The concept of virtual material testing and its application to sheet metal forming simulations

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Abstract. A crystal plasticity based full-field microstructure simulation approach is used to virtually determine mechanical properties of sheet metals. Microstructural features like the specific grain morphology and the crystallographic texture are taken into account to predict the plastic anisotropy. A special focus is on the determination of the Lankford coefficients and on the yield surface under plane stress conditions. Compared to experimental procedures, virtual material testing allows to generate significantly more data points on the yield surface. This data is used to calibrate anisotropic elasto-plastic material models which are commonly used for sheet metal forming simulations. A numerical study is carried out to analyze the influence of the chosen points on the yield surface on the calibration procedure.

1. Introduction

An accurate description of the elasto-plastic material behavior is needed for a precise simulation of sheet metal forming processes. Here, the two most important aspects of the material models are the description of the hardening and the yield locus. To account for the anisotropy of sheet metals, an increasing number of anisotropic yield locus models is available, starting from the well-known Hill48 [1] yield locus description up to more modern models like Yld2000-2d [2]. It is known, that the simpler yield locus descriptions are usually not sufficient to model the plastic material behavior accurately, especially for recently developed advanced high strength steels and also for aluminum alloys. In the case of an associated flow rule, the curvature of the yield locus defines also the development of the plastic strain components which is of high importance for sheet metal forming simulations.

Besides the choice of an appropriate yield locus model, the identification of the model parameters is an important issue, especially when more complex yield locus models with more parameters are considered. The determination of the parameters of more sophisticated yield locus models requires a large number of experiments which can be difficult and expensive to realize. In a standard parameter identification procedure the number of experimental results (yield stresses, r-values) usually corresponds to the number of free parameters in the yield locus model. The experimental data which were considered for the parameter identification can then be precisely reproduced by the yield locus model. However, accuracy for other stress states is unclear.

Here, the concept of virtual material testing is an interesting approach. It allows to significantly extend the limited experimental data base by additional virtual experiments. These virtual data can be used as additional input for a precise parameter identification or for the assessment of yield locus models.

2. The concept of virtual material testing

The main idea of the “virtual material testing” approach is to describe the material on the micro scale (grain scale) and to calculate the macroscopic properties like flow curve, r-values or yield surface by numerical homogenization. To predict the macroscopic material behavior, it is necessary to take the most important aspects of the microstructure into account. For this reason, a so-called unit cell model is used. This model represents a sufficiently large part of the microstructure and considers the size, shape and orientation of individual grains. The elasto-plastic deformation on the grain scale is described by a single crystal plasticity material model that was implemented into the finite element software Abaqus/Standard following [3]. The material model allows the consideration different initial orientations of the crystallographic lattice for each single grain. The real texture of a sheet metal can be represented if a sufficiently large number of grains are included. Thus, the anisotropic material behavior on the macro scale with respect to yielding and r-values is a direct outcome of the applied microstructure model.

