Mathematical Optimization for the Virtual Design of Process Chains with Electromagnetic Forming

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Abstract

In this work, a framework for virtual process design for coupled processes including electromagnetic impulse forming is presented. Virtual process design is here understood as the computer based identification of suitable geometry and process parameters to reach a predefined forming result via physically feasible process paths. Implementation of this concept relies on three pillars: a physical process model, its implementation within a numerical simulation, and a mathematical optimization algorithm. This methodology is particularly applied to a combination of deep drawing and subsequent electromagnetic forming (EMF). In this case, the model is given by an anisotropic elasto-viscoplastic material model augmented by damage evolution and coupled with the magneto-quasistatic approximation to Maxwell's equations. For constrained mathematical optimization, an inner point algorithm is applied. With this method for virtual process design at hand, several technological problems are addressed including tool coil design and the identification of ideal electrical parameters of the tool coil circuit. Employing this framework requires the identification of the material model described above. It turns out that a high precision identification of material parameters can be achieved with basically the same mathematical algorithm as derived for process identification.

Keywords

Metal forming, Design optimization, Finite element method

1 Introduction

Contemporary forming technology has to cope with increasing demands resulting from requirements of light-weight construction on the one hand, and from the claim for high-strength parts on the other hand (Stiemer et al., 2011). To satisfyingly consider such opposing trends, the invention of new processes is required that extend the forming limits of classical quasi-static forming such as deep-drawing. A viable method to reach this goal are process combinations of a classical quasi-static forming method and a subsequent impulse forming process (Vohnout, 1998). Due to different damage mechanisms acting during the quasi-static and during the high-speed phase, the overall formability is increased even if both processes act on similar strain paths (Kiliclar et al., 2016). However, for certain process combinations such as deep-drawing and subsequent EMF, an increase in formability can only be achieved if all parameters of the combined process are carefully tuned (Taebi et al., 2012). Hence, a successful process control requires the identification of suitable process and geometry parameters, such as parameters describing the blank holder adjustment, tribological conditions, punch force and velocity on the quasi-static side, and tool shape and position or the discharging current on the electromagnetic side.

An experimental adjustment of these parameters is very time consuming. The high competition in modern markets forces technological solutions to be found in an increasingly short period. Hence, computer based methods become more and more important, since they allow for a reduction of expensive experiments required for a parameter identification process. In an ideal setting, only a final experimental verification of virtually identified technological solutions would remain.

In this work, virtual process design is understood as the computer based identification of suitable geometry and process parameters to reach a predefined forming result via physically feasible process paths. Implementation of this concepts relies on a physical process model, its implementation in a finite element simulation, and a mathematical optimization algorithm. The methodology developed here is particularly applied to a combination of deep drawing and subsequent EMF of aluminum EN AW 5083. In this case the model is given by a combination of an anisotropic elasto-viscoplastic material model (Vladimirov et al., 2010) augmented by damage evolution with the magneto-quasi-static approximation to Maxwell's equations (Vladimirov et al., 2014). For constrained mathematical optimization, an inner point algorithm is applied. With the method for virtual process design at hand, several technological problems can be addressed including tool coil design and the identification of ideal electrical parameters of the tool coil circuit. Employing this framework for virtual process design requires the identification of the material model described above. It turns out that the identification of material parameters in a high precision can be achieved with basically the same mathematical algorithm as derived for process identification.

In the following Chapter 2, a short introduction into the here exemplarily considered type of process combinations is given. Then, in Chapter 3, the mathematical framework of the method is sketched. In the main part of this work, Chapter 4, some concrete technological applications are discussed. The article ends with some conclusions in Chapter 5.

2 Combination of Quasi-static and Impulse Forming

EMF is a contact free impulse forming method yielding strain rates over 1000 s^{-1}. It is suited for electrically good conducting materials such as copper, aluminum, and even steel (see, e.g., Daehn 2006, or Psyk et al., 2011). In EMF, forming is triggered by Lorentz forces resulting from the interaction of eddy currents induced in the work piece by a pulsed magnetic field with the triggering magnetic field itself. The latter results from the discharging current of a capacitor bank into a tool coil close to the work piece. In the case of sheet metal forming, it acts most efficiently when applied to small areas as part of a process chain combined with a classical quasi-static process (Vonhout, 1998). In this particular context, classical forming limits of quasi-static processes can be extended yielding a broader range of applications (Psyk et al., 2011). In Fig. 1, a combined process setup for cup forming is depicted as an example. It consists of deep drawing followed by an electromagnetic calibration close to the bottom edge of the die. The tool coil is incorporated in the punch. This type of process combination will frequently be considered as an example in the following.

