ON THE MODELING OF DUAL PHASE STEELS: MICROSTRUCTURE-BASED SIMULATION FROM THE HOT ROLLED SHEET TO THE DEEP DRAWN COMPONENT

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ABSTRACT: A major part of the industrial development in sheet metal forming is supported by numerical simulation. While individual simulation solutions for each application are available to study the producibility or serviceability of parts, a more unified approach that considers the results from the previous step along the production chain has not been presented so far. Within a joint research project that is founded by the German Federal Ministry of Education, a simulation strategy to model the process chain of dual phase steels from the hot rolled strip up to the behavior of components under crash conditions is developed. One important aim is to close the virtual process chain that ranges from steel design to crashworthiness simulation. The proposed concept will take into account micro-structural aspects of the material as well as macroscopic approaches, depending on the process step. This contribution presents the current status of the project considering the process steps cold rolling, annealing and deep drawing.

KEYWORDS: process chain simulation, dual phase steel, multi scale modeling, cold rolling, annealing, deep drawing

1 INTRODUCTION

The objective of this research project is the development of a simulation concept for the process chain simulation of a dual phase steel. It covers consecutive stages of production beginning with the hot rolled strip which is followed by cold rolling, heat treatment, deep drawing and finally the analysis of the crashworthiness of the deep drawn component [1]. Due to the developed data transfer structure, see Section 5.1, it is also possible to add further simulation steps such as skin pass rolling. An important aspect is to take into account the changes of the microstructure during the different process steps since this also affects the mechanical properties on macroscopic level like yield stress, formability and anisotropy. For this reason, the proposed concept will be based on integral constitutive simulations which consider the micro-structural aspects and take space and process dependent quantities of the material properties into consideration.
Depending on the process step, different simulation strategies on different length scales are applied, see Figure 1. This requires an adequate data structure to transfer the required data between the simulation models of different process steps. Further, this data structure should be adaptable to modifications of the process chain or for additional process steps.

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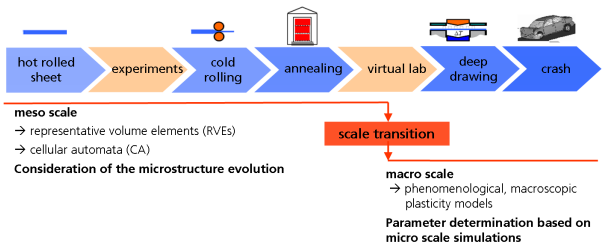

Figure 1: *Process chain from the hot rolled sheet to the crashed part.*

A simulation tool which is called ”Virtual lab” is used for the numerical homogenization of the microstructure properties and to provide a macroscopic material description which is necessary for deep drawing simulation and crash analysis. In principle, this virtual material testing may be carried out after each process step to predict the material characteristics during the entire process chain.

The coupling between the deep drawing simulation and the crash analysis is not discussed in this contribution. Here, we refer to [1, 2] for a more detailed description.

2 EXPERIMENTAL ANALYSIS

For the production and processing of the dual phase steel the alloy which is presented in Table 1 is considered. The material of the hot rolled strip corresponds to the initial

Table 1: *Alloy of the examined material in CR. %*

C	Si	Mn	Al	V	Nb
0.147	0.403	1.868	0.037	0.098	0.047

state of the process chain simulation. It consists of ferrite and perlite where the perlite phase shows a line-wise arrangement. The hot rolled strip is being cold rolled to three different thicknesses. The corresponding data are summarized in Table 2. Figure 2 shows the stress-strain

Table 2: *Variation of cold rolling degree.*

Hot rolled strip thickness	Cold rolled strip thickness [mm]	Forming degree [%]	Grain aspect ratio [-]	Dislocation density [cm^{-2}]
3.75	2.20	41.3	2-3:1	1.65×10^{11}
3.75	1.75	53.3	5:1	2.10×10^{11}
3.75	1.45	61.3	8:1	3.20×10^{11}

curves for the three different forming degrees obtained from tensile tests of the cold rolled strips. It can be recognized that an increasing forming degree leads to an increasing strength of the cold rolled material. Texture data were also measured. While the texture of the hot rolled strip is directly considered as initial texture in the cold-rolling simulation, the texture of the cold rolled strips were used to validated the simulation model. The samples with a forming degree of 41 % show a weak texture development which is significantly more pronounced for samples with a forming degree of 61 %.