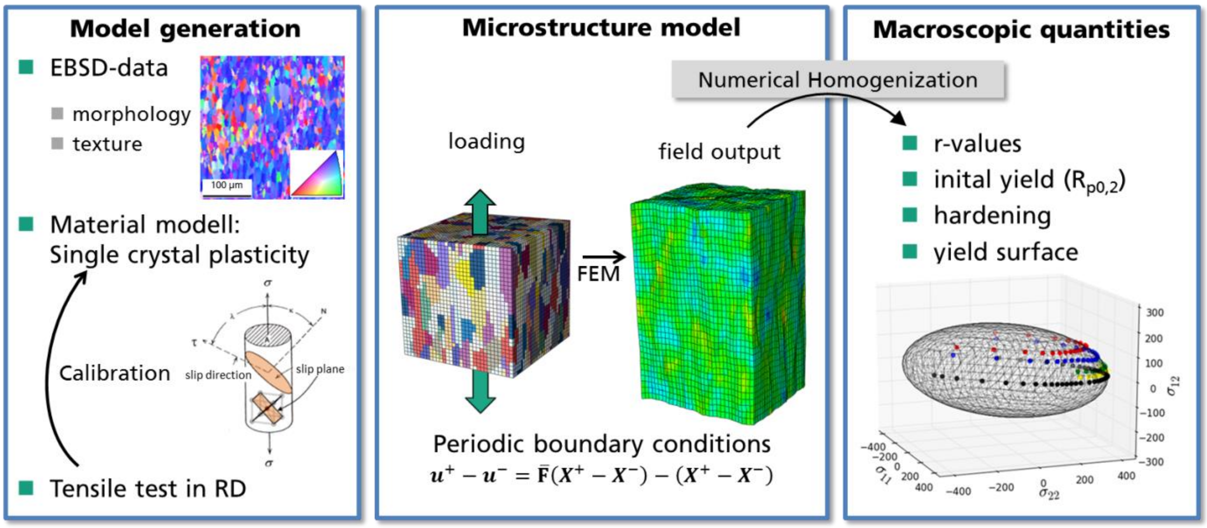

Figure 1. Concept of the “virtual material testing” approach.

Experimental data from standard material characterization are used to generate a finite element model of the microstructure and to calibrate and validate the unit cell model. Once the model is calibrated, it can be used for the analysis of arbitrary loading conditions. Figure 1 gives an overview of the applied procedure. To set up the microstructure model, an EBSD measurement and a tensile test in rolling direction of the sheet are sufficient. From the EBSD measurement, information regarding the texture and the grain morphology are obtained. The flow curve from the tensile test is used to adjust the hardening parameters of the crystal plasticity model. Details of the procedure can be found in [4].

3. Application to a mild steel DX56

The described procedure was applied to a mild steel grade DX56 with a thickness of 1.2 mm [5]. The elongated shape of the grains in rolling direction which was observed in the EBSD measurements was considered within the finite element model of the microstructure as illustrated in Figure 2. The microstructure model consists of 500 grains. By choosing an appropriate set of 500 initial orientations, the experimentally measured texture could be represented with good accuracy.

The parameters of the crystal plasticity model which describe the hardening of the slip systems were adjusted via inverse simulation with respect to the macroscopic stress-strain curve from a tensile test in rolling direction. Some results of the calibrated microstructure model are given in Figure 3. The adjusted flow curve of the calibrated model is in very good agreement with the experimental data. Furthermore, the initial yield stresses and the r-values were analyzed with respect to the orientation of the specimen. The r-values depend strongly on the orientation of the specimen which is well captured by the micromechanical model.

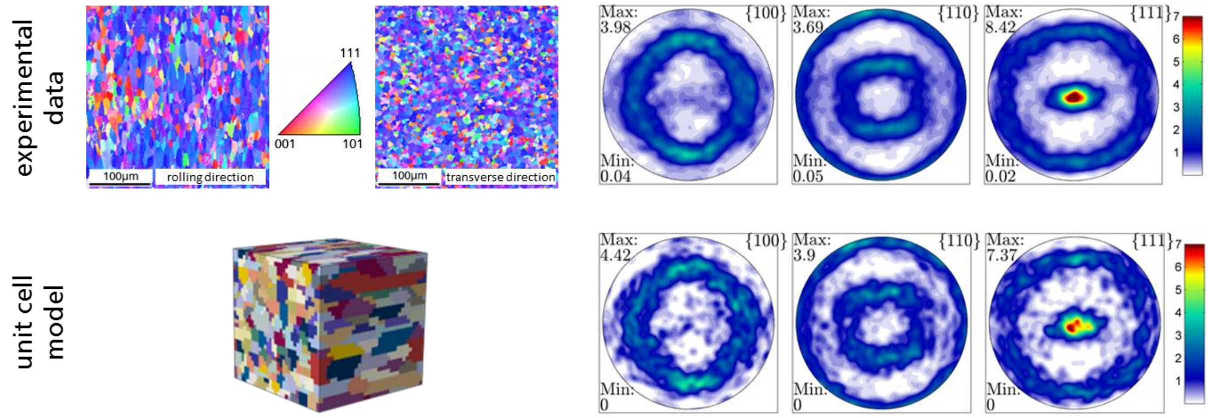

Figure 2. Generation of the microstructure model of the DX56 steel sheet: Comparison of the grain structure (left) and the crystallographic texture (right).

