Comput. Methods Appl. Mech. Engrg. 198 (2009) 1535–1547

Contents lists available at ScienceDirect

Comput. Methods Appl. Mech. Engrg.

journal homepage: www.elsevier.com/locate/cma

An arbitrary Lagrangian Eulerian approach to the three-dimensional simulation of electromagnetic forming ☆

M. Stiemer [a,*], J. Unger [b], B. Svendsen [b], H. Blum [a]

[a] University of Dortmund, Chair of Scientific Computing, Vogelpothsweg 87, 44227 Dortmund, Germany
[b] University of Dortmund, Chair of Mechanics, Germany

ARTICLE INFO

Article history:
Received 30 September 2006
Received in revised form 4 January 2009
Accepted 8 January 2009
Available online 27 January 2009

PACS:
45.10.−b
46.35.+z
02.70.−c

Keywords:
Continuum mechanics
Electromagnetic–inelastic coupling
Multifield problems
Finite-element method

ABSTRACT

Electromagnetic metal forming is a contact-free high-speed forming process in which strain rates of more than $10^3\ s^{-1}$ are achieved. The deformation of the workpiece is driven by the Lorentz force, a material body force, that results from the interaction of a pulsed magnetic field with eddy currents induced in the workpiece by the magnetic field itself. In this work, a coupled 3D simulation of this process is presented. For the mechanical structure a thermoelastic, viscoplastic, electromagnetic material model is relevant, which is incorporated in a large-deformation dynamic formulation. The evolution of the electromagnetic fields is governed by Maxwell's equations under quasi-static conditions. Their numerical solution in 3D requires particular arrangements due to problems connected with an adequate gauging of the fields. Hence, Nédélec elements are employed. Coupling between the thermomechanical and electromagnetic subsystems takes the form of the Lorentz force, the electromotive intensity, and the current geometry of the workpiece. A staggered scheme based on a Lagrangian mesh for the workpiece and an ALE formulation for the electromagnetic field is utilized to solve the coupled system, guaranteeing the efficiency and accuracy of the data transfer between the two meshes.

1. Introduction

Electromagnetic metal forming (EMF) is a contact-free high-speed forming process in which strain rates of more than $10^3\ s^{-1}$ are achieved. In this process, the deformation of the workpiece is driven by a material body force, the Lorentz force, that results from the interaction of a pulsed magnetic field with eddy currents induced in the workpiece by the magnetic field itself. The magnetic field is triggered by a tool coil adjacent to the workpiece, which is excited by a current produced by a capacitor bank. Fig. 1 displays a typical device for sheet metal forming. EMF offers certain advantages over other forming methods such as an increased formability, the avoidance of contact, a reduction in wrinkling, reduced tool making costs, the opportunity to combine forming and assembly operations, and many more. However, the highly dynamic nature of this process inhibits its monitoring and control. Consequently, its industrial use has been limited to joining tubular semi-finished materials, while e.g., electromagnetic sheet metal forming is not ready for a profitable application yet. This emphasizes the significance of reliable simulations of this process to identify relevant process parameters and to optimize them. For details of the design of electromagnetic forming processes the reader is referred to [1].

Since the introduction of high-speed computers in the 1980s, a number of numerical simulations of EMF have been undertaken including [2–5]. More recently, Beerwald et al. [6] and Brosius et al. [7] utilized commercial programs like ABAQUS or MARC for the simulation of the process. However, in all approaches reported on above emphasis is placed on the modeling and simulation of the coupling between the electromagnetic and the mechanical model, while the employed material models were not adapted to the particular requirements of the process. These include first of all a consideration of the rate-dependence, which is typical of the behavior of metallic materials at high forming rates such as those achieved during EMF. This is connected to the fact that the mechanical dissipation may result in a possibly significant temperature increase in this nearly adiabatic process. Recently, a relevant thermodynamically-consistent electromagnetic thermoelastic multifield model has been developed by Svendsen and Chanda [8,9] and implemented in [10], based on a Lagrangian formulation for the mechanical system and an Eulerian formulation on a fixed mesh for the electromagnetic system within an axisymmetric context.

☆ This work is funded by the German Research Foundation (DFG) under the contract FOR443. The authors which to express their gratitude for the financial support.

* Corresponding author. Tel.: +49 231 755 3061.
E-mail address: stiemer@math.uni-dortmund.de (M. Stiemer).

0045-7825/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.cma.2009.01.014

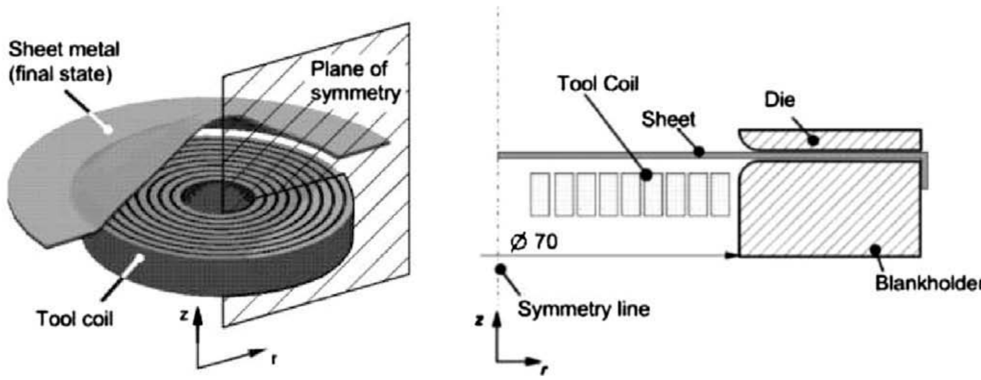

Fig. 1. A typical device for electromagnetic sheet metal forming.

