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; shape functions for the finite element approximation are vectors with a specific shape.

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 - the unknown fields being magnetic vector potential field A.

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

$$[M]\left\{\frac{\partial^2 A(t)}{\partial t^2}\right\} + [\mathbf{C}]\left\{\frac{\partial A(t)}{\partial t}\right\} + [\mathbf{K}]\{A(t)\} = \{\mathbf{B}(t)\},\tag{7}$$

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. Solid mechanics model

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

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

$$\int_\Omega \dot{\sigma}':\dot{\varepsilon}^* dv - \int_\Omega \dot{p}\, div\,(v^*)dv = 0\,.\tag{8}$$

$$-\int_\Omega (div\,(v) + \frac{\dot{p}}{\kappa})\, p^* dv = 0\,.\tag{9}$$

3.2. 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;

To day 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:

$$R_n^V = \int_\Omega \rho \gamma N_n \, dV + \int_\Omega 2K(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1} \dot{\varepsilon} : B_n \, dV - \int_\Omega ptr(B_n) \, dV = 0 \, . \tag{10}$$

$$R_m^P = \int_\Omega M_m (div(v) + 3\alpha_d \dot{T}) \, dV = 0 \, . \tag{11}$$

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.

Prediction of possible formation of folding defects during forging is based on the analysis of the contact of the part with itself, so providing a similar problem like the coupling with tools.

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.

For industrial, complicated applications with short delays, the computing time can be decreased dramatically using several or several tens of processors. This requires to use an iterative solver and to define 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 [Zienckiewicz 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. Identification of material behaviour

A specificity of electromagnetic forming processes lies in the knowledge of the material behaviour. Electromagnetic forming processes typically lead to strain rates that can be comprised between 10^2 and 10^4 s^{-1}. Identification of parameters for a constitutive law in that range can be quite difficult. We introduce here an identification procedure and a mechanical test based on tube expansion and meant to achieve material behaviour identification under mechanical loads quite close to the ones experienced in the process.

4.1. The selected constitutive law

Many constitutive models have been proposed to take into account dynamic effects in material behaviour: 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.

In the following, it has been chosen to model the behaviour of aluminium with the Johnson-Cook's model (Eq. 1).

$$\sigma = \left[A + B \cdot \overline{\varepsilon_{pl}}^n\right] \cdot \left[1 + C \cdot ln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right],$$

(12)

where σ denotes the effective Von Mises stress, $\overline{\varepsilon}_{pl}$ the effective plastic strain, $\dot{\overline{\varepsilon}}$ the effective strain-rate, $\dot{\overline{\varepsilon}}_0$ 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.

4.2. The identification procedure

The identification of the Johnson-Cook's model parameters is based on an inverse analysis approach, performed by means of the optimization tool LS-Opt®. Axisymmetric LS-Dyna simulations are launched iteratively, taking as an input the measured current and a set of values defined by the LS-Opt algorithm for the material constitutive parameters. The objective function – to be minimized by the optimization algorithm – is the mean square error between the velocity measurement and the calculated radial velocity. This method is applied simultaneously on two tests at different energies: to identify 4 parameters, the experimental basis has to be wide enough [Henchi&al.].
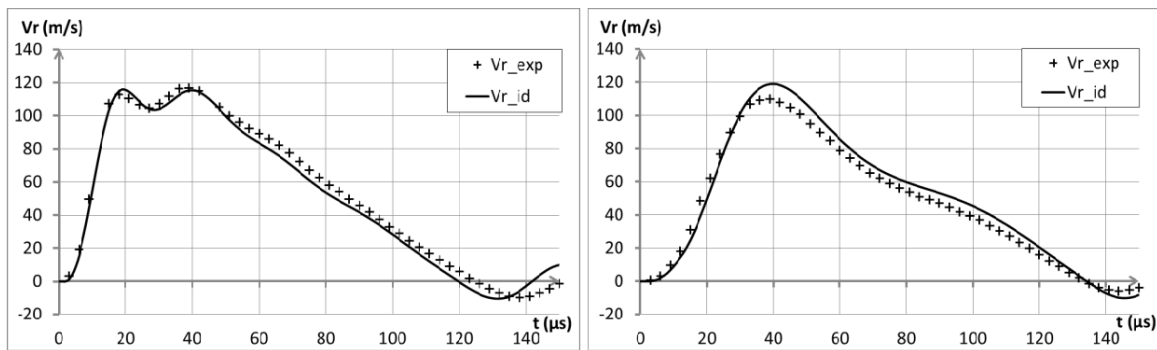

Fig.2. Radial expansion velocity curves, from PDV measurement (Vr_exp) and identification result (Vr_id) for two tests with different pulse.

