Possibilities for specific utilization of material properties for an optimal part design

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Abstract. High-strength, cold-formable steels offer great potential for meeting cost and safety requirements in the automotive industry. In view of strengths of up to 1200 MPa now attainable, certain aspects need to be analysed and evaluated in advance in the development process using these materials. In addition to early assessment of crash properties, it is also highly important to adapt the forming process to match the material potential. The steel making companies have widened their portfolios of cold-rolled dual-phase steels well beyond the conventional high-strength steels. There are added new grades which offer a customized selection of high energy absorption, deformation resistance or enhanced cold-forming properties. In this article the necessary components for material modelling for finite element simulation are discussed. Additionally the required tests for material model calibration are presented and the potentials of the thyssenkrupp Steel material database are introduced. Besides classical tensile tests at different angles to rolling direction and the forming limit curve, the hydraulic bulge test is now available for a wide range of modern steel grades. Using the conventional DP-K®60/98 and the DP-K®700Y980T with higher yield strength the method for calibrating yield locus, hardening and formability is given. With reference to the examples of an A-pillar reinforcement and different crash tests the procedure is shown how the customer can evaluate an optimal steel grade for specific requirements. Although the investigated materials have different yield strengths, no large differences in the forming process between the two steel grades can be found. However some advantages of the high-yield grade can be detected in crash performance depending on the specific boundary and loading conditions.

1. Introduction

There is no doubt that modern high-strength steels are vital for meeting the weight and cost saving requirements in today’s automotive industry. When it comes to structural parts with high safety relevance dual-phase steels have become an important steel family for cold forming that can be found in many applications in the body-in-white, see Figure 1 (a). With their well-balanced material properties (e.g. yield/tensile strength or strain hardening behaviour) as well as their forming or welding performance, “classic” dual-phase steels which cover a broad strength range from 500 to 1200 MPa TS have already been launched into the market.

Nevertheless, there is much more potential to be offered. With respect to the application purpose, individual material properties can be “tuned” to fulfill the specific requirements of the final stamped part or the forming process, if needed. Crash properties and part complexity for example are such driving elements that the product portfolio of dual-phase grades steel producers [1]. Figure 1 (b) explains the logic and the portfolio structure for a given strength class: The classic grade is designed
for universal purpose and already fulfils the requirements thanks to a sum of well-balanced properties. A higher deformation resistance and intrusion protection, e.g. in side impacts, can be realized by choosing the high-yield variant instead. On the other hand, further degrees of freedom in view of part complexity can be achieved by an enhanced elongation if that specific feature is in focus.

(a) (b)

Figure 1. Typical applications of dual-phase steels (a) and portfolio structure dual-phase family (b)

2. Material modelling
Nowadays FEM simulation is the adequate tool for feasibility studies and process layout. The material description is an essential prerequisite for successful part design. For this purpose thyssenkrupp has developed a material database [2] to ensure optimal customer process design. With its help it is possible to provide the required material data for a variety of FE tools. In the database the results of different standardized experiments are stored, e.g. tensile tests in different directions to rolling direction at specific temperatures and strain rates, forming limit curves and cyclic tests. The material database was recently extended to include hydraulic bulge tests. This provides a convenient way for customers to prepare simulations for the variety of thyssenkrupp hot and cold rolled steel grades.

Figure 2. thyssenkrupp material database
The necessary material model components for a comprehensive description of the material possibilities and limits are adequate plasticity and failure descriptions. For the simulation of a conventional cold forming and crash process, plasticity is characterized by the yield locus, the hardening behaviour and strain rate dependency. The classical forming limit curve or advanced fracture models define the failure limits of the specific material.

In the article the use of the database is shown with reference to modern dual-phase steel grades. Two grades with a strength level of 1000 MPa are chosen, the classic DP-K®60/98 and the DP-K®700Y980T with increased yield strength. The calibration of the necessary material models is shown regarding forming as well as crash analysis. Table 1 illustrates the mechanical properties of the chosen materials. The hardening parameters are given in rolling direction; in addition the Lankford coefficients in three directions are listed.

### Table 1. Mechanical properties

| Material       | Young’s modulus (N/mm²) | Y.S. (N/mm²) | T.S. (N/mm²) | T.E. (%) | 0°     | 45°    | 90°    |
|----------------|-------------------------|-------------|-------------|----------|--------|--------|--------|
| DP-K®60/98     | 215020                  | 591         | 1004        | 15.2     | 0.11   | 0.54   | 1.2    |
| DP-K®700Y980T  | 213000                  | 712         | 993         | 13.9     | 0.07   | 0.71   | 1.2    |

The preparation of material modelling is discussed in the following sections.

