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Chapter 1

Introduction

In the last decade, the deployment of simulation systems in the automotive industry on the basis of the finite element method (FEM) became a standard for the evaluation of sheet metal forming processes. The scope of application begins with the car development phase and ends with the engineering phase of the production process. During the product design phase, the forming simulation enables to evaluate the producibility of parts and to derive necessary part modifications as early as possible. Another application in this phase is the investigation of the springback behavior that allows identifying actions for reducing this effect, which decreases the scattering of part shape in the press shop. Furthermore, the prediction of the process forces on the basis of the FEM supports the selection of the best possible press line for each part and the computed forming history increases the quality of simulations regarding the product functionality. During the engineering phase of the production process the forming simulation is applied for optimizing its design. Possibly, the springback is compensated by deriving a tool modification from the predicted part geometry. The mentioned applications of the finite element method in the field of the production of sheet metal parts underline its economic importance. Nevertheless, the benefit of the FEM based simulation strongly depends on the accuracy of the computed prediction.

The prediction of the forming simulation is based on laws, which originate from theoretical physics. The aim of theoretical physics is to construct mathematical models such as to enable us, from use of knowledge gathered in a few observations, to predict by logical processes the outcome in many other circumstances [1]. Consequently, the predictive capability of FEM based simulations is mainly determined by the chosen physical theory and its numerical solution. The laws, utilized for forming simulations, can be grouped in universal and non-universal laws of nature. This thesis focuses on constitutive laws, which are material specific and therefore non-universal laws of nature. The universal laws of nature are the balance relations for mass, linear momentum, rotational momentum and energy. In this context, the term material represents the sheet metal, which is shaped
by a forming operation. For each material a specific stress-strain relation has to be identified and calibrated, which belongs to the group of the constitutive laws. Additionally, a constitutive law for modeling the frictional response between the material and the tool surface is needed. In order to follow the fundamental idea of theoretical physics, the mentioned constitutive laws, which are mathematical models, have to be calibrated on the basis of a few experiments and should be predictive for their field of application. Consequently, in this thesis, the calibration of given constitutive laws is performed by considering the minimum possible experimental data. Additional experiments are applied solely for investigating the predictive capability of the calibrated constitutive laws. The applied numerical solution of the physical laws based on the finite element method is considered to be sufficiently accurate in this thesis.

Subsequently, the term material model is used as a synonym for the stress-strain relation. In the last decades, manifold material models have been proposed for modeling the elasto-plastic material behavior of sheet metals (For example: [2], [3], [4], [5], [6], [7], [8] and [9]). Unfortunately, a general recommendation regarding the choice of the material model for a given material is not available. Generally, it is expected that the best choice of the material model depends on the considered steel grade or aluminum alloy. In order to treat all aspects concerning material modeling, which are introduced below, this thesis is limited to the investigation of the interstitial free mild steel DX54. However, it is expected that the findings of this thesis are transferable to other materials.

Microstructural models are not considered in this thesis. The investigations are limited to hypo-elasto-plastic material models. Furthermore, thermodynamic effects are neglected. These stress-strain relations comprise a model for the elasticity, the yield locus and the material hardening. Regarding the yield locus models, only phenomenological ones are considered, which are not directly derived from microstructure-based models [11]. This choice is made, as these yield loci are not computationally expensive and therefore enable the solution of elasto-plastic mechanical problems for industrial applications. A major focus of this thesis is the choice of the yield locus model and its calibration. Apart from the commonly applied Hill ‘48 [8] model also the Barlat ’89 [2] and the Barlat 2000 [3] yield locus are investigated. This set of yield loci represents different levels of complexity regarding the model parameters. Today, yield loci have been published, which comprise much more parameters as the Barlat 2000 model [5]. Such models are able to reflect the input data of the calibration experiments highly accurate. However, the amount of necessary calibration experiments rises, which leads to an additional cost for the model calibrations. One has to bear in mind that material model calibrations of various steel grades and aluminum alloys need to be provided for the application of the forming simulation in the engineering phase of the product and the production process. Consequently, at the moment the complexity of the Barlat 2000 or similar yield loci is assumed to be the limit, which