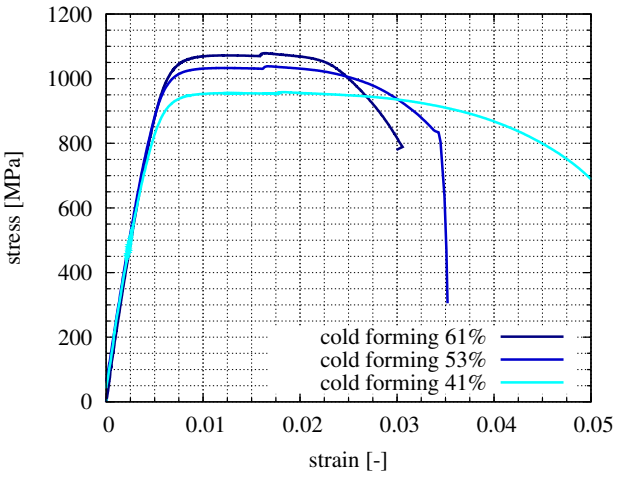

Figure 2: *Tensile tests of the cold rolled strips in rolling direction with different forming degree.*

3 COLD ROLLING SIMULATION

To take into account the initial ferritic-pearlitic microstructure morphology of the hot rolled sheet and its evolution during cold rolling, the concept of representative volume elements (RVE) is applied within the finite element method. A unit cell with 400 ferrite grains and two band-shaped perlite regions is shown in Figure 3. The red regions represent the perlite phase. The volume fraction of the perlite phase is 22%. To avoid artificial stiffening of the RVE, periodic boundaries are applied.

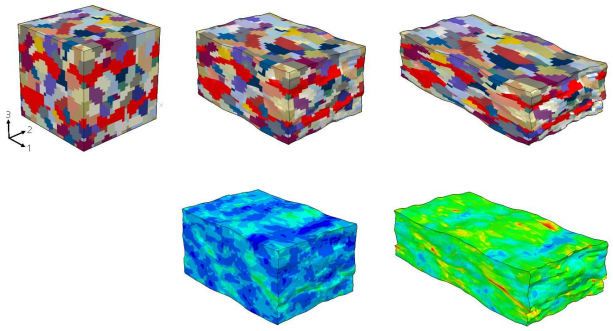

Figure 3: *Representative volume element of the hot rolled sheet in the initial state and after cold rolling (41% and 53% deformation). The corresponding accumulated plastic shear strains are illustrated in the second row.*

The mechanical behavior of the grains in the polycrystalline aggregate is modeled within the framework of crystal plasticity [3]. This physically based theory describes plastic flow as a movement of dislocations in a continuum way. From this follows, that plastic deformation is the result of continuous shearing or slip along well defined planes of the crystal lattice. This constitutive model considers the texture evolution due the rotation of single grains during deformation and thus takes into account the development of anisotropic material properties caused by the rolling process.
The strain hardening behavior of one slip system during plastic deformation is described with the following Voce-type hardening law [4]

$$\tau(\Gamma) = \tau_0 + (\tau_1 + \theta_1 \Gamma) \left[1 - \exp\left(-\frac{\Gamma \theta_0}{\tau_1} \right) \right] . \quad (1)$$

The quantities τ_0, τ_1, θ_0, θ_1 are parameters to describe hardening as a function of the accumulated shear on all slip planes of one slip systems. With respect to the bcc crystal lattice of ferrite, the two slip systems $\{110\}\langle 111\rangle$ and $\{112\}\langle 111\rangle$ are considered in the simulation. The initial orientation of the grains is prescribed in order to represent the experimentally measured texture of the hot rolled sheet.
To model the process of rolling, the following macroscopic quantities are prescribed within the finite element simulation of the unit cell model

$$F_{33} = \Delta s \qquad F_{22} = 0 \qquad P_{11} = 0 \quad . \quad (2)$$

F_{ij} represents the deformation gradient and P_{ij} is the first Piola stress tensor. The thickness reduction of the sheet due to rolling is prescribed with the quantity Δs. Some

exemplary results of the cold rolling simulation are illustrated in Figure 3.

The parameter identification of the crystal plasticity model is done via inverse simulation. Since the applied material model has a large number of parameters, it is questionable to determine a unique set of material parameter with the data available from the hot rolled sheet. Therefore, the test data from the cold rolled material with different degrees of deformation, see Figure 2, were additionally considered within the inverse simulation procedure. A further improvement of the parameter identification is expected when the texture evolution is also taken into account.

4 ANNEALING SIMULATION

During the thermal treatment the final dual phase steel microstructure composed of ferrite and martensite is obtained. The aim of the annealing simulation is to describe the material behavior and the microstructure change due to the thermal treatment during hot-dip galvanizing. As described in Section 2, the hot rolled strip and also the cold rolled one show a ferritic and perlitic microstructure with a line-wise arrangement of the perlite. The cold rolling process leads to a decrease of the line spacing, a straining of the ferrite grains in rolling direction, a compression in normal direction and to an increase of the dislocation density within the grains.

The simulation of the thermal treatment is carried out by cellular automata (CA). For this computational principle the considered volume is divided into a number of cells which are discrete and homogeneous. The internal state of each cell is described by internal variables which evolve independently according to their local neighborhood. For the simulation of annealing processes the state of each cell is based on the crystal orientation and the dislocation density as driving force, see e.g. [5]. The evolution of the internal state is defined by the switching rules. For this project, a three dimensional cellular automaton was implemented and tested with respect to experimental data obtained from a number annealing experiments. It could be shown that the developed automaton is able to reproduce the results of the analytic recrystallization theory by Johnson, Mehk, Avrami & Kolmogorov (JMAK) correctly.

