CHALLENGES IN MATERIAL MODEL SELECTION FOR INDUSTRIAL FORMING SIMULATION

Dr. Lutz Kessler*, Dr. Jörg Gerlach*, Thorsten Beier*
Ingo Heinle +, Arnulf Lipp +, Dr. Hannes Grass+

*ThyssenKrupp Steel Europe AG
+BWM Group

ThyssenKrupp Steel Europe
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Starting situation for material calibration

Constant advances in simulation systems for analyzing metal forming processes are increasingly influencing and expanding the capabilities available for the modeling of materials. The descriptions of strain hardening and yield locus are closely linked but are mostly investigated in isolation in research work. The more complex yield locus models, such as Barlat 2000 or Banabic 2005, have more parameters and therefore allow increasingly precise matching with existing test data, promising more accurate predictions of material influence in simulations of practical forming processes (Fig. 2).

<table>
<thead>
<tr>
<th>Model</th>
<th>(\sigma_1)</th>
<th>(\sigma_{11})</th>
<th>(\sigma_{22})</th>
<th>(R_1)</th>
<th>(R_{11})</th>
<th>(R_{22})</th>
<th>(\sigma_9)</th>
<th>(R_9)</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill ’48</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
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<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Hill ’90</td>
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<td>-</td>
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<td>X</td>
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<td>X</td>
<td>-</td>
<td>5</td>
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<tr>
<td>Barlat ’89</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Banabic 2005</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
</tr>
<tr>
<td>Barlat 2000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 1: Material model and necessary test data for calibration (\(\sigma\): Stresses and R: strain relation in different orientations to rolling direction respectively in “biaxial tension state”)

In further applying material models, researchers in Europe are increasingly turning to complex, non-standardized test methods and experiments to derive the necessary parameters. Yet a necessary prerequisite for sustainable industrial application of the material models is standardization of test conditions. This is being pursued for example in working groups of the German Group of the IDDRG for the topics of forming limit curves and hydraulic bulge tests. However, in selecting test methods it must be taken into account that some steel materials display varying behavior when loaded in compression or tension. Simply exchanging the results of stack compression tests with those of hydraulic bulge tests for extrapolation or yield behavior under biaxial stresses can therefore result in sometimes widely differing conclusions for the selection of model.

The commercial benefit of simulation-based predictions is determined to a large extent by the prediction capability and accuracy of the model. Potential for improvement is often seen in the area of constitutive equations. The paper and presentation therefore discusses models of the yield locus and the strain rate sensitivity of hardening. Fundamentally, however, more general models of elasticity and the Bauschinger effect must be studied for an improved description of general stress-strain relationships as well. In addition, the modeling of friction behavior between material and die can also influence the simulation results to a quite considerable degree.
Experience in the calibration of material models

Probably the simplest and cheapest method of material calibration for forming simulation is to select a constant yield curve extrapolation method (e.g. Swift) in combination with a yield locus that can be determined exclusively via tensile testing parallel, diagonal and transverse to the rolling direction (e.g. Hill ’48). If this description models the material behavior sufficiently well, there are numerous advantages to be gained. The method can be adapted to new materials very quickly and with few data, and in analyses of process robustness clear correlations of yield locus shape or hardening allow simple variation of these parameters. With a number of special tests, therefore, fixed modeling rules can be generated for material groups.

Where materials demand specific extrapolation methods or yield locus models, additional experiments are mostly necessary. ThyssenKrupp Steel Europe has developed a method for the extrapolation of yield curves which, based on tensile test data, estimates material behavior in hydraulic bulge testing and therefore introduces a necessary additional point at higher strains for identifying the extrapolation. In addition, “biaxial” stress information is also generated for the yield locus. However, it is difficult to determine the specific shape of the whole yield locus clearly via additional experiments because many areas are only very inadequately covered by experiments, or the necessary experimental accuracy is not available, for example for determining the yield locus exponent. Tests have shown both that the orientation of the additional experiment to the rolling direction can have effects on the identification of the yield locus and that the number of additional experiments influences the results. Preliminary tests based on a deep drawing steel DX54 showed that the results of the experiments commonly used today for calibrating yield loci (tensile test, hydraulic bulge test, shear test) can be modeled well with the Barlat 2000 model. However, it remains open whether the parameters of the yield locus can be determined clearly and optimally for all expected practical forming conditions using this experimental basis.

