A computational model for magnetic pulse forming processes – Application to a test case and sensitivity to dynamic material behaviour

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Abstract

This paper aims at presenting an efficient computational tool for magnetic pulse forming processes. This too - based on the coupling between the FORGE® thermomechanical solver and an electromagnetic module - is then applied to investigating a test case provided by the I^{2}FG Group for benchmarking purposes. Comparisons carried out between the results obtained using a quasi-static constitutive law with one taking into account the dynamic behaviour of the material emphasize the sensitivity to dynamic material behaviour – and thus the need for carrying out material behaviour identification for strain rates close to the ones experiences by the material in such processes.

Keywords

Magnetic pulse forming, Computational modelling, Material Behaviour

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 (Psyk et al. 2011).

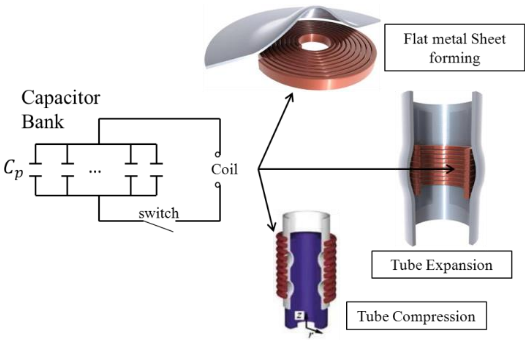

***Figure 1**: General Scheme of electromagnetic forming & typical forming configurations*

Designing and optimising these processes can be a quite intricate task due to the multiphysics couplings involved. It is therefore necessary to use approaches based on computational modelling of these processes. We present here an efficient multiphysics coupled electromagnetic/solid mechanics computational tool based on the coupling between the FORGE® thermomechanical solver and the electromagnetic module FORGE®\Induction. We then investigate a test case provided by the I^2FG Group on an aluminium alloy AW-6060 T6 for benchmarking purpose. We compare the simulation results obtained using a quasi-static point-wise constitutive data with the ones obtained using the material data software JMatPro®V.9. These results emphasize the need for carrying out material behaviour identification for strain rates close to the ones experienced by the material in such processes.

2 The computational model

The computational model (Alves Z and Bay 2016)is based on the coupling between an electromagnetic model and a thermomechanical model .

2.1 The electromagnetic model

The electromagnetic model is based on the classical Maxwell equations using the quasi-steady state approximation

$$\nabla \times \vec{H} = \vec{J} \tag{1}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \vec{B} = 0 \tag{3}$$

where $\vec{H}$ refers to the magnetic field, $\vec{B}$ the magnetic induction, $\vec{E}$ the electric field, and $\vec{J}$ the electric current density.

In order to consider the material properties, the constitutive laws of electromagnetic conductors must complete these equations

$$\vec{J} = \frac{1}{\rho}\vec{E} \tag{4}$$

$$\vec{B} = \mu\vec{H} \tag{5}$$

which correspond to the Ohm law and the magnetization law. ρ and μ denote respectively the electrical resistivity and the magnetic permeability. These parameters of course strongly depend on temperature; moreover, the magnetic permeability also depends on magnetic field strength for non-linear ferromagnetic materials. These equations are then integrated in a global A-V potential formulation.

$$\frac{1}{\rho}\frac{\partial\vec{A}}{\partial t} + \frac{1}{\mu_0}\nabla\times\frac{1}{\mu_r}\nabla\times\vec{A} = -\frac{1}{\rho}\nabla\phi \tag{6.1}$$

$$\nabla\cdot\left(\frac{1}{\rho}\nabla\phi\right) = 0 \tag{6.2}$$

Where, $\vec{A}$ is the magnetic potential, ϕ is the electric potential.

Finite element discretisation is then carried out using tetrahedral finite elements; edge finite elements (Nédélec 1986) are used for determining the magnetic vector potential field A while classical nodal elements are used for the electric potential ϕ. In order to be more efficient in terms of parallel computations, it has been decided to use a global finite element approach to solve the problem – rather than a mixed finite element/boundary element approach (L'Eplattenier and Cook 2009). A global domain is thus defined - embedding the workpiece, the inductors, as well as an air domain wide enough in order to model accurately electromagnetic wave propagation.