5 DATA TRANSFER ARCHITECTURE

5.1 DATA TRANSFER ON MESO SCALE

To transfer the data between different simulation tools on the meso scale, see Figure 1, the development of an appropriate data structure is essential. Therefore a data pool containing all necessary information for the description of the actual state of the microstructure was designed. This comprises the description of the microstructure morphology of the material, the characteristics of the individual grains like lattice orientation and constitutive parameters as well as internal variables for the description of the current state of a material point. For each process step an appropriate interface was developed to generate the desired simulation model from the data provided in the data pool. When the simulation is done, the updated values or additional data are given back to the data pool. The main advantage of this data storage is avoiding an exact definition of the data transfer between two consecutive simulation steps. This leads to more flexibility because it is possible to skip or to add further simulation steps.

5.2 VIRTUAL LAB

For the deep drawing simulation of the desired component, macroscopic models are used to describe the plastic behavior of the material. For this reason, it is necessary to homogenize the obtained data from the annealing simulation or the skin pass rolling simulation, respectively.

Therefore, the ”Virtual lab” is used. This is a finite element simulation tool that allows to calculate the macroscopic material behavior based on the current microstructure for any prescribed deformation or loading history. From the homogenization procedure all components of the stress and strain tensor are obtained. Thus, it is possible to calculate the equivalent quantities as well as the Lankford coefficients. The obtained macroscopic uniaxial

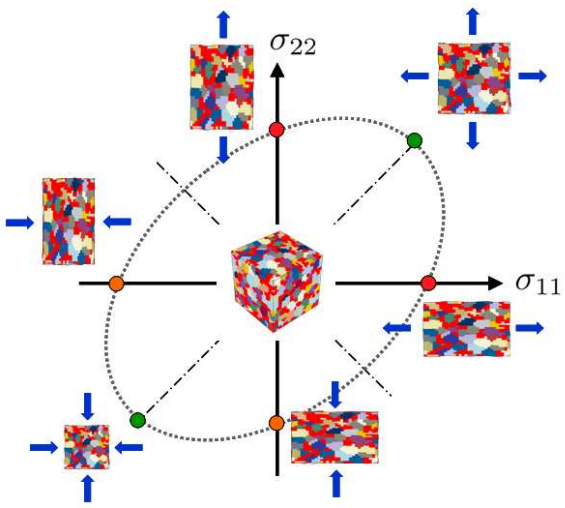

Figure 4: *Application of the Virtual lab to determine a yield locus diagram.*

stress-strain curves can be used - similar to experimentally measured data - to adjust the parameter of macroscopic plasticity models. For instance, the coefficients of the yield functions according to Hill48 or Barlat89 which are typically used for sheet metal forming simulations can be determined. Besides the simulation of common uniaxial loading, it is also possible to model more complex loading conditions like biaxial tension or biaxial compression. Thus, the virtual lab permits the numerical determination of an entire yield locus diagram in stress space as illustrated in Figure 4. Further, it is also possible to analyze the evolution of the yield locus for different direction with respect to the accumulated plastic strain.

6 SHEET METAL FORMING

Forming simulations based on finite element simulations are an established tool to design deep drawn parts and the tools for industrial application. The detailed modeling of the deformation, spring back and forming limits of the sheet metals play an important role.
For representing the material's behavior in yielding and hardening on macroscopic level the Barlat89 yield function [6] and the Swift hardening law were used. The Virtual Lab was used to simulate three tensile tests oriented in 0, 45 and 90 degree with respect to the rolling direction. The corresponding Lankford coefficients were calculated from the homogenized strain tensor. Some first results of the deep drawing simulation of a cross die are illustrated in Figure 5.

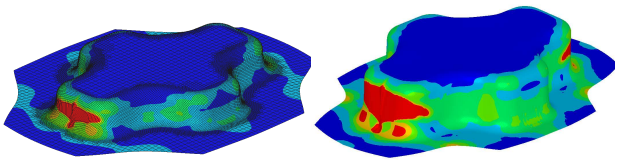

Figure 5: *Deep drawing simulation of a cross die. The parameter for the Barlat89 yield function were determined from the data of the virtual lab.*

7 CONCLUSIONS AND OUTLOOK

The proposed simulation approach is a suitable strategy for the successful introduction of a complete process chain simulation. It brings different modeling approaches on different length scales together which is essential for the prediction of the material properties along the process chain. Further, the simulation of the complete process chain will bring more insight into the individual mechanical interconnections which will help to optimize the individual process steps. By conclusion of the joint research project, the steel manufacturer will be enabled to modify the process parameters and thus material properties fast and purposeful. The application of the process chain simulation enables an enormous time and cost reduction during the introduction of new steels into the automotive market.

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