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This thesis is focused on constitutive laws, which are suitable for forming simulations in an industrial environment. For modeling the elasto-plastic material response, an elasticity model, a yield locus and a hardening model needs to be chosen. Additionally, the Bauschinger effect, the strain rate dependency of the hardening effect and the dependency of the Young’s modulus with respect to plastic yielding might need to be taken into consideration. The completion of the material model by the consideration of the Bauschinger effect or the strain rate dependent hardening is interpreted as a boolean model parameter and is considered to be unknown. For reflecting the dependency of the Young’s modulus with respect to plastic yielding, this model parameter is also treated as unknown. The frictional response between the sheet metal and the tool surface is described by the Coulomb model, which comprises one model parameter - the friction coefficient. In this context, this parameter is also assumed to be unknown.

For the identification of potentials regarding the improvement of the predictive capabilities of the forming simulation, additional experiments are necessary. The examination of these experiments can be performed by formulating optimization problems, which comprise an objective function quantifying the deviation between the simulation based prediction and the measured data. The task of the optimization is to search for a choice of the unknown model parameters, which leads to the best possible prediction of the measured data. The result of such an optimization is twofold: Firstly, the best possible predictive capability of the simulation based on the selected material model (elasticity model, yield locus and hardening law) is known by the variation of the unknown model parameters. Secondly, information regarding the sensitivity of the unknown model parameters with respect to the simulation based prediction is obtained. Thereby, the optimization based procedure assures the consideration of the interactions between the unknown model parameters. For this task, a $(1, \lambda)$-DR-ES is applied, which belongs to the group of evolutionary strategies. This algorithm allows treating integer-valued and real-valued object variables. Additionally, as this algorithm is based
on statistical methods, the \((1, \lambda)\)-DR-ES allows combining the task of searching for an optimum and deriving information regarding the sensitivities of the object variables within a single optimization. Subsequently, the findings, obtained from this procedure are discussed.

The presented investigations based on the YLIT-Experiments show that the Barlat 2000 yield locus is advantageous compared with the widely applied Hill ’48 or Barlat ’89 yield locus for modeling the material response of the steel grade DX54. Unfortunately, the choice of the exponent of the Barlat 2000 model cannot be determined by the considered fundamental experiments. A disadvantageous choice of this exponent can lead to worse simulation based predictions than applying a simpler model like the Hill ’48. Therefore, a carefully performed validation has to precede the application of a complex yield locus like the Barlat 2000 for the forming simulation. A general ranking of the suitability with respect to industrial applications cannot be given, as other steel grades or aluminum alloys might be sufficiently described by a model comprising less model parameters like the Hill ’48. Basically, the Barlat ’89 also enables a satisfactory modeling of the material response in terms of the YLIT-Experiments. However, this yield locus does not reach the same level of quality concerning the reproduction of the measured stress and strain rate ratios, derived from the fundamental experiments, like the Barlat 2000 yield locus. Therefore, in this thesis the Barlat 2000 yield locus is preferred, as this model should give a better prediction of the material response for arbitrary stress states.

The analysis shows the need for taking the strain rate dependency of material hardening into account, if the Barlat 2000 yield locus is applied and the flow curve is entirely derived from the fundamental experiments. Otherwise, the simulations of the YLIT-Experiments show unsatisfactory predictions of the measured data. The investigation also shows the connection between modeling the material hardening and the yield locus. If the strain rate dependency of the material hardening is taken into account and the Hill ’48 yield locus is applied, the maximum drawing depth is overestimated. The yield locus Hill ’48 leads to better predictions concerning the YLIT-Experiments, if the strain rate dependency of the material hardening is not taken into account. However, one has to bear in mind that these findings are only valid for the chosen way of deriving the flow curve. The industrial relevance of the examinations based on the YLIT-Experiments is shown in [114] based on an industrial part (body side). This publication comprises an investigation of the influence of the choice of the yield locus, its exponent and the consideration of the strain rate dependency of the hardening on the prediction of the material thinning. Essentially, the findings derived from the YLIT-Experiments are confirmed by this study. For example the application of the Barlat 2000 yield locus without consideration of the strain rate dependency of the hardening effect leads to an unrealistic prediction of the material thinning.