Based on existing results an alternative and new method to identify and verify yield locus parameters was developed, validated and applied in a collaboration of ThyssenKrupp Steel Europe with the BMW Group. Starting from the classic tensile test and hydraulic bulge test, final identification of yield locus shape and parameters is achieved by specifically developed validation experiments which present inhomogeneous field problems and are simulated by FEM analysis. Using blanks in different orientations to rolling direction, a comparison is drawn with the experiments by simulation for several applications/experiments and the optimal model for hardening and yield locus shape is determined. It was shown that the numerical value of the yield criterion exponent of 6 often proposed in the literature for steel materials results in very unrealistic modeling. In addition, the material description specifically derived for the FEM program is not transferable to other programs without modifications, i.e. the desire for an optimum material model to be independent of the FEM code used cannot be fully met.

The outcome of the studies is a process principle including experimental and simulational components which makes it possible to assess models relatively quickly and effectively with regard to modeling real material behavior under forming conditions.
**Analysis of yield locus and strain rate sensitivity**

Besides the usual parameters from the tensile test, the influence of strain rate to improve failure prediction is being increasingly discussed in the literature. The parameter field is thereby extended by a further dimension, which however must be seen in close connection with strain hardening and the yield locus. The paper / presentation illustrate by way of example an inverse approach to determining the yield locus in combination with consideration of strain rate sensitivity through the use of optimization strategies. The hardening behavior of the material is assumed to be isotropic. At the end of the optimization, an assessment can be made as to which parameter combinations have contributed to modeling the given experimental values effectively. In this way the amount of additional experiments can be limited to an industrially viable number.

The experiments and approaches presented resulted from a joint development effort by ThyssenKrupp Steel Europe and BMW (Fig. 2 and 3). Fig. 3 underlines the relevance of the yield locus with regard to the prediction of material failure. It becomes clear that the choice of yield locus model and of model parameters can significantly influence the position of the predicted failure as well as its starting point in the forming process.

![YLIT-1-TKSE and YLIT-2-TKSE](YLIT-1-TKSE.png) ![YLIT-2-TKSE](YLIT-2-TKSE.png)

**Figure 2: YLIT-1-TKSE and YLIT-2-TKSE (Yield Locus Identification Tool) for material model validation**

![Simulation, Barlat '89 m=2](Simulation_Barlat_89_m=2.png) ![Simulation, Barlat '89 m=8](Simulation_Barlat_89_m=8.png) ![Simulation, Barlat 2000 a=5](Simulation_Barlat_2000_a=5.png) ![Experiment](Experiment.png)

**Figure 3: Application of YLIT-3-BMW (Yield Locus Identification Tool) for failure location prediction**
Validation

Based on the insights gained regarding the choice of model parameters for yield locus and strain rate sensitivity of hardening, the results of several validation experiments are compared. The quality of the material model is assessed by comparing the results of the simulation with the measured data from all experiments. The parameters for this are strain fields and the location of material failure. In this way the possibility can be excluded that the material parameters in conjunction with the FE software deliver good results for one experiment only. An acceptable agreement between measurement and simulation for all validation experiments indicates a generally valid material model for the steel grade under investigation.

Conclusion

The studies essentially show the need for an extended process for calibrating and validating material models. The reason for this is that available standard experiments are unable to calibrate complex yield loci clearly and can lose their advantages over simple models such as the Hill `48. The optimization approach also allows the possibility of limiting the number of additional experiments. In addition, the strategy presented gives the user a good overview of whether a particular model tends to over- or underestimate a material's forming capabilities. This can provide valuable pointers for die design and reliable process design. Users are given the ability to choose how work on robust process design is to be distributed, in the simulation phase or in try-out.

