

The Impact of Advanced Material Simulation Parameters in Press Shop Operations Using Mild Steel Grades

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ABSTRACT

Forming simulation is a widely used tool to estimate production forming capabilities. During the last three to four years the prediction of process robustness by sensitivity analysis has been developed for industrial applications. The change of material parameters is one key figure and has a large impact on the final findings. Thus the user has to ensure that the variations done are in correlation with real material behaviour and the selected numerical model is reliable. Up to now the permitted changes in modelling are seldom secured by real measurements, especially when more advanced material models and hardening options are applied.

Various materials chosen out of the production process for mild steel grades have been investigated for their mechanical properties using different tests. The limits of failure are defined by a reduced number of Nakajima tests to predict the forming limit curve (FLC). All data is prepared in the same manner to meet simulation program needs. The calibration of yield locus by solely tensile tests and in combination with hydraulic bulge tests gives a first estimation of possible compromises in data preparation. More advanced material calibration strategies allow a better fit of the models to the measured values (Hill '90, Banabic 2005). Furthermore some principles can be noticed for yield locus calibration in biaxial stress space. The experimentally measured forming limits are compared to the TKS-in-house regression formula, Keeler's approach and other models.

Finally simplified state of the art simulations (input tensile test) are compared to simulation results gained with more accurate material data input parameters for yield locus and hardening for different complex parts. The resulting

difference in the feasibility findings are then discussed with respect to a virtual process design chain.

INTRODUCTION

With respect to material aspects, feasibility studies with the help of forming simulations are characterized by the hardening rule, yield locus and the failure criteria applied. In daily practice the strain distribution is mostly compared with the forming limit curve (FLC). In addition, the friction law, the Youngs-modulus, in particular for spring-back requirements and the modelling of a combined isotropic-kinematic hardening all play an important role. During the design phase of robust processes the awareness of possible scatter in the material parameters is helpful. However the impact of this scattering with respect to different forming targets depends on the part design as well as on the process conditions.

A qualified statement about the process safety for a given part by simulation is only possible where reliable statistical data provide enough information about the limits and/or the correlations of material parameters. This data (e.g. yield locus calibration based on non-standardized experiments) is often not available. However even when this data is available the interpretation and transformation to robust simulation models has to be done with care. Consequently it is therefore desirable to find some valuable information using solely tensile test results. The restriction of using the tensile test is based on the fact that only this test is available for every steel coil and standardized.

This idea and method will be discussed in the next chapters and selected results shown.

MATERIAL MODELS FOR FORMING SIMULATION

THEORETICAL MODELS AND EXPERIMENTS

In [figure 1](#) different proposal for modelling the plastic behaviour of steel sheets are shown. During the last years an increasing number of yield locus definitions have been presented in order to allow a better material modelling for forming simulations. All of the newer models have in common that a larger number of experiments are needed.

<[figure 1](#) here>

Here the classification of different levels is based on the effort to calibrate the models. In general a level one model can be fitted by tensile tests in three directions of the sheet plane. All models listed in higher level groups two and three need at least one more experiment. Naturally the higher level models allow a more flexible calibration and fit to the real material needs. In contrast to the possibilities of university studies however (where a number of special experiments for model calibration are available) in industrial practice the determination of material parameters using such non-standardized experiments is very expensive and time consuming. This results in a nearly impracticable situation in the application of these models. This is even more essential when a large number of steel grades in combination with different thicknesses and coatings are in operation. [Figure 1](#) right shows an extraction of possible experiments for yield locus and partly hardening calibration. All tests differ in the stress state, generated during testing. The existing difference of assured stress interpretation, here noted by the strain range to be used, has to be mentioned. Furthermore not all testing procedures guarantee a constant strain rate during the whole experiment.

Due to the fast ongoing virtual process development the evaluation of process robustness with solely simulation methods is a main focus of research. To allow such methods an intensive knowledge of the material response and permitted material model assumptions are needed. For research and generation of final findings the above shown experiments can partly been done. For industrial application stronger simplifications are needed. In the end it is desirable and worthwhile to correlate these special experimental findings with tensile tests.

To prove possible simplifications within one material grade a comprehensive study is done for a hot dip galvanized extra deep drawing quality. All grades have nearly identical gauge and are variously extracted from ThyssenKrupp Steel industrial lines. The mechanical data derived by tensile tests in rolling, diagonal and transverse direction are shown in

[table 1](#). While the original study contained over twenty different production runs, here only a selection of up to nine will be discussed.

