Modelling and Simulation of 3D electromagnetic metal forming processes

J. Unger\(^1\), M. Stiemer\(^2\), M. Schwarze\(^3\), B. Svendsen\(^1\), H. Blum\(^2\), S. Reese\(^3\)

\(^1\)Chair of Mechanics - Leonard Euler Str. 5 D-44227 Dortmund  
URL: www.mech.mb.uni-dortmund.de  
e-mail: unger@mech.mb.uni-dortmund.de  

\(^2\)Chair of Scientific Computing - Vogelpothsweg 87, D-44227 Dortmund  
URL: www.mathematik.uni-dortmund.de/lsx  
e-mail: Marcus.Stiemer@math.uni-dortmund.de  

\(^3\)Chair of Mechanics - Schleinitzstr. 20, D-38023 Brunswick  
URL: www.tu-braunschweig.de/fm  
e-mail: marco.schwarze@tu-bs.de

ABSTRACT: The purpose of this work is the formulation of a thermo-magneto-mechanical multifield model and presentation of the numerical strategies applied. In particular, this model is used to simulate electromagnetic sheet metal forming processes (EMF). In this process, deformation of the workpiece is driven by the interaction of a current generated in the workpiece with a magnetic field generated by a coil adjacent to the workpiece. The interaction of these two fields results in a material body force known as Lorentz force. Up to now, modeling approaches found in literature for EMF are restricted to the axisymmetric case. For real industrial applications however, the modeling of 3-dimensional forming operations becomes crucial for an effective process design. The development and application of such a 3D model is the subject of the work at hand.

KEYWORDS: 3D electromagnetic forming processes, Magneto-thermomechanical coupling, staggered solution algorithm, finite-element method

1 INTRODUCTION

Electromagnetic forming is a dynamic, high strain-rate forming method in which strain-rates of \(\geq 10^3\) s\(^{-1}\) are achieved. In this process, deformation of the workpiece is driven by the interaction of a current generated in the workpiece with a magnetic field generated by a coil adjacent to the workpiece. In particular, the interaction of these two fields results in a material body force, \(i.e.,\) the Lorentz force and the electromotive power, representing an additional supply of momentum and energy to the material.

In recent years considerable effort has been made to simulate such coupled processes. However, approaches tested sofar were mainly restricted to 2D or axisymmetric geometries [1, 2, 4]. Yet, it is just the 3D modeling capability that is required to advance effectively in the design of industrial EMF processes. In this work the modeling and simulation approaches for such a 3D model are discussed and results for a relatively simple forming setup with a square shaped sheet metal and an angled tool coil are presented.

2 SYNOPSIS OF MODEL FORMULATION

The coupled multifield model for electromagnetic forming of interest here, represents a special case of the general continuum thermodynamic formulation for inelastic non-polarizable and non-magnetizable materials given in [7]. The algorithmic realization of the model is discussed in [6], for further details we refer to these publications. In particular, this special case is based on the quasi-static approximation to Maxwell’s equations, in which the wave character of the electromagnetic (EM) fields is neglected. Here, the system consists of the workpiece, the tool coil, and air (see Figure 2). As such, \(R\) contains in particular the fixed reference configuration \(B_0\), and all subsequent \((i.e.,\) deformed\) configurations, of the workpiece. Note that \(F := \nabla \xi\) represents the deformation gradient, and \(L := \nabla v\) the spatial velocity gradient. In this case, the unknown fields of interest are the motion field \(\xi\), the scalar potential \(\chi\) and the vector potential \(a\) determining in particular the magnetic field in the usual fashion. Assuming Dirichlet boundary conditions for all fields, one derives the weak field re-
lations

\[ 0 = \int_{R} (q_{r} \tilde{\xi} - l_{r}) \cdot \dot{\xi} + \kappa_{F} \cdot \nabla \dot{\xi}, \]

\[ 0 = \int_{R} \{ a + L^{*} a \} \cdot a_{s} + \]

\[ \int_{R} (\chi - a \cdot v) \text{div} a_{s} + \kappa_{EM} \text{curl} a \cdot \text{curl} a_{s}, \]

\[ 0 = \int_{R} \nabla \chi \cdot \nabla \chi_{s}, \]