Corresponding literature from the authors:


/4/ J. Gerlach, L. Kessler: “A consistent approach for simplifying the material modelling in forming simulations aiming on cold rolled steel grades”. In Steel Grips 4, 2006, pp. 255-260

Outline

- Introduction
- Material models, testing and validation
- Risks and challenges
- A new approach (to derive material cards)
- Application example and discussion
- Conclusion
Some Requirements for Forming Simulations

- Fast computation
- Good average result
- Standardization of process
- Stochastic simulation capability
- Robust
- Cost efficient
- Reliable
- Realistic

➤ To identify the best overall set-up for the own demands!
Material Models, to be Checked from Time to Time

- FE-method
- Geometry
- Material
- Process
- Total result

*FE-method* | *Simulation*
---|---
*Geometry* | *Simulation*
*Material* | *Simulation*
*Process* | *Simulation*
*Total result* | *Simulation*
Material Models, to be Checked from Time to Time

- FE-method
- Geometry
- Material
- Process
- Total result

No impact on overall result
Material Models, one Brick in a Complex System

- FE-method
- Geometry
- Material
- Process
- Overall result

reality | simulation
Material Models, one Brick in a Complex System

FE-method
Geometry
Material
Process
Over all result

Worth to spend money for!
The benefit of the identified best material model has to be evaluated within its application context and all other parameters influencing the final result.
# Material Model Choices

<table>
<thead>
<tr>
<th>Hardening</th>
<th>Failure Criteria</th>
<th>Yield curve</th>
<th>Yield locus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotrop</td>
<td>FLC</td>
<td>Swift</td>
<td>v. Mises</td>
</tr>
<tr>
<td>v. Mises</td>
<td>Non-linear FLC</td>
<td>Hocket-Sherby</td>
<td>Tresca</td>
</tr>
<tr>
<td>Isotropic-kinematic</td>
<td>FLSC</td>
<td>Gosh</td>
<td>Hill-Family</td>
</tr>
<tr>
<td>Prager</td>
<td>Duct. shear fracture</td>
<td>Mixture-Function</td>
<td>Hill ´48</td>
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<tr>
<td>Chaboche</td>
<td>Ductile-fracture</td>
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<td>Backhaus</td>
<td>Nucleation (Gurson)</td>
<td></td>
<td>Barlat-Family</td>
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<tr>
<td>Yoshida</td>
<td>CrachFEM</td>
<td></td>
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<td>Distorsion</td>
<td></td>
<td></td>
<td>Barlat ´96</td>
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<td>ICT-Theory</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Banabic 2005</td>
</tr>
</tbody>
</table>

- Level 01 = Standard
- Level 02 = Advanced
- Level 03 = Complex

⇒ To identify the best combination to meet the individual needs!
Material Input Values for Yield Locus Formulation

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$</th>
<th>$\sigma_{45}$</th>
<th>$\sigma_{90}$</th>
<th>$r_0$</th>
<th>$r_{45}$</th>
<th>$r_{90}$</th>
<th>$\sigma_b$</th>
<th>$r_b$</th>
<th>Parameter</th>
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</thead>
<tbody>
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<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Barlat ´89</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Barlat 2000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
</tr>
<tr>
<td>Banabic 2005</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
</tr>
</tbody>
</table>

Hill ´48

$$\sigma^T T \sigma = \sigma_r^2$$

$$\sigma^T = [\sigma_{11}, \sigma_{22}, \sigma_{12}]^T$$

$$\sigma = a[K_1 + K_2]^M + a[K_1 - K_2]^M + c|2K_2|^M = 2^{M-\mu}$$

$$F = \Phi' + \Phi'' = 2\sigma$$

$$\Phi' = |X'_1 - X'_2|^\mu$$

$$\Phi'' = |2X'_2 + X'_1|^\mu + |2X'_1 + X'_2|^\mu$$

$$X' = L\sigma$$

$$X'' = L^{\mu}\sigma$$

$$\sigma^T = [\sigma_{11}, \sigma_{22}, \sigma_{12}]$$

Barlat ´89

$$K_1 = \frac{\sigma_{xx} + h \sigma_{xy}}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_{xx} - h \sigma_{xy}}{2}\right)^2 + p^2 \sigma_{xy}^2}$$