Table 1. Mechanical properties of the test material (hot dip galvanized mild steel)

No.	YS MPa	TS MPa	TE %	UE %	HE (n)	R ₀	R ₄₅	R ₉₀
1	156	299	46.5	23.2	0.228	2.19	1.58	2.23
2	169	313	41.3	23.1	0.224	2.38	1.78	2.31
3	152	295	44.3	22.6	0.230	1.94	1.92	2.53
4	150	293	44.9	23.1	0.229	1.90	1.92	2.53
5	161	308	44.2	3.6	0.229	1.86	1.55	2.23
6	153	289	45.1	23.2	0.230	2.15	1.73	2.53
7	165	301	40.4	22.8	0.223	2.38	1.64	2.38
8	158	304	44.5	22.9	0.229	1.82	1.95	2.60
9	152	301	43.4	23.3	0.229	1.54	1.99	2.50

YIELD LOCUS CALIBRATION AND MATERIAL HARDENING

For finite element simulations a model for yield locus, a flow rule and a hardening curve are needed. Normally the flow rule is associated with the selected yield locus and therefore seldom of user interest.

The simplest way to model deep drawing quality steel sheets is based on the yield locus theory of Hill '48 [11]. The advantage of this model is the exclusive need of tensile test data for calibration. State of the art is to use the three Lankford coefficients to calibrate the yield locus shape and a stress strain curve in rolling direction for the hardening. The hardening could also be defined by making an average of the overall hardening from all three directions and use this artificial curve as a master yield curve.

If we use the model of Hill '48 for all the grades and values listed in [table 1](#), we find the yield loci result shown in [figure 2](#). On the left the original yield loci based on individual yield stress are presented, whereas on the right all values are normalized to yield stress in rolling direction.

To prove the validity of the well known Hill '48 model for the selected grade, additional experiments can be carried out allowing an interpretation of model deviations from measured stresses in non uniaxial stress state. For our studies we selected the hydraulic bulge test with nearly ideal biaxial stress state. All material batches were tested in the same way. In order to derive the yield curves the pressure, curvature at the test pole and the thinning at the pole have been recorded for each test. This data allows a large variety of later interpretations for FEM models. It should be mentioned that

the hydraulic bulge is of special interest in Germany for use as a standard for extrapolations in FEM simulations. The results shown here are based on the actual research state of a special working group of the GDDRg. The aim of this working group is the development of an interpretation standard for hydraulic bulge testing. The need for such standardisation is shown in [1].

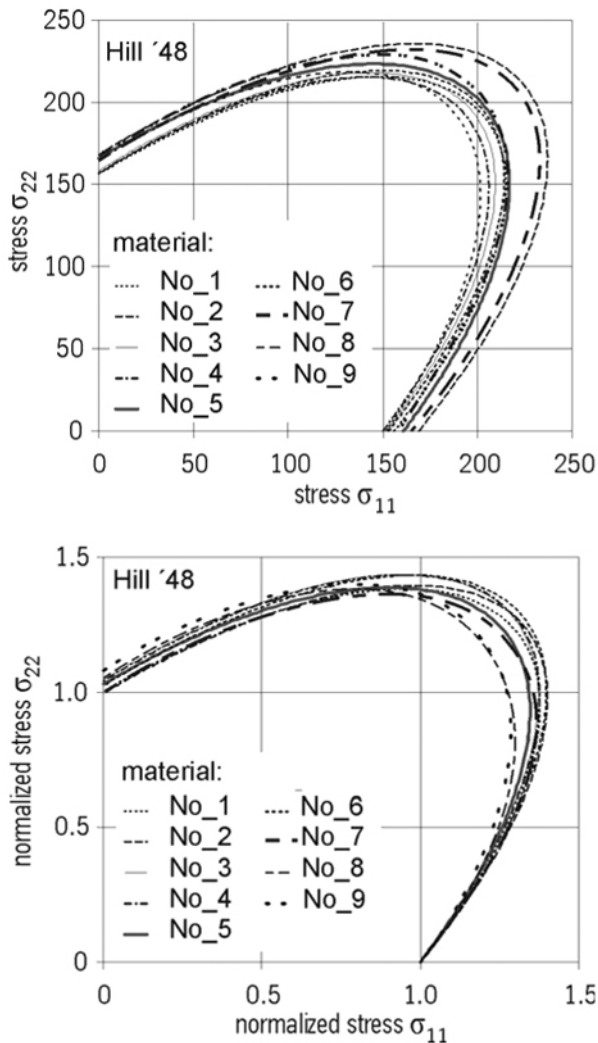


Figure 2. Yield locus according to Hill '48 in original and normalized representation.