A drawback of the numerical schemes reported on above is their restriction to two-dimensional or axisymmetric situations. However, practical forming devices often significantly deviate from axisymmetry. The much larger number of unknowns dramatically increases the numerical efforts needed to solve the problem. This requires much more algorithmic sophistication to avoid unacceptably long computing times. In addition, three-dimensional electromagnetic simulations demand a particular numerical treatment connected with the requirement of an appropriate gauging (see Section 3). There are several methods to cope with this problem, including penalty or least square approaches [11]. Here, Nédélec finite elements [12,13] are employed.

There are several coupling mechanisms between the thermomechanical and the electromagnetic subsystem. On the one hand, the Lorentz force computed from the electromagnetic simulation serves as load term in the mechanical impulse balance. On the other hand, the conductivity distribution entering the electromagnetic simulation via the diffusivity in the eddy current model is determined by the current position of the structure. Further, the electromotive intensity represents an additional coupling term. The most natural way to discretize the field equations in the context of their usual formulation is to employ a fixed Eulerian mesh for the electromagnetic field and to use a moving Lagrangian mesh for the mechanical structure. However, it has turned out that such an approach leads to serious problems in the data transfer between the fixed and the moving mesh. Particularly, the computed Lorentz forces tend to oscillate and are not sufficiently accurate. To overcome this difficulty an arbitrary Lagrangian Eulerian (ALE) formulation for the electromagnetic field has additionally been developed (see Section 4).

Outside the area of good conducting material (i.e. the workpiece and the tool coil), the electromagnetic field equations in the here employed form of an equation for an electric scalar and a magnetic vector potential require an additional gauging to provide a unique solution. Particularly in an ALE approach a careful treatment of the problem of gauging is indispensable: on a moving ALE mesh, the mesh adaption induces a temporal variation of the divergence of the computed vector potential. This temporal variation would have to be considered in the equation for the electric scalar potential, which would result in an additional coupling of the equations for the vector potential and for the scalar potential. To avoid such difficulties, the irrotational part in the Helmholtz decomposition of the vector potential could be held temporally constant by use of a Lagrangian multiplier or by interpolation techniques. Here, a semi-gauged approach based on a non-isoparametric version of Nédélec elements is presented, working with trial functions possessing zero divergence on each single finite element. Unfortunately, this does not mean that a global Coulomb gauge is strictly fulfilled, since no continuity of normal components over interfaces between adjacent finite elements is enforced. The corresponding jumps provide a certain amount of "residual divergence". But it turns out that all test and trial functions are "sufficiently orthogonal" to the kernel of the curl-operator, such that an efficient solution of the resulting linear system of equations is possible [cf. [14]]. This approach ensures that the equations for the vector and for the scalar potential remain decoupled despite of the movement of certain parts of the configuration.

The paper is organized as follows: In Section 2, the model relations governing the coupled multifield model are presented. The algorithmic formulation of the mechanical and of the electromagnetic subsystem in the context of the finite-element method is described in Section 3. Next, the incorporation of the coupling between the two subsystems is discussed in Section 4. The paper ends with some remarks on the numerical validation of the simulation techniques presented here as well as with further conclusions.

2. Coupled electromagnetic–mechanical model

The magnetomechanical system to be modeled here consists of a *fixed* region $R \subset E$ of Euclidean point space E containing the workpiece (e.g., sheet metal) and the tool coil (see Fig. 1). As such, R contains the reference (e.g., initial) $B_r \subset R$ and current $B_c \subset R$ configurations of any one of these two bodies. They are modeled as electromagnetic, mechanical continua characterized by a time-dependent deformation field ξ together with the additional degrees of freedom represented by the electromagnetic fields to be introduced below. In the following, we will confine ourselves to the case that the tool coil remains fixed, which is an appropriate assumption in many situations.

Whereas the time-dependent electromagnetic fields are defined on the entire region R, i.e., also in the air surrounding stationary or moving material bodies, the deformation field ξ and all kinematic fields derived from it, are logically restricted to the configurations of deforming and moving bodies. Hence, no interface conditions need to be formulated for the mechanical fields, but only adequate boundary conditions. Particularly, the interaction of the moving workpiece and the surrounding air is neglected in the mechanic model, and hence a possibly non-continuous continuation of the material velocity field $\boldsymbol{v}$ to the air region does not need to be considered. The latter could be relevant, if e.g. supersonic shock waves triggered in the air significantly influenced the forming result. Experiments, however, suggest that such interactions may be neglected. Even in the case that the desired shape is formed with the help of a die, the material character of the air between workpiece and die can be neglected as long as the air can escape, e.g. through a hole in the die, according to experimental results.