The set of parameters corresponding to the minimum of the objective function is found to be {A = 80 MPa; B = 100 MPa; n = 0.36; C = 0.035} for the case of Al 1050 annealed tubes, at strain-rates of about 2000 s^{-1}. The experimental curves are well fitted (Fig. 2) and the corresponding mechanical behaviour shows higher stress levels than in quasi-static tensile tests (Fig. 3).
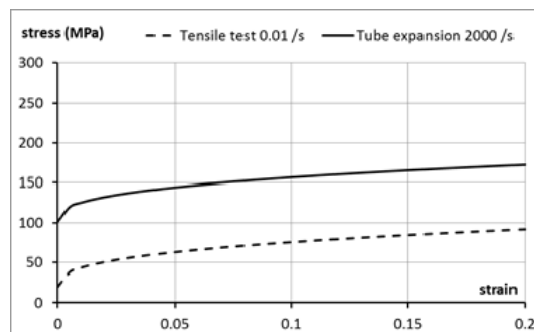

Fig.3. Stress-strain curves in quasi-static (0.01 /s) and dynamic (2000 /s) conditions.

5. 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 – different from the one used in the identification procedure hereabove. Figure 5 shows the global three-dimensional mesh encompassing both the coil and the workpiece. Figures 6a and 6b provide results at an intermediate stage regarding current densities and material velocities.
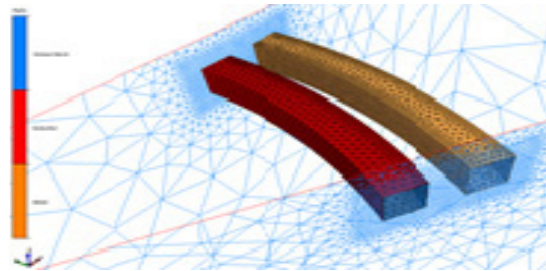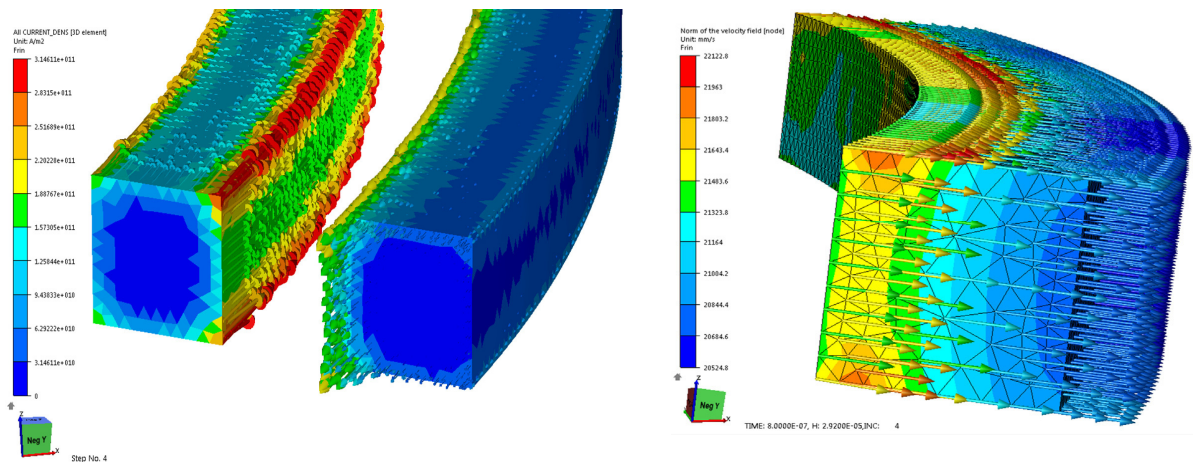

Fig.4 .Global mesh for a ring expansion case.

Fig.5. Results a) Current densities b) Mesh velocities.

6. Conclusion

We have present 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. We have also introduced an identification procedure and a mechanical test based on tube expansion and meant to achieve material behaviour identification under mechanical loads quite close to the ones experienced in the process.

Regarding the development of the numerical 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 on the parameter identification model will be extended to sheet forming, which is the most employed form for industrial applications.

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