Another effect, investigated in this thesis, is the dependency of the Young’s modulus with respect to plastic yielding. Based on the bending experiment, the observations of Doege et al. can be confirmed. The bending experiment enables
to estimate a reduction of the Young’s modulus with respect to the dimension of equivalent plastic strain induced by this experiment. The examination of the u-profile experiment showed, that this approach leads to an improved prediction of the springback. Using this reduced Young’s modulus, the consideration of the Bauschinger effect worsens the prediction of the springback behavior of the u-profile. However, if a model is applied, which considers the non-linear dependency of the Young’s modulus with respect to plastic yielding and the Bauschinger effect, a satisfying prediction of the springback of the u-profile can be obtained. Thereby, the relation between the Young’s modulus and the accumulated plastic strain, which is taken from Doege et al., is extrapolated. For getting more insight into this issue, the determination of the Young’s modulus with respect to the maximum expected level of accumulated plastic strain, occurring in industrial forming simulations, is necessary. However, this effect of the material response needs to be analyzed on the basis of another experiment. The inverse determination of the reduced Young’s modulus based on the bending experiment, is only a simplified approach in order to improve the springback prediction. Furthermore, an experiment is needed, which shows a stronger sensitivity with respect to the Bauschinger effect.

For the description of the frictional response between the sheet metal and the tool surface, the Coulomb model is applied. The examination of this model is performed in order to describe the frictional response concerning the experimental conditions of the introduced experiments. Thereby, the friction coefficient is determined inversely based on the friction experiment. For an improved prediction of the frictional response under the press shop conditions, the applied model should take the temperature, the pressure and the relative velocities between the tool and the sheet metal in the contact interface into consideration. If such a model and its calibration is available, the introduced friction experiment can be applied for validation purpose.

The strain state, induced by the hole extrusion experiment cannot be easily obtained from the Nakajima test. However, a tensile test enables to create such a strain state. Therefore, the hole extrusion test can be performed to validate a forming limit curve, derived from the results of the Nakajima and the tensile test. This validation assures the right choice of the slope of the forming limit curve with respect to its left branch. The validation of the prediction of localized necking with respect to the plane strain state is of special importance as most of the industrial deep drawing parts fail by this strain state. Therefore, the validation of the predictive capability of the forming simulation is complemented by the cylindrical deepening experiment. The analysis of this thesis shows that the applied forming limit curve is able to reflect the failure mode localized necking sufficiently accurate with respect to the investigated strain states using the identified constitutive laws and their parameters. In other words, the prediction of the simulation is in accordance with the experimental observations concerning the onset of localized necking.
CHAPTER 11. SUMMARY AND OUTLOOK

The sensitivities, obtained from the optimization based investigations, allow formulating a simplified inverse determination of the yield locus exponent of the Barlat 2000 yield locus, the reduction of the Young's modulus and the identification of the friction coefficient of the Coulomb model. Thereby, the determination of the yield locus exponent has to precede the identification of the Young's modulus and the friction coefficient. Provided the $R_b$ value and the weighting of the stress and strain rate ratios, obtained from the fundamental experiments, are known, the search for the yield locus exponent is one dimensional. By applying the golden section interval division, within 7 objective function evaluations, a satisfying value of the yield locus exponent can be computed for the investigated material. The YLIT-Experiments also allow to determine the weighting of the input data and the $R_b$ value. In this case the object variable space is 10 dimensional, if the Barlat 2000 yield locus is calibrated. As this search space is solely real valued, the $(1, \lambda)$-DR-ES, the $(\mu/\mu, \lambda)$-CMA-ES, the $(1+1)$-CMA-ES and the SQP algorithm are investigated. The best performance is obtained by applying the $(1, \lambda)$-DR-ES.

The inverse determination of the friction coefficient and the reduction of the Young's modulus can be performed simultaneously. In both cases, the dimension of the parameter space is one-dimensional. The best of the investigated methods for finding the friction coefficient is the Lagrange interpolation. The reduction of the Young's modulus can be efficiently determined by applying the Regula Falsi iteration. However, the friction coefficient as well as the reduction of the Young's modulus can be also efficiently determined by applying the golden section interval division. Generally, the result of the inverse determination of unknown parameters depends on the formulation of the universal and non-universal laws of nature and their numerical solution. Therefore, if possible, direct methods should be preferred. Provided, direct methods for the determination of the yield locus exponent, the Young's modulus and the friction coefficient are available, the introduced complementary experiments can serve as validation experiments.

The inversely identified unknown parameters should lead to the desired predictive capability of the constitutive laws. In order to analyze the quality of the chosen way of modeling the material and the frictional response, the predictions of the simulation and the measured data are compared on the basis of the validation experiments. Obviously, the calibrated constitutive laws are only satisfying, if they lead to a successful prediction of the measured data of all the validation experiments. As the amount of validation experiments is limited, the underlying validation should be interpreted as an indication of the predictive capability of the forming simulation. However, this procedure should not be regarded as proof of the general validity of the chosen constitutive laws, their calibration, the applied universal laws of nature and the associated numerical solution.