Barlat 2000

$$-\sigma = \left[ a(\Lambda + \Gamma)^{\mu} + a(\Lambda - \Gamma)^{\mu} + b(\Lambda + \Psi)^{\mu} + b(\Lambda - \Psi)^{\mu} \right]^{1/M}$$

$$\Gamma = L\sigma_{11} + M\sigma_{22}$$

$$\Lambda = \sqrt{(N\sigma_{11} - P\sigma_{22})^2 + \sigma_{12}\sigma_{21}}$$

$$\Psi = \sqrt{(Q\sigma_{11} - R\sigma_{22})^2 + \sigma_{12}\sigma_{21}}$$

A material specific exponent of the Barlat ´89 yield locus may be determined using a hydraulic bulge test.

The exponents of the Barlat 2000 and Banabic 2005 yield loci are often assumed.

(A value of 6 is recommended for steel grades and 8 for aluminum in literature)
Classical Process in Material Modeling

Material

Testphase:
• tension
• shear
• bulge
• ...

Laboratory

Modeling:
• hardening
• yield locus
• failure
• ...

Institute

Material card

Test results

Operation:
• part 01
• part 02
• part 03
• ...

Tool maker

Material card

Hardening
- Isotropic
- v. Mises
- Isotropic-kinematic

Failure Criteria
- VIS-FLC
- Non-linear FLZ
- FLD

Yield curve
- von Mises
- Hocket-Sharpe
- Gough

Yield locus
- 
- 
- 

Test results

- Creep
- Chaboche
- Bashein
- Yoshida
- Eshelby
- ICT-Theory

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Forming Result by Model Variation

A strong influence of the yield locus model exists! How to handle it?
# Overview for Material Model Input Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$</th>
<th>$\sigma_{45}$</th>
<th>$\sigma_{90}$</th>
<th>$R_0$</th>
<th>$R_{45}$</th>
<th>$R_{90}$</th>
<th>$\sigma_b$</th>
<th>$R_b$</th>
<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>Hill ´48</td>
<td>X</td>
<td>-</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>Barlat ´89</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
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</tr>
<tr>
<td>Banabic 2005</td>
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<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Barlat 2000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>8</td>
</tr>
</tbody>
</table>

For the table above:

- **$\sigma_0$** - Initial stress
- **$\sigma_{45}$** - Stress at 45 degrees
- **$\sigma_{90}$** - Stress at 90 degrees
- **$R_0$** - Parameter for 0 degrees
- **$R_{45}$** - Parameter for 45 degrees
- **$R_{90}$** - Parameter for 90 degrees
- **$\sigma_b$** - Stress at yield
- **$R_b$** - Parameter for yield

Forming operations

→ **New yield locus models result in additional experimental effort!**
### Material Input Values for Yield Locus Calibration

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$</th>
<th>$\sigma_{45}$</th>
<th>$\sigma_{90}$</th>
<th>$R_0$</th>
<th>$R_{45}$</th>
<th>$R_{90}$</th>
<th>$\sigma_b$</th>
<th>$R_b$</th>
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<tbody>
<tr>
<td>Experiment</td>
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<td>472</td>
<td>470</td>
<td>0.77</td>
<td>0.90</td>
<td>1.01</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Hill `48</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Banabic 2005</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

⇒ Additional model parameters allow to meet fundamental test data correctly.

![Graph showing yield stress ($\sigma$) and $r$-value vs. angle to R.D.](image)
The yield locus exponent is hard to identify using available material tests!
A New Process Design for Material Modeling

Testphase:
- tension
- shear
- bulge
- ...

Material Modeling:
- hardening
- yield locus
- (failure)
- ...

Operation:
- part 01
- part 02
- part 03
- ...