(1)

for \( \xi, a, \) and \( \chi \), respectively. Here, \( \xi_{s}, a_{s}, \) and \( \chi_{s} \) represent the corresponding test fields. Further, \( R \) represents a fixed region in Euclidean point space containing the system under consideration in which the electromagnetic fields exist and on whose boundary the boundary conditions for these fields are specified. Further, \( \kappa_{EM} \) represents the magnetic diffusivity, \( v \) the spatial velocity field, \( q_{r} \) the referential mass density, \( K \) the Kirchhoff stress, and \( l_{r} = \text{det}(F) j \times b \) the Lorentz force in terms of the magnetic flux \( b = \text{curl} a \) and the current density \( j \). Note that (1) follow from Maxwell’s equations, while (1) represents the weak form of momentum balance. The above weak field relations are completed by the thermodynamically consistent formulation of the adiabatic thermo-elasto-viscoplastic material model.

Consider next the finite-element discretization of (1). The difference in electromagnetic and thermomechanical timescales together with the distinct nature of the fields involved (i.e., Eulerian in the electromagnetic case, Lagrangian in the thermomechanical large deformation context), argue for a staggered numerical solution procedure resulting in the following algorithmic system:

\[ f_{n}(x_{n+1}, a_{n+1}) = 0, \]

\[ e_{n}(x_{n+1}, a_{n+1}) = 0, \]

(2)

in terms of the arrays \( x_{n+1} \) and \( a_{n+1} \) of time-dependent system nodal positions and vector potential values at time increment \( t_{n+1} \). The solution of the mechanical part of (2) involves in particular the consistent linearization required for the Newton-Raphson iteration in the context of large deformation inelastic problems. In detail, the staggered algorithm procedure consists of the following steps:

1. Initialize \( a_{0}, x_{0} \) and their time derivatives and proceed to (4).

2. A starting value \( a_{n+1} \) of the nodal vector potential array is computed for the measured amperage in the tool coil at time \( t_{n+1} \) and the known mechanical state of the system at time \( t_{n} \) via (2).

3. From \( a_{n+1} \), a corresponding value \( l_{n+1} \) for the Lorentz force is obtained. Using this, the system consisting of (2) is solved via Newton-Raphson iteration (i.e., at fixed \( a_{n+1} \)) to obtain \( x_{n+1} \).

4. Proceed to next time step \( t_{n+1} = t_{n} + t_{n+1} \) and proceed with (2). Else, if \( l_{n} \geq l_{s} \), terminate the simulation. Where \( l_{s} \) is the total simulation time.

Besides the physical motivation, the staggered algorithm offers the possibility to apply specialized solutions for both, the mechanical as well as the EM-system without interference with the corresponding counterpart. Here, on the mechanical side an effective continuum shell formulation is applied to minimize the computational effort [5]. On the electromagnetic side, in contrast to the axisymmetric case, the Coulomb gauge condition is generally not satisfied and the electromagnetic fields are not regular for standard boundary conditions. To ensure that the corresponding finite element solution reflects this lack of smoothness, a penalty method or a least-squares approach is required. In the simulation presented here, Nédélec elements [3] are employed to overcome this difficulty. These are based on averaged degrees-of-freedom with respect to the element edges instead of discrete degrees-of-freedom at the element nodes. The discussion of the basic modeling aspects is concluded with a brief discussion of data transfer and meshing characteristics. In previous finite element models of the EMF process the nodal positions of the EM finite-element mesh was fixed in space at any time. This required a relatively fine discretization in the region where the workpiece is moving to minimize the error induced by elements containing Gaussian points in both domains (see Figure 1 above).
Figure 1: Different meshing strategies. Above: fictive boundary method with inaccurate modeling of boundaries. Below: Improvement by means of ALE approach.