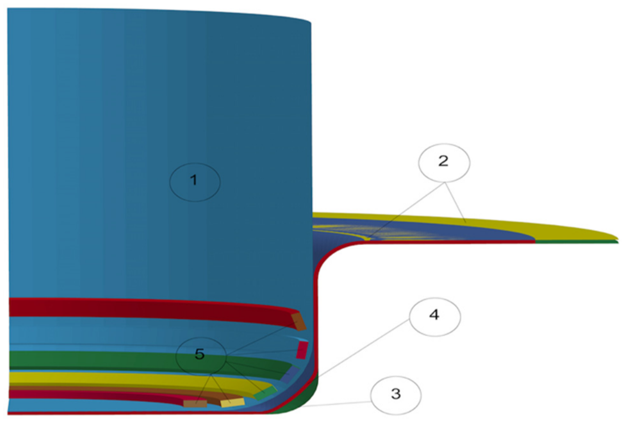

Figure 1: *Example of a process chain combining deep drawing and EMF: (1) punch, (2) blank holder, (3) die, (4) work piece, (5) tool coils (CAD model by Kiliclar, IFAM, Aachen)*

Several problems arise in the design of process chains including EMF: Particularly, it has turned out that an increase in formability can only be achieved if the process parameters are carefully tuned (Taebi et al., 2012). Moreover, the design of suitable, sufficiently stable and long living tool coils yielding the optimum Lorentz force is technologically challenging.

3 Mathematical Concepts

The paradigm followed in this work relies on a physical model of the combined process, which is capable of predicting the outcome of the process. Then, a process simulation is developed that is based on the physical model. Separation of physical modeling and numerical implementation is essential for a control of the accuracy of the process simulation. The next step is a quantitative validation of the simulated process result. The corresponding value could be the quadratic mean deviation between the shape resulting from the forming process as computed via simulation and an ideal shape (Taebi et al. 2012). The function that assigns to each set of certain process parameters of interest such a quantitative validation of the forming process is called an *objective function.* From the mathematical point of view, process identification can be considered as finding a local or even global extremum of the objective function. The case of a local extremum corresponds to the situation that only fractions of the parameter space are searched for, while the search of a global extremum refers to consideration of the whole space of suitable parameters. The latter is a more difficult task, and in many cases only local optima can satisfyingly be found by numerical algorithms (Nocedal, J. and Wright, S., 2006). Optimization problems resulting from parameter identification are typically constrained: all parameters are subject to bounds resulting from physical or technical considerations (Tarantola, A., 2005).

In this chapter the three mathematical pillars of a framework for virtual process design, the process model, its numerical simulation, and the mathematical optimization are individually discussed in case of a process combination of deep drawing and subsequent EMF as described in Chapter 2.

3.1 Process Models

Corresponding to the different physical nature of the individual constituents of the coupled process, both mechanical and electromagnetic fields have to be mathematically described. On the mechanical side, one model is employed that is both suitable for the quasi-static and for the high speed regime. This flexibility is achieved by an elasto-viscoplastic material model including strain rate effects and material anisotropy due to Vladimirov et al. (2010), which is coupled with a damage model to separate viable strain paths from those leading to material failure (Vladimirov et al. 2014). In this approach, a Hill-type plastic anisotropy model is employed. Further, a Perzyna rate dependent formulation is coupled with rate independent Kuhn-Tucker conditions, to model both regimes. Kiliclar et al. (2012) demonstrated the suitability of the model for the simulation of aluminum EN AW 5083.

On the electromagnetic side, the magneto-quasistatic approximation to Maxwell's equations is relevant. Since the wavelengths at typical field excitations for EMF (e.g., 50 kHz) are much longer than the size of a forming device, and since induction is the relevant coupling process between tool coil and work piece, displacement currents may be omitted.

3.2 Numerical Simulation

As the considered process relies on different physical models, various discretization techniques have to be considered to obtain a fast simulation scheme. In the context of the commercial software LS-DYNA, a boundary element solver for the air between tool coil and work piece, coupled with Nédélec edge finite elements for conducting material, is available. On the mechanical side, standard vertex based 3d volume elements can be used.