The measured data, obtained from the fundamental experiments is expected to deviate from the true values. For the investigation of the related consequences concerning the inverse determination of the discussed model parameters and the performed validations, an optimization based approach is suggested. Thereby, the
space of the object variables comprises all the measured data, obtained from the fundamental experiments. The objective of the optimization is to determine the worst possible simulation based prediction by considering the uncertainty with respect to results obtained from the fundamental experiments. For this investigation, the inversely determined unknowns are excluded from the search space. Provided, the worst possible prediction of the simulation still gives acceptable results, the influence of this uncertainty is assumed to be small. In this context, a general valid definition for the distinction between acceptable and unacceptable results cannot be given, as such a classification depends on the needed predictive capabilities of the forming simulation. As the associated search space of this optimization is real-valued, the performance of different optimization algorithms is compared. The best performance is obtained by applying the $(1, \lambda)$-DR-ES algorithm. Apart from the experiments related to the springback effect, none of the investigated experiments show a strong influence of the uncertainty of the input data with respect to the accordance between the simulation and the measured data, which confirms their desired field of application. However, the bending experiment can only give an estimation of the reduction of the Young’s modulus in order to capture its dependency with respect to plastic yielding.

The presented results confirm that a stress-strain relation, consisting of a complex material model, does not necessarily lead to an improved accuracy of the forming simulation. All the known effects of the material response need to be analyzed in order to obtain the desired benefits from a complex model. Additionally, an extensive validation procedure is necessary in order to assure the functionality of the applied stress-strain relation. The $(1, \lambda)$-DR-ES shows the best performance with respect to the optimization tasks, presented in this thesis, among the investigated algorithms. An exception is the calibration of the Barlat 2000 yield locus, which seems to be an unimodal optimization problem within the investigated search space. Therefore, the application of the SQP in combination with an additive aggregation of the objectives is recommended for this task.

In this thesis, potentials and a procedure for the identification and validation of material models are shown, in order to maximize the benefit of the forming simulation. Additionally a method, for taking the uncertainties of the input data for the identification and validation of material models into account, is suggested.

### 11.1 Outlook

The most limiting factor for the presented investigations is the computational cost of the FEM simulations. In chapter 10 the effect of the uncertainty with respect to the input data on the identification and the validation of material models is examined. For this task the budget of 100 objective function evaluations is rather small. More objective function evaluations would be desirable in order to obtain a more reliable assessment of this issue.

The investigations of this thesis are limited to a single batch of the considered material. However, different batches of the same material might show scattering
material properties, which can for instance affect the feasibility of the parts and their springback behavior. For the consideration of fluctuating material properties in an industrial environment, a suitable compromise between the benefit of modeling this effect and the related additional cost has to be found, since it seems to be too expensive to perform the presented investigations for different batches of the same material.

The assumption of an isotropic hardening behavior might not be suitable for all steel grades and aluminum alloys, applied for a car body. Consequently the information regarding the material hardening with respect to different stress states obtained from the fundamental experiments, could be utilized for the calibration of enhanced material models. As a consequence, the shape of the yield locus changes depending on the material hardening. As the shape of the yield locus has a significant influence on the predicted strain and stress states, such a model needs to be validated very carefully. The findings, which result from the YLIT-Experiments, show that slight modifications of the yield locus shape can cause significant changes of the predicted strain state. The challenge of deploying a yield locus, which is able to consider the anisotropic hardening behavior, is to assure for any deformation history a meaningful response of the model. Possible mathematical models for taking an anisotropic hardening into account can be found in [115] and [101]. At this point one should also think of a non-associative flow rule, which would allow combining a simple flow potential with a complex yield locus. Such a model allows avoiding any negative side effects of a changing yield locus surface, caused by an anisotropic hardening law.

None of the presented experiments is highly sensitive with respect to the Bauschinger effect. Therefore, an additional experiment for the validation of a kinematic hardening model is required. Such a validation should also take into account that the Bauschinger effect especially affects the material response of material points, which undergo a non-linear strain path.

High strength steels can show apart from localized necking the failure modes shear and normal fracture. For the prediction of such failure modes the forming limit curve is not suitable. Hence, other failure criteria have to be deployed and the validation process has to be complemented by further experiments for assuring their predictive capability.

Today, theoretical physics is the best known method for predicting the behavior of the nature on the basis of few experimental observations. Nevertheless, the laws, given by theoretical physics are not equivalent to reality. Thereby, in the future, theoretical physics will only improve but will never be able to describe nature exactly. As the forming simulation is embedded in this theoretical framework, one should never expect exact predictions from it.