Such elements suffer from their inability to represent sharp transitions imposed by the different EM-properties of the surrounding air and the workpiece. This approach is known from fluid structure interaction as the fictive boundary method. A more recent approach applies an incrementally progressing mesh-updating algorithm [6] and is based on the arbitrary Lagrangian Eulerian solution scheme (ALE). Here, the position of the nodal coordinates of the EM-Mesh is adopted by means of solving the Laplace problem. The surface of the workpiece, tool coil and the surface limiting the EM-System represent the constraints in terms of the workpiece deformation for the mesh smoothing procedure. In particular note, that at each time increment the boundary of the workpiece moves and imposes a prescribed displacement for the new nodal positions of the EM-mesh such that the nodes of both meshes match at the boundary of the workpiece. As a result, at any time, and EM-mesh exhibits a consistent morphology as depicted in Figure 1 below.

3 APPLICATION

Results shown here are obtained on the basis of a square shaped sheet metal and an angled tool coil. Simulations have been carried out for a sheet metal plate consisting of the aluminium alloy AA 6005. The identification of the dynamic viscoplastic material parameters for this material has been carried out with the help of experimental data of the dynamic expansion of metal tubes via a maximum likelihood estimation using finite-element simulation together with experimental data and can be obtained from [?]. The forming setup for the electromagnetic sheet metal forming process of interest here is depicted in Figure 2. It has a width and depth of 60 mm and a height of 7 mm. The air gap between the sheet metal and the tool coil and the thickness of the sheet metal measure 1 mm. The height of the tool coil measures 5 mm and each winding has a width of 20 mm.

As indicated in Figure 2 the sheet metal is fixed at its lateral edges representing the mechanical Dirichlet boundary conditions. For the tool coil the eddy current contribution to the current density is neglected. This facilitates the implementation of the measured input current $I$ as a Neumann boundary condition via $\mathbf{j} = -\sigma_{\text{EM}} \nabla \chi$ where $\mathbf{j} = (0, I/A_{\text{con}}, 0)$. Here, $A_{\text{con}}$ represents the area of the surface connecting the tool coil to the capacitor bank that provides the energy for the forming operation. The other connection surface is grounded ($\chi = 0$). For the remaining surfaces $\nabla \chi \cdot \mathbf{n} = 0$ is postulated meaning that no electric current leaves the coil through any surface but the connection surfaces. Since the deformation of the sheet metal and thus the correct modeling of the electromagnetic loading represents the main concern in this study the neglect of the eddy currents in the tool coil is justified. As a consequence the current flux distribution is relatively homogeneous in the cross section of the tool coil (no skin effect). However, the effect of this assumption on the magnetic field strength outside the coil and in particularly in the sheet metal is relatively small since the total current $I$ is considered correctly. An additional assumption refers to the sheet metal. Here the physical constraint $\mathbf{j} \cdot \mathbf{n} = 0$ is not considered. Since tool coils utilized for EMF generally induce circular eddy currents, the error made by this assumption can be considered to be small. The
simulated magnetic field and eddy current distribution development for this setup is shown in Figure 3. In the sheet metal, eddy currents are induced which are orientated in opposition to the tool coil current. This leads to a reduction of the magnetic flux density above the sheet metal and to a concentration of $b$ in the air gap between the sheet metal and the tool coil. As shown in Figure 3, $b$ and $j$ are in general parallel to the sheet plane and perpendicular to each other resulting in a lorentz force which acts normal to the sheet plane. Initially, the values of $b$ and $j$ in the sheet metal and so the Lorentz force are extremely high. As the sheet-plate is accelerated away from the tool coil, however, it moves into a region where $b$ is nearly zero.

Forming stages for the plate at various instances are shown in Figure 4. The contours represent the development of the accumulated inelastic deformation $\epsilon$. Maximum values of the strain rate reached here are on the order of $10^4$ s$^{-1}$. At the beginning of the process, the center of the plate remains at rest, whereas just above the tool coil winding, the plate experiences high Lorenz forces and begins to accelerate. In later stages, the center of the plate is then pulled along by the rest of the plate and accelerated via predominantly inertial forces, resulting in the roof top shaped structure at the end of the process with maximal inelastic strain in the top.

Figure 3: Development of the of the magnetic flux (above) and eddy current distribution in the sheet metal (below) at $t = 12\mu s$.

Figure 4: Development of the deformation and equivalent inelastic strain $\epsilon$, with max($\epsilon$) = 0.18 at instances $t = 60\mu s$, $t = 120\mu s$ and $t = 300\mu s$ (final state).

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