The result of the hydraulic bulge test can be used for the identification of one additional point in stress space to allow a better yield locus calibration on the one hand and on the other to obtain a better extrapolation of the tensile test hardening curve [2].

Yield locus calibration

The basic idea of the yield locus today is the transformation of the multiaxial stress states on the uniaxial stress strain curve. If focusing on a larger area of strain, as is present in normal forming situations, a yield locus is a fixed and static

factor for stress state transformation. A change of the yield locus shape with increasing strain is not used in industrial simulations.

There different ways, of transforming the hydraulic bulge to uniaxial tension, two of which are mentioned here:

- Use of strictly plastic work as an integral of the measured stress strain curve. Corresponding points have the identical work and each stress point from the hydraulic bulge is then a point of the yield locus. A derivation of this method is the strict punctual interpretation for a fixed equivalent plastic work level. Doing this, the stress of both tests are compared at only one limited point, for example a plastic work corresponding to 5% strain in tensile testing.
- Assuming a proportional development of stress and strain in both directions in bulge test the formulation of plastic work, given in figure 3, can be simplified. This method is also used in the FEM formulations using isotropic hardening.

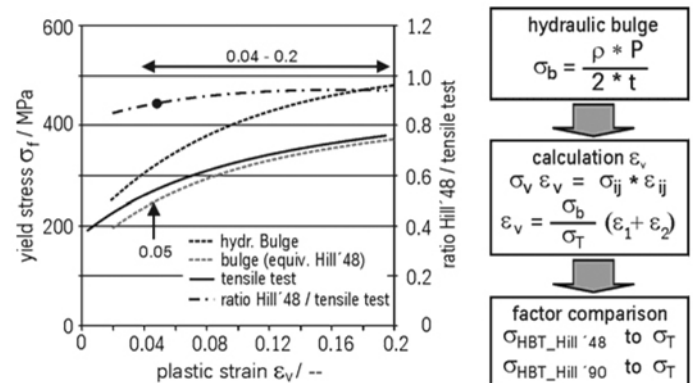


Figure 3. Identification strategies for a yield locus based on proportional plastic work.

As the model findings are used in industrial simulations with isotropic hardening and no change of yield locus with plastic strain we use method number two. All findings shown below are based on this method. Figure 3 shows the typical strategy for the transformation of bulge test results in uniaxial stress state. Directly from the bulge raw data the v. Mises equivalent stress and strain are derived. In a next step a constant ratio of biaxial stress to the uniaxial stress is searched for. By having only limited curvature for interpretation in between 0 % to 4 % strain the data evaluation process for calibration ignores this range. To identify the ratio a given yield locus is selected and the hydraulic bulge curve is transformed using the given formula to meet the uniaxial tensile test. If, for example Hill '48 is chosen and the transformed curve lies below the tensile test curve for the complete strain range, a yield locus allowing a calibration to smaller biaxial stresses is needed. This can be done by selecting a non-quadratic yield locus like Hill '90, Barlat '89, Banabic 2005 and so on [9,10]. A good yield

locus, representing both tensile and bulge test results, has only minor deviation for the transformed bulge stress strain curve and the tensile test result in rolling direction. Normally the formulation of Hill '90 already allows a valuable transformation with limited error in approximation. It has to be noted here that the assumption of plastic work and isotropic hardening make a compromise for FEM modelling. Looking at different equivalent plastic strain levels greater or lesser deviations in the ratio of biaxial stress to the uniaxial tensile test are noted. This ratio is dependent on material and thus varies according to grade or material type differently.