#### 2.1. Hardening behaviour

In forming and crash simulation the assumption of isotropic hardening is often used. That’s why tensile tests are sufficient for calibrating the models. The uniform elongation for the high-strength DP grades is about 10 %. Good experiences for extrapolation of the hardening curve have been made by using the hydraulic bulge tests. The experimental procedure is nowadays standardized [3] and the results are used for calibrating the yield locus as well as the hardening behaviour at large strains. The procedure of transformation of the bulge test results is illustrated in Figure 3. Every point of the biaxial stress-strain curve is transformed to the uniaxial stress state to fit this curve in the best way. To do this different methods and assumptions are given in the literature. One method is explicitly given in ISO16808. For the two dual-phase steel grades the factor Y is nearly identical to 1.0, so the difference between the biaxial bulge and the uniaxial curve is not visible. As an example the test results of DP-K®60/98 are shown in Figure 4.
Swift: \[ \sigma = k \cdot (\varepsilon_0 + \varepsilon_{eq})^n \]  
Voce: \[ \sigma = k \cdot (1 - b \cdot e^{-n\varepsilon_{eq}}) \]  
\[ \sigma = \alpha \cdot \text{Swift} + (1 - \alpha) \cdot \text{Voce} \]

It can be found that a linear combination (3) of an exponential function (2) and a power law (1) represent the transformed bulge curve. Using this approach it is very simple to extrapolate the hardening behaviour to larger strains, Figure 4. Applying this methodology for both steels the hardening behaviour is obtained, shown in Figure 5. Note that the tensile test results are reflected in the strain range up to 0.1, which means different yield strengths and n-values but comparable tensile strength. If a hydraulic bulge test is not available, the extrapolation is done according to [4].

Figure 4. Fitting of DP-K®60/98

Figure 5. Extrapolated yield curves

2.2. Yield locus calibration
The simplest way to characterize anisotropic material behaviour is to use the yield locus model Hill48 [5]. In this case the Lankford parameters in three directions to rolling direction are sufficient for its calibration. Considering the bulge test results the yield locus according to Barlat89 [6] is more general. Adjusting the yield locus exponent it is possible to fit the biaxial stress point. With the more flexible yield conditions of Barlat2000 [7] or Banabic2005 [8] the user is able additionally to meet the stress ratio in different angles to rolling direction. An easy but not the best way is to calibrate the formula referring to the different yield points.

Figure 6. Stress ratios according to RD – DP-K®700Y980T
Figure 6 shows the prediction of the stress ratios according to Hill48, using the measured yield strengths and the development of the stress ratios with respect to the plastic work of the stress-strain curves in different directions.

In the following are some remarks on choosing the exponent for the yield loci of Barlat2000 and Banabic2005. In the literature the values of 6 for steel and 8 for aluminium grades can be found. The general value of 6 is not in accordance with our experiences of the past [9, 10]. A value of 5 leads to realistic forming results and is set to an internal standard for forming simulations.

In summary, it should be noted that the material database now contains all necessary values even for calibration of complex yield loci and the hardening behaviour.

2.3. FLC

Forming limit curves are also part of the material database. The experimental procedure is according to ISO12004 and the final definition of the forming limit curve (FLC) is given in [11]. In Figures 8 and 9 the experimental data, the tkSE-specific definition of the FLC and its theoretical prediction using regression of the mechanical properties are illustrated. The regression is used specifically to take into account varying sheet thicknesses or for press shop applications where only tensile test results are available.

![Figure 7. FLC DP-K®60/98](image)

![Figure 8. FLC DP-K®700Y980T](image)

2.4. Strain rate sensitivity

Especially for crash simulations the time-dependent material phenomena are essential. For this purpose tensile tests with different strain rates are the basis for the calibration of these models. The procedure of calibration was the following. In a first step the strain rate dependency (m-value) was evaluated using the available test results according to (4). Afterwards the m-value was applied to the extrapolated stress-strain-curve using bulge test results, see section 2.1. In Figures 9 and 10 the calculated strain rate behaviour of the two DP grades is given.

\[
m = \frac{\ln(\sigma_p/\sigma_S)}{\ln(\dot{\epsilon}_p/\dot{\epsilon}_S)}
\]  

(4)
To sum up, the tkSE material database is the basis for a quick and convenient way to calibrate material models for FEM simulation. This is an essential prerequisite for a successful customer-specific process design. This will be shown in the following two examples.

3. Forming analysis

The methodology as described above is now applied to industrial forming process. Using the information in the material database the specific input of DP-K®60/98 and DP-K®700Y980T is generated. In this case the extrapolation based on the bulge tests, the yield loci Banabic2005 and the measured FLCs are used.

As an example a A-pillar reinforcement from the InCar® plus project is used [12]. Dual-phase steels are designated for such automotive parts. The forming process design of such crash-relevant parts is challenging regarding formability and springback. Figure 11 gives an overview of the part, blank shape and the die layout of the first drawing step.
4. Crash analysis
One part of the thyssenkrupp material development process is verification of crash resistance, carried out using internally standardized experiments. One of these is an axial crash of a double u-profile at defined loading speeds. Qualitative experimental and quantitative numerical results are given in Figure 14. By using the DP-K®700Y980T with increased yield strength a generally lower maximum deformation of the sample can be found.

Another experiment for characterizing material suitability is a three-point-bending test, Figure 15. For this load case too, the predicted reaction force differs minimally and the maximum intrusion also shows a difference <2mm.
It should be mentioned again that different geometries, load cases and boundaries can lead to more diversified results.

5. Summary
A variety of innovative steel grades have been developed for specific customer needs. Especially the dual-phase steel family offers high potential for applications in the body-in-white. The thyssenkrupp material database allows a fast and cost efficient FEM input for forming and crash analysis. Therefore an optimal fit of implemented material models is possible. This is essential for numerical process design. Customers have the possibility to choose the steel grades from the thyssenkrupp portfolio, to evaluate their concept and process with the help of numerical simulations and finally to compare the grades according to their specific needs.

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