2.2 The solid mechanics model – The constitutive law

Regarding displacements and stresses, the model is classically based on the conservation of momentum equations.

$$\nabla\cdot\sigma + \vec{f} = \vec{0} \tag{7}$$

The Lorentz forces are taken into account through the volume force term.

$$\vec{f}_{lorentz} = \vec{J}\times\vec{B} \tag{8}$$

A specificity of EMF forming processes lies in the knowledge of the material behaviour. EMF forming processes typically lead to strain rates that can be comprised between 10^2 and 10^4 s^{-1}. Many constitutive models have been proposed to take into account dynamic effects in material behaviour, and can be basically sorted in three classes: 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); the models that are more specific to shock regimes and viscous drag; and the phenomenological models such as the [Cowper-Symonds] or the [Johnson-Cook's] models (Eq. 9).

$$\bar{\sigma} = \left[A + B\bar{\varepsilon}_{pl}^{n}\right]\left[1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}\right] \tag{9}$$

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

Our computational modelling tool has been designed to deal with either analytical macroscopic constitutive laws – such as the Johnson-Cook models – or with tabulated point-wise data provided by experimental tests or computer-aided tools – such as JMatPro®.

2.3 Multiphysics coupling strategy

Selecting an appropriate coupling strategy needs to be related to the strength of the multiphysics coupling and the specific time scales differences between the electromagnetic problem and the thermomechanical model. For magnetic pulse forming processes, the strong coupling between the electromagnetic problem and the mechanical problem – magnetic inductance changes strongly with material deformation – have led us to implement a coupling at each time step between the electromagnetic and thermomechanical models.

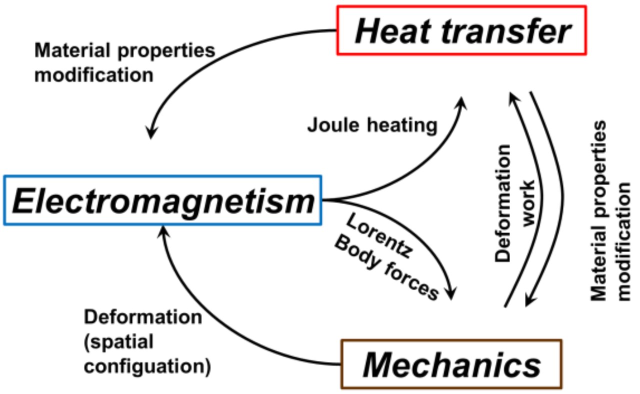

Figure 2: *Scheme of the mutliphysics couplings and interactions*

One of the main challenges for solving multi-physical problems is how to set-up the resolution scheme in terms of the coupling between the physics. As shown in Figure 2, all the physical aspects are highly dependent one on each other. The two main options that can be proposed are: (a) To include all the physics in a single solver for a simultaneous resolution (strongly-coupled). Or (b) solve each physics in a separate fashion, communicate and correct iteratively. We have chosen to follow this sequentially-coupled approach because solving the physics separately has the advantage of allowing independent management of the meshes – meaning that each problem will have a finite element space adapted to its own requirements.

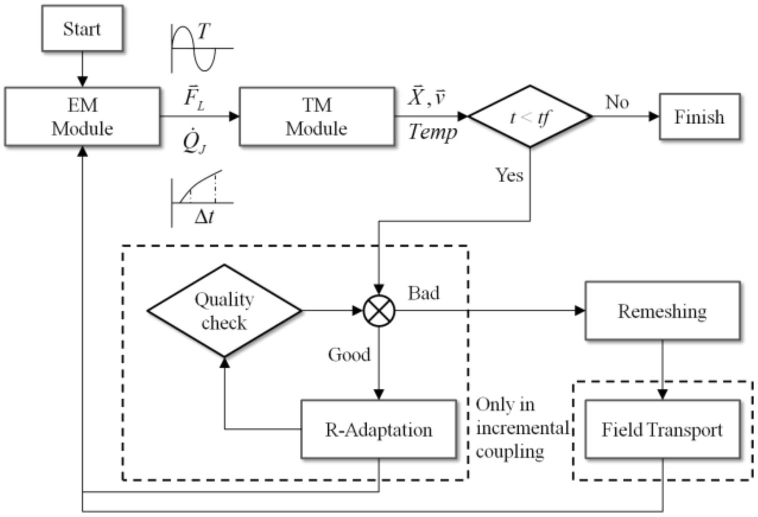

Figure 3: *Global algorithm: coupling between the solvers and the mesh adaptation modules.*

3 Analysis of the test case - Application to a test case and sensitivity to dynamic material behaviour

3.1 The test case

We shall now deal here with the analysis of the influence of the dynamic behaviour of the material on a magnetic pulse forming test.

The case has been provided by the I^{2}FG group. We shall carry out the modelling stage with a quasi-static constitutive law and then with a modified constitutive law taking into account the dynamical behaviour.

A tube of length 200mm, outer diameter 40 mm and nominal wall thickness 2 mm is subject to magnetic forces (Figure 6) created by the discharge of current in a coil.