The calibrated model was used to calculate points on the yield surface to provide a set of yield points in the plane stress space for the identification of the model parameters of commonly used yield models. Different load cases which fulfill the assumed plane stress condition ($\sigma_{33} = \sigma_{23} = \sigma_{31} = 0$) for sheet metals were imposed to the microstructure model. It is assumed that the values of the identified parameters of the yield functions depend on the number of the yield points and their location on the yield surface. For this reason, the following numerical study was carried out: Three different sets of yield points were calculated and considered for the identification of the yield functions. In case 1, all points on the yield surface are located in the σ_{11}-σ_{22} plane in which the stress component σ_{12}=0. Case 2 considers five different levels of the component σ_{12}. Case 3 takes more points with a pronounced shear component σ_{12} into account. The yield locus models according to Hill48 [1], Yld89 [6] and Yld2000-2d [2] were adjusted to these three different sets of points on the yield surface. The results are given in Figure 4. All three cases give a good representation of the initial yield surface in the plane of σ_{12}=0. However, the yield functions predict different yield stresses and r-values as a function of the loading angle to the rolling direction. It is noted that – in contrast to the standard procedure – no r-values were considered for the identification of the parameters which partly explains the deviations to the experimental r-values. Nevertheless, the more flexible yield function Yld2000-2d is able to capture the plastic anisotropy of the DX56 if a sufficient amount of yield points with a pronounced shear stress is used for the fitting procedure (case 2 and case 3).

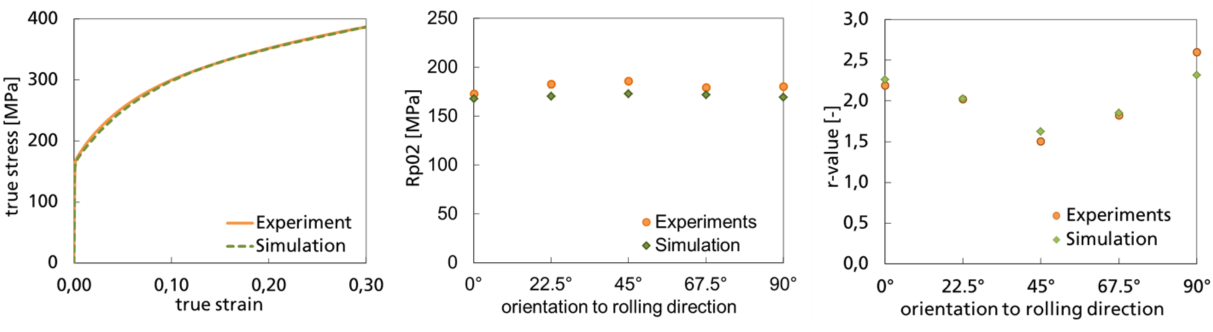

Figure 3. Results of the calibrated microstructure model and comparison with experimental data: Flow curve (left), initial yield strength (center) and r-value (right).