\footnote{An approach for modeling a forming process based on microstructural plasticity is given by Thieme-Marti [10].}
can be treated for the mentioned application. The findings regarding the choice of the yield loci and the calibration procedure are assumed to be transferable with respect to other yield loci. Hence, only the mentioned yield loci are investigated. Additionally, the need for the consideration of the strain rate dependency of the hardening effect of the material and the Bauschinger effect are analyzed. Thereby, only simple isotropic models are applied, which can be calibrated based on tensile tests. Finally, steels can show a significant dependency of the Young’s modulus with respect to the forming history [12]. This effect can affect the quality of the prediction of the elastic springback and is, therefore, analyzed too. As mentioned above, constitutive laws of forming simulations also comprise the modeling of the frictional response between the sheet metal and the tool surface. Hence, also a friction law needs to be analyzed. However the treatment of the friction model is in this context aligned to the temperature conditions, which hold for the experiments, considered in this thesis. Also the dependency of friction with respect to the contact pressure and the relative velocity between the sheet metal and the tool surface are neglected.

The objective of this thesis is threefold: Firstly, the identification of potentials regarding material models in order to maximize the benefit of the FEM simulation and, secondly, the development of an identification and validation procedure for material models. Thirdly, the investigation of the effect of the deviations between the measured data and the true values of the calibration experiments on the predictive capabilities of material models.

Authoritative for the evaluation of the accuracy of the predictions of the simulation is the press shop process. Unfortunately, the FEM cannot capture all effects influencing the production process. Examples are wear, thermodynamic effects and scattering material properties. Furthermore, the material model should be validated in advance for the application in the product and production process development, which excludes the press shop process as a source for the model identification and validation in the case a new material is introduced for the car body. Some of the non treatable effects, occurring in the press shop, are avoided, if the prediction of the simulation is investigated on the basis of experiments, performed under laboratory conditions. This implies the application of the same batch of the material for all calibration and validation experiments. It has to be mentioned that the calibration of the constitutive laws on the basis of another batch of the same material may lead to other model parameters. However, for the subsequent investigations it is assumed that a representative batch is selected for the calibration and validation of the constitutive laws. Apart from the standard calibration experiments (tensile test, bulge test, shear test), which are also referred to as fundamental experiments in this thesis, further experiments are introduced for the identification of the model parameters (complementary experiments) and the validation of the constitutive laws (validation experiments).

The parts, produced in the press shop, should not show any material failure. In order to avoid the occurrence of material failure, the design of the production process needs to be optimized. Thereby, failure criteria, which are based on the
results of the forming simulation, are deployed. These failure criteria are also considered by the validation experiments. However, the evaluations are limited to the failure mode localized necking. The failure is analyzed on the basis of an experimentally determined forming limit curve, as the applied experiments do not show a pronounced non-linear strain path.

The design and the commissioning of the experiments are parts of this thesis. However, more emphasis is given to the mathematical procedures, which are applied to reach the above mentioned objectives.

Both, the complementary and the validation experiments, introduced in this thesis, are designed for the investigation of constitutive laws and their parameters. Under ideal conditions, each experiment shows a different sensitivity with respect to the constitutive laws and the associated parameters regarding the prediction of the measured quantities. However, this desired property of the complementary and validation experiments has to be assured. Generally, it is difficult to predict all these sensitivities solely by theoretical considerations. As the identification of the model parameters depends on the chosen constitutive laws, this choice is made first. Subsequently, the sensitivities of the model parameters with respect to the deviation between the prediction of the simulation and the measured data of the experiments are investigated. Based on the determined sensitivities and the knowledge about the choice of the model parameters, leading to an accurate prediction of the measured data, allows selecting the investigated experiments for the identification and validation of the selected constitutive laws. For the determination of the desired information, an optimization problem can be formulated. The objective is to minimize the deviation between the prediction of the simulation and the measured data by searching for the best possible choice of the model parameters. A second component of this solution is the application of evolutionary strategies. As these optimization algorithms are based on statistical methods, also information regarding the sensitivity of the object variables (model parameters) is given. Another aspect for choosing evolutionary strategies is that these minimization problems are expected to be multimodal. Generally, it is intended to add only model parameters to the search space of the optimization, which cannot be determined by the fundamental experiments. These parameters will be referred to as unknown model parameters in this thesis. In this context it has to be mentioned that the procedures for evaluating the results of the fundamental experiments are not investigated in this thesis. Therefore, the quantities, derived from these experiments are assumed to be given. One should consider that this set of unknown model parameters and the above introduced distinction between complementary and validation experiments depends on the applied constitutive laws. Originating from the selected constitutive laws and the determined unknown model parameters, the validation experiments are applied for analyzing the predictive capability of the calibrated constitutive laws.