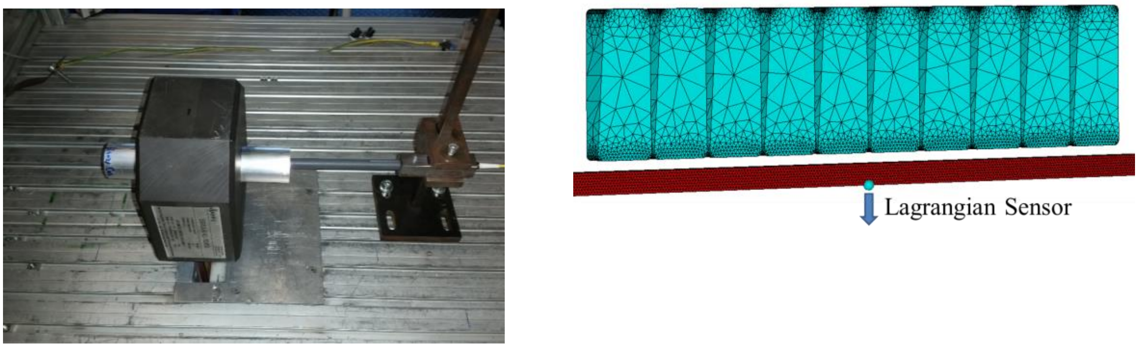

Figure 6: *The modeled case: (left) experimental test case (right) 5° simulation model.*

The tube is made out of an AlSiMg0.5 alloy. Data for quasi-static behaviour have been provided for this case.

Additional data for dynamic behaviour have been extrapolated using the JMATPRO tool. The stress-strain curves for quasi-static behavior, as well as at various strain rates (10^{-3} s^{-1}, 1 s^{-1}, 10^{3} s^{-1}) are displayed in Figure 7

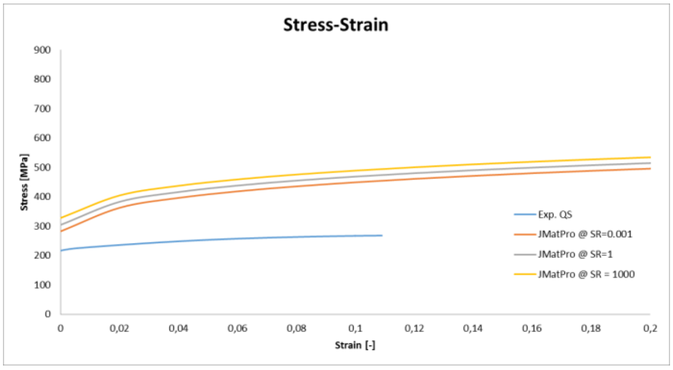

Figure 7: *Material constitutive behaviour*

Different initial energy values have been used (3kJ, 4kJ, and 5 kJ)

3.2 Modelling and results

The presented case has been modelled using 3 different energy levels: 3kJ, 4kJ, and 5 kJ and the quasi-static as well as dynamic behaviour constitutive law for the tube material. Tube velocities are plotted in Figure 7. As expected, we can observe from these results that the higher the energy level, the higher the velocity. Another point is related to the material behaviour which induces a more rigid behaviour when considering dynamic effects.

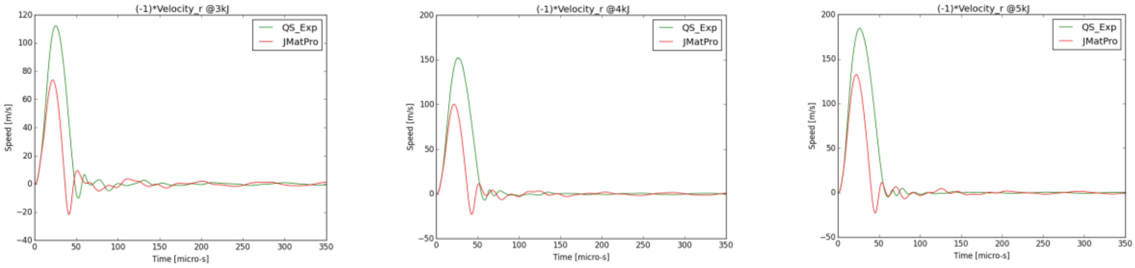

Figure 7: *Velocity curves from the simulation results at the centre of the tube (Lagrangian sensor).*

Figure 8 presents the electric current outputs for 3 different energy levels and the two different material behaviours. One of the first observables is that regardless of the rheological material law used, the predicted current peak is higher than the value obtained from the experiments by about 15kA (for all three cases). We suspect that the equivalent electric resistivity in the simulation is lower compared to the experiment. From a simple 0D approach we can (roughly) estimate the equivalent parameters of a coupled system by (Fenton 1996; Alves Zapata 2016)

$$R_{eq} = R_m + R_{ind} + \frac{M^2}{L_{billet}^2} R_{billet} \tag{10}$$

We can argue that the symmetric simplification of the study case reduces the geometrical inductance of the inductor and also the mutual inductance seen between the bodies. In such a case, the resulting resistance can be highly affected.