While LS-DYNA allows for a direct numerical solution of the coupled partial differential equations of the underlying model, it is sometimes more efficient not to solve the linear system of equations resulting from the finite element method directly, but to hand the assembled matrices over to the mathematical optimization routine. In the optimization step, compliance with the finite element system then defines a set of constraints for any critical state of the objective function. The latter guarantees that only physically feasible states are considered for optimization of the objective function, without solving the finite element system. This leads to an enormous gain in efficiency as Rozgiċ and Stiemer (2014) indicated. However, most commercial code that is employed as a black box solver lacks the flexibility to be employed in such a way.

3.3 Mathematical Optimization

The identification of suitable parameters is controlled by an exterior mathematical optimization algorithm. Here, the inner point method as implemented within IPOPT by A. Wächter and L. T. Biegler (2006) is employed. A complete algorithmic variant is depicted in Fig. 2, which relies on a use of LS-DYNA as black box solver. In this case, the mathematical model equations are solved and the objective function is computed from the identified state. This is not as efficient as the method described in the preceding section, where feasibility of the state was only established indirectly via constraints, but it is often more convenient to employ the finite element solver in its original fashion instead of accessing its internal data.

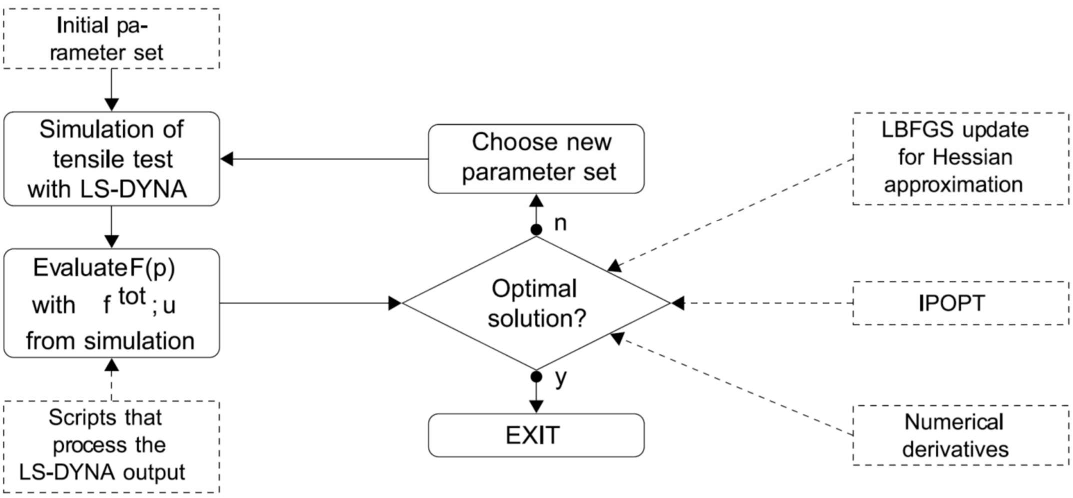

***Figure 2**: A flow chart of the process parameter identification algorithm (Kiliclar et al. 2016)*

4 Technological Applications

In this chapter typical technological applications of the method outlined before are presented including both process and model identification.

4.1 Identification of Material Parameters

Applications of the method described above to the identification of the underlying material model have been presented in Kiliclar et al. (2016), and, in more detail, in Rozgiċ et al. (2016). In the identification process simple experiments (e.g., uni-axial stress-strain curves etc.) are carried out and their outcome is compared to simulation results. As objective function a distance function between simulation result and experimental data can be taken. Via optimization those internal parameters of the material model are identified that yield the best agreement between experiments and simulation. The material model parameters obtained by the previously outlined procedure refer to quasi-static strain rates only. However, results by Clausen et al. (2004) show, that EN AW 5083 under high strain rates exhibits an increase in yield stress, but not in hardening. Therefore, the obtained results can be extended to high-strain rates by a linear extrapolation of the model's damage threshold (Kiliclar et al. 2016). This approach is validated by comparison to tensile tests with strain rates up to 1000 s^{-1}.