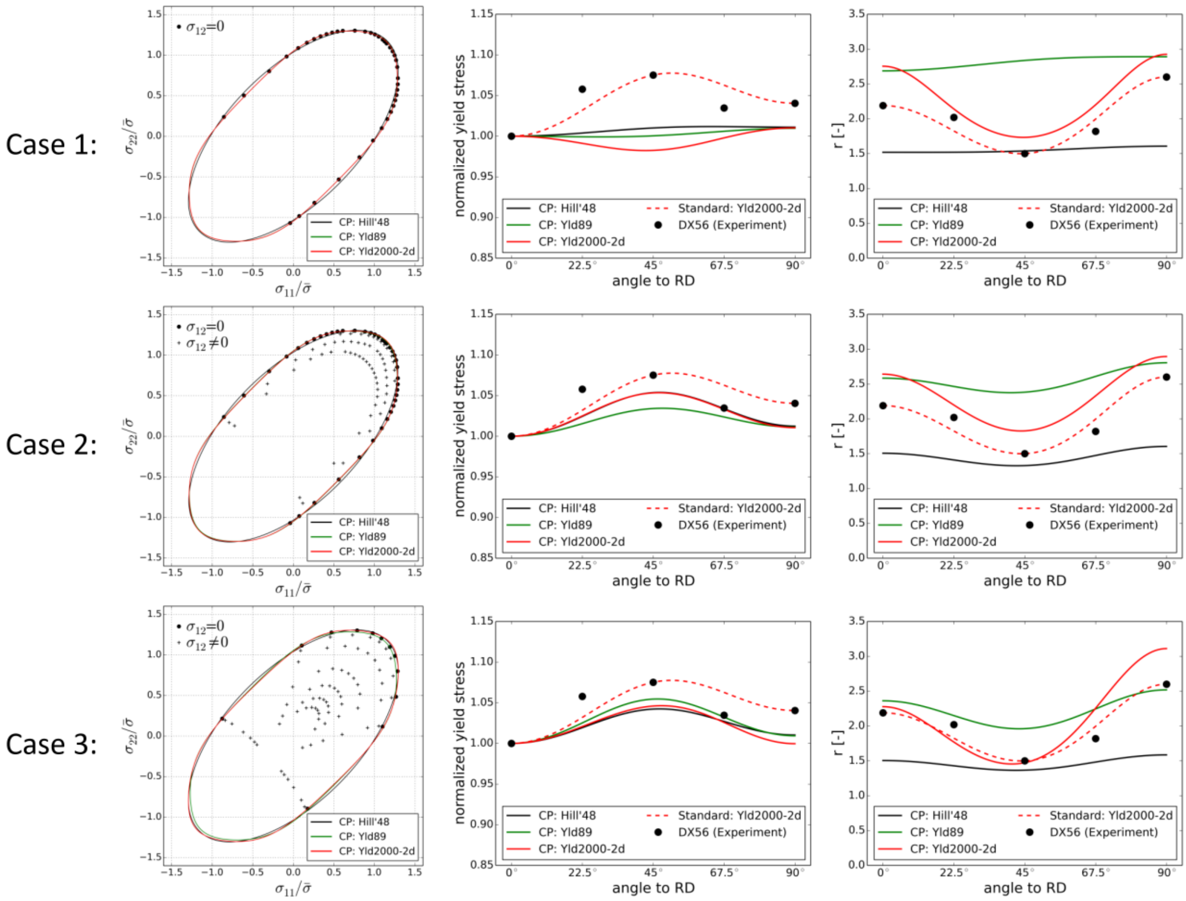

Figure 4. Yield surface, yield stress and r-value for DX56 predicted by yield functions that were fitted to different sets of numerically generated points on the yield surface. The Yld2000-2d function fitted to the experimental data (standard procedure) is shown for comparison.

4. Conclusion

The concept of virtual material testing is a promising approach for an extended characterization of sheet metals. The microstructure model used in this work gave a good representation of the experimentally available results and could be used for the determination of arbitrary points on the yield surface. Due to the high number of data points, the parameter identification problem of the yield locus models becomes highly overdetermined. As shown in the example, the identified parameters of the yield locus models depend on the number of yield points and their location on the yield surface. For this reason, further work will focus on the development of appropriate parameter identification strategies for complex yield surface models under consideration of additional, virtual material data.

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