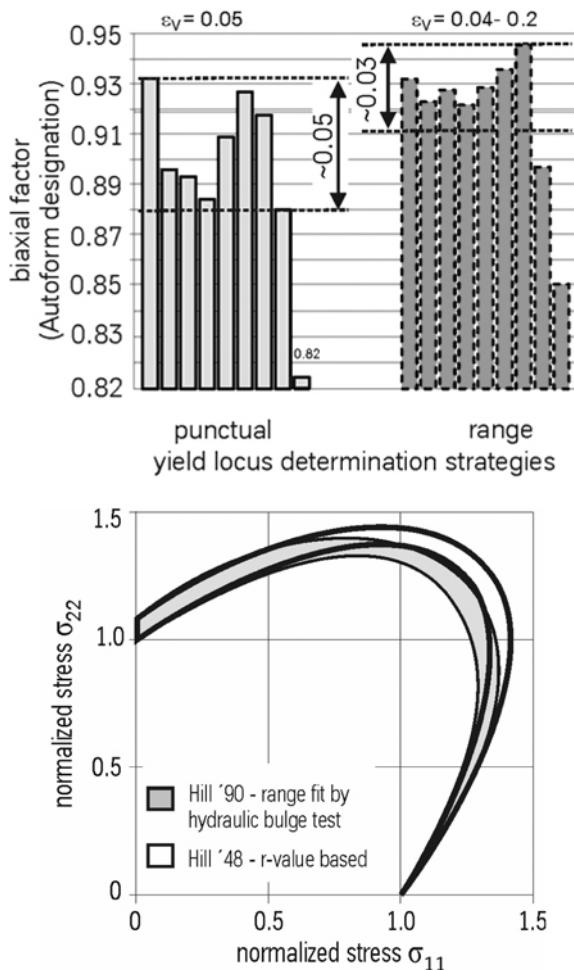


Figure 4. Identified yield locus Hill '90 parameters based on yield locus finding strategy

To illustrate a possible difference in yield locus findings using a fixed plastic work level in comparison to an integral interpretation we used these two methods. The plastic work level for the fixed interpretation is identified for a tensile strain of 5%. As an integral interpretation the transformation according to the selected yield locus model tries to fit the stress strain curve in a range of 4% to uniform elongation (figure 4). First of all the formulation of Hill '48 was not identified by any of these two methods. The recalculation of

the tensile test curve needs a non-quadratic yield locus. The yield locus of Hill '90 fulfils these needs. A better interpretation of the change from Hill '48 to Hill '90 is facilitated using the AutoForm program definition of a biaxial stress factor. This consists of a ratio of the biaxial stress from Hill '90 to the biaxial stress according to Hill '48. Lower values than 1.0 signalize a compression of the yield locus with Hill '90, larger values than 1.0 lead to an expansion of the yield locus on the axis $\sigma_1 = \sigma_2$ in major stress state. A value of 0.9 represents therefore a 10% reduction of the biaxial stress point to the inside compared to Hill '48 yield locus.

The strictly punctual interpretation shows slightly more variations and results in lower biaxial stress factors for the model calibration. The interpretation with a larger strain range results in less scatter in between the nine investigated materials. A selection of around 0.93 for the biaxial stress factor seems to be a good choice here. If using any other yield condition (e.g. Barlat '89) the data could form the basis for a rough estimation of the exponent of the yield function if not equal to 2.0.

Material hardening

By using the defined yield locus from both of the above mentioned strategies it is possible to calculate the hardening curve from the hydraulic bulge test. With respect to the plastic work assumption we found a general tendency for the hardening curves derived. The equation of Swift, fitted to the tensile test, overestimates the material hardening for most of the grades at large strains. Changing to the equation of Hockett-Sherby the hardening is less pronounced and the extrapolated yield curves nearly meet the recalculated yield curves from the bulge test. A slightly too strong material hardening is assumed for some of the grades.

FAILURE DEFINITION USING FORMING LIMIT CURVES (FLC)

Determination of forming limit curves

The most common and widely used method for the failure criterion in press-shop application is the concept of forming limit curve in addition to a simple thinning approach. Many ways to determine FLCs exist today; the in-house method of ThyssenKrupp Steel is based on a Nakajima tests and discussed in the following.

In general, forming processes are not defined using splits; already an onset of (visual) necking indicates unsafe processes. Therefore the forming limits should correspond to the beginning of the necking phenomena. Different strategies for the determination of the onset of necking are used in practice; ThyssenKrupp Steel historically uses the visual method but applies the new ISO 12004 as well. Here we discuss the visible determined necking points in correlation to