4.2 Identification of Current Parameters

Taebi et al. (2012) offered a first approach to the identification of ideal current parameters for the EMF step. The objective is to find those parameters for the pulse that make the bottom radius of a round cup formed from a disc-shaped metal sheet under axi-symmetric conditions as small as possible, such that no damage occurs. In that work, a damped cosine has been assumed as current function in the tool coil with amplitude I_0, angular frequency ω, damping parameter β, and phase angle φ:

$$I(t) = I_0 e^{\beta t} \cos(\omega t + \varphi) \tag{1}$$

While phase and damping have been held on a constant level, a two parameter optimization for the angular frequency and the amplitude has been performed. Forming limits were not included via a physically motivated damage model, but by a phenomenological approach resorting to so called forming limit surfaces, which account for rate dependency by rescaling a quasi-static forming limit curve according to the phenomenological Johnson, Cook (1985) damage model. These results have been experimentally validated.

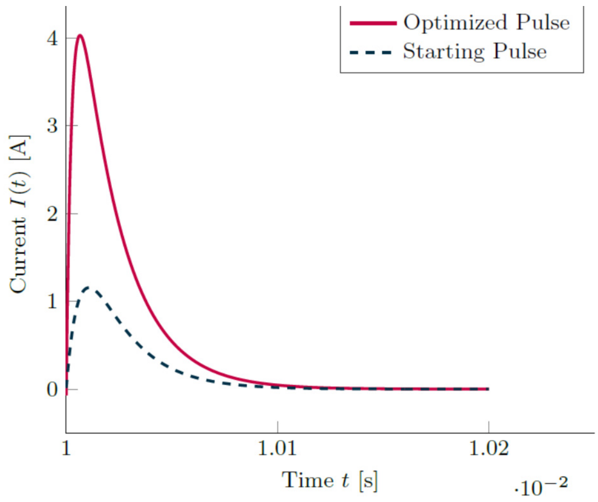

***Figure 3**: Current I(t) for the identified parameters* $I_\alpha = 65570$ A *and* $I_\beta = 64868$ A, *as well as the corresponding exponential factors* $\alpha = 6879\ \mathrm{s}^{-1}$ *and* $\beta = 973\ \mathrm{s}^{-1}$ *(Rozgiċ et al. 2016)*

Although a damped cosine seems to be a natural adjustment for the coil current, there are severe disadvantages connected to such an arrangement: The opposite sign of the second half-wave yields coil abrasion, since the work piece has already moved so far that it cannot bind a significant amount of momentum. Hence, the complete momentum resulting from the Lorentz force is absorbed by the tool coil, which makes the tool windings bend up and eventually break (Gies et al. 2012). This leads to the demand of avoidance of second half-waves. A technical approach to this claim is the construction of electrical supply circuits that prevent the second half wave. To analyze such approaches numerically, Rozgiċ et al. (2016) approximated the damped cosine with removed second half-wave by a double exponential pulse, which can quite conveniently be treated within the mathematical framework described above. To obtain the optimized characteristics of single pulse excitations, Rozgiċ et al. (2016) identified the two amplitudes I_α and I_β, as well as the corresponding exponential factors α and β in the pulse representation

$$I(t) = I_\alpha e^{-\alpha t} + I_\beta e^{-\beta t} \qquad (2)$$

Starting and resulting pulse of the parameter identification process are displayed in Fig. 3. For the complete set of data, see Rozgiċ et al. (2016).

4.3 Identification of Coil Parameters

An interesting application is the numerical identification of geometry parameters of the tool coil embedded in the punch employed for deep drawing.