A second observation shows that the frequency slightly increases in the dynamic behaviour case compared with the quasi-static one. This can be explained by the fact that as the tube motion is slower in the dynamic case due to the dynamic hardening, the coupling inductance decreases less rapidly than in the quasi-static case – and thus the frequency slightly increases.

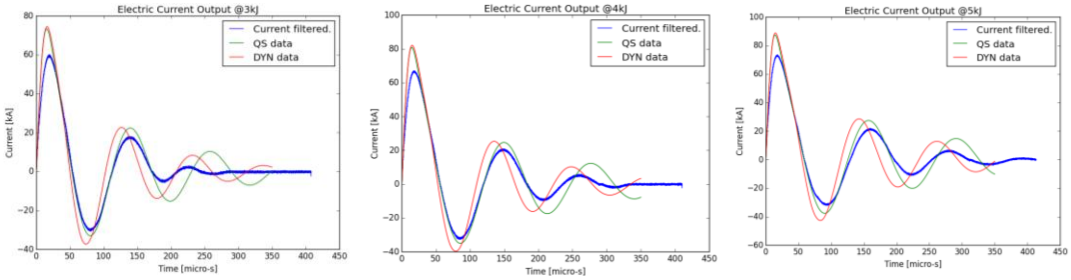

Figure 8: *Electric current output*

The influence of the strain rate on the dynamic behaviour can in fact be explained by the strain rate levels reached during the process. Figure 9 displays some strain rate isovalues during the process which emphasize the need to consider dynamic behaviour in the constitutive law.

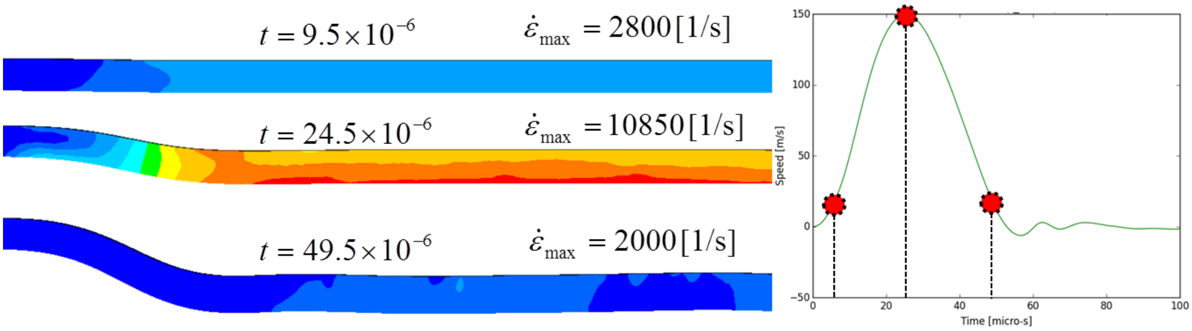

Figure 9: *Strain rate isovalues (QS @4kJ)*

4 Conclusion

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

This model has been applied to a magnetic pulse forming case. The results obtained show the importance of considering dynamic behaviour in the constitutive law. This emphasizes the need for identification procedures for a constitutive law under mechanical loads quite close to the ones experienced in the process.

The next stages of this work will deal with the development of numerical strategies aiming at reducing computation times and based on an intensive use of parallel computations, as well as coupling and integrating this model in a complete automated optimisation approach for magnetic pulse forming processes.

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REFERENCES

Alves Z, Jose R., and François Bay. 2016. "Modeling and Analysis of Electromagnetism in Magnetic Forming Processes." *IEEE Transactions on Magnetics* 52 (5): 1–12. doi:10.1109/TMAG.2015.2501758.

Alves Zapata, José Rodolfo. 2016. "Magnetic Pulse Forming Processes : Computational Modelling and Experimental Validation." PSL Research University. https://pastel.archives-ouvertes.fr/tel-01417196.

Fenton, GK. 1996. "Development of Numerical Tools to Model Plasticity in Aluminum due to Electromagnetic Forces." The Ohio State University. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.127.1140.

L'Eplattenier, P, and G Cook. 2009. "Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical-Thermal-Electromagnetic Simulations." In *3rd International Conference on High Speed Forming*, 85–96. http://onlinelibrary.wiley.com/doi/10.2374/SRI08SP152/abstract.

Nédélec, J.C. 1986. "A New Family of Mixed Finite Elements in] R 3." *Numer. Math* 50: 57–81. http://www.math.purdue.edu/~santos/research/Curcio/papers_reference/nedelec_numerische_86.pdf.

Psyk, V., D. Risch, B.L. Kinsey, a.E. Tekkaya, and M. Kleiner. 2011. "Electromagnetic forming—A Review." *Journal of Materials Processing Technology* 211 (5): 787–829. doi:10.1016/j.jmatprotec.2010.12.012.