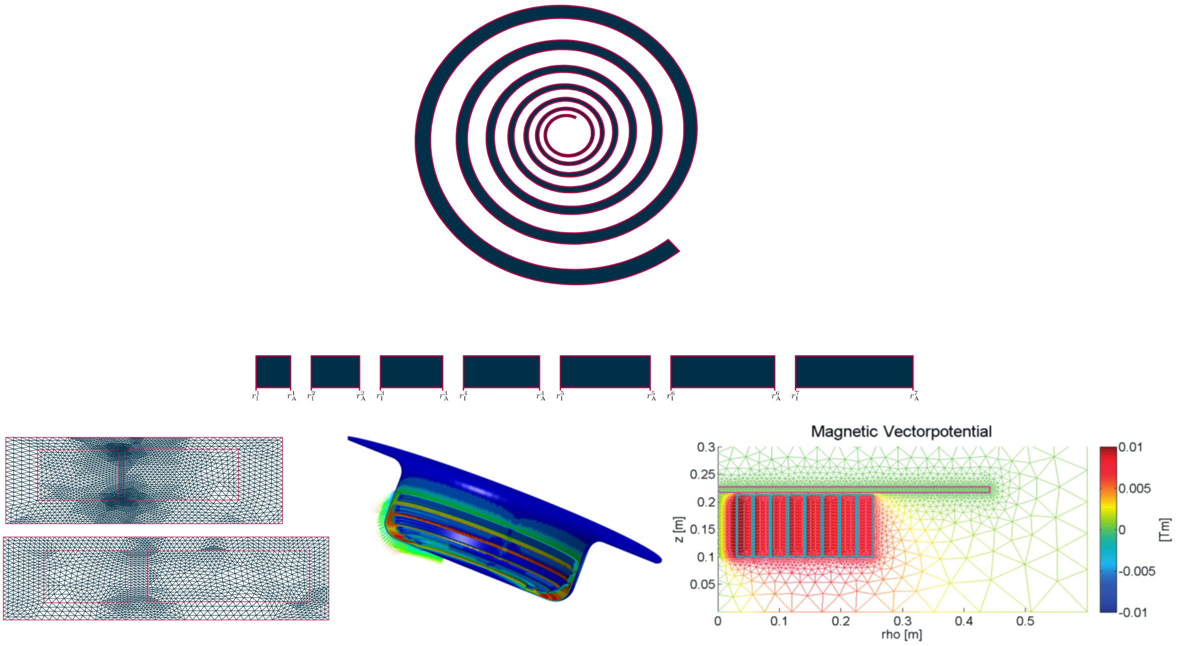

Figure 4: *Components of an algorithm for the identification of coil geometry parameters: tool coil (top), axi-symmetric adaptation of the tool coil (middle), meshes of different geometries (down, left), 3d field computation (down, middle), axi-symmetric field computation (down right)*

A sketch of such an algorithm is depicted in Fig. 4. Here, the problem arises that different geometries may lead to different mesh structures after discretization, and, hence, to different instances of optimization problems that cannot easily take part in a common parameter search. There are several approaches to overcome this difficulty: in case of consideration of only small geometrical deviations during parameter variation, the mesh structure does not need to be altered, and just a displacement of the mesh vertices has to be done. The structure of the resulting optimization problems is consequently not changed (see the two grids on the left hand side in Fig. 4). However, if large geometrical variations or even topology changes shall be taken into account, it could be helpful to consider a new mathematical approach, where optima to whole classes of optimization problems are searched for. The key to such an approach are uniformity properties of all members in such a family, which could be deduced if the optimization problem is considered as a continuous problem in a certain function space, which is only discretized, after analytical conditions for optimality have already been applied on the continuous level.

4.4 Identification of Quasi-static and of High-speed Parameters

Finally, parameter sets should be considered that both define electromagnetic and mechanical quantities. It will be interesting to investigate in what cases a splitting between the quasi-static regime and the impulse forming regime is always possible during optimization. Such a split always applies when strain paths are relevant where the full quasi-static forming limit can be exhausted before additional formability is gained by the fast forming method, since in this case both processes can be optimized independently of each other. The existence of such strain paths has been shown by Kiliclar et al. (2016).

5 Conclusions

In this work, a mathematical optimization scheme is coupled with a numerical process simulation to establish an environment for the automated identification of geometry and process parameters. The parameters are identified as stationary points of a suitable objective function under constraints and can be considered as the outcome of a virtual design process, since the identified process is described by these parameters.

To obtain efficient algorithms that allow to treat large problems, the finite element solver should not be employed as primary solver, but only as prepare-unit for the optimization method, which, hence, assumes the role of the solver. The idea behind this is to choose a rather simple objective function, such as, e.g., a distance function between an optimum part and a part that corresponds to the currently chosen parameters. The system of partial differential equations governing the technological processes is here just interpreted as side conditions to the optimization algorithm. Hence, a large speed up can be achieved. However, if an existing commercial code shall be employed as black box solver, this method can usually not be applied, since the required data are often not available.

By the virtual environment presented here, many important technological questions can be tackled: The identification of electrical current parameters in the EMF step minimizing drawing radii under the site condition that damage is avoided, the identification of parameters of the material model, the design of suitable tool coils, and, as intended in near future, complete sets of parameters including deep drawing parameters as well as electromagnetic parameters.

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