Validation:
- exactness
- robustness
- ...

Combined modeling

Laboratory

Tool maker

Testphase:
- tension
- shear
- bulge
- ...

Material Modeling:
- hardening
- yield locus
- (failure)
- ...

Operation:
- part 01
- part 02
- part 03
- ...

Validation:
- exactness
- robustness
- ...

Combined modeling
## Selected Material Input from Testing

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$</th>
<th>$\sigma_{45}$</th>
<th>$\sigma_{90}$</th>
<th>$R_0$</th>
<th>$R_{45}$</th>
<th>$R_{90}$</th>
<th>$\sigma_b$</th>
<th>$R_b$</th>
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<tbody>
<tr>
<td>Hill ´48</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Barlat ´89</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Barlat 2000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

In our studies we totally rely on the following material data values:

- Results from tensile test (static, with rates of 0.001 1/s up to 1.0 1/s)
- Yield stress from tensile test (0°, 45° and 90°) to rolling direction
- Lankford coefficient (r-value) in 0°, 45° and 90° to rolling direction
- Yield curve extrapolation based on a hydraulic bulge test
- Biaxial stress point $\sigma_B$ identification with a hydraulic bulge test
A strong influence of yield locus model can be identified!
Comparison of Drawing Depth and Neck Location

FEM-input (AutoForm):
- r-values (0°, 45°, 90°)
- \( \sigma_{0.2} \) (0°, 45°, 90°)
- biaxial stress point (bulge)
- extrapolation by bulge test
- strain rate (SR=off)

- Hill ’48
- Hill ’90
- Barlat ’89
- Banabic 2005

Barlat ’89
43.5 mm 35.7 mm
in TD in RD

Banadic 2005, M=5
in TD in RD

Banabic 2005, M=6
in TD in RD

A just fundamental data yield locus fit is insufficient for this material grade

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Validation of a Mild IF-Steel (DC 06) in LS-Dyna

FEM-input (LS-Dyna):
- ✓ r-values (0°, 45°, 90°)
- ✓ σ_{0.2} (0°, 45°, 90°)
- ✓ biaxial stress point (bulge)
- ✓ extrapolation by bulge test
- ✓ strain rate (SR=on, Cowper S.)

Drawing depth

Experiment Simulation

Barlat 89
Barlat 2000

B 89

a=5
a=6

Drawing depth in mm

35 40 45 50 55

0° 90°
Validation of a Mild IF-Steel (DC 06) in LS-Dyna

FEM-input (LS-Dyna):
- r-values (0°, 45°, 90°)
- σ₀.₂ (0°, 45°, 90°)
- biaxial stress point (bulge)
- extrapolation by bulge test
- strain rate (SR=on, Cowper S.)

Critical Element FEM

Drawing depth

2 Experiments:
- Major strain 0° and 90° to R.D.

Location of failure

Arc length from pole in mm

Experiment

Simulation

B 89

a=5

a=6

Barlat 2000

Barlat ’89

Drawing depth

Critical Element FEM
Validation of a Mild IF-Steel (DC 06) in LS-Dyna

FEM-input:
- r-values (0°, 45°, 90°)
- \( \sigma_{0.2} \) (0°, 45°, 90°)
- biaxial stress point (bulge)
- extrapolation by bulge test
- strain rate (SR=on, Cowper S.)

2 Experiments:
Major strain 0° and 90° to R.D.

Strain path of the critical element that failed at first

Barlat ´89
Barlat 2000

Major strain

FLC

0°

Barlat 2000, a=6
Barlat89
Experiment
Barlat 2000, a=5

90°

Barlat 2000, a=6
Barlat89
Experiment
Barlat 2000, a=5

Minor strain
Outline

- Introduction
- Material models, testing and validation
- Risks and challenges
  - A new approach (to derive material cards)
- Application example and discussion
- Conclusion
Use of Optimization Algorithms for Modeling

Fundamental data:
\[ \sigma_0, \sigma_{45}, \sigma_{90}, R_0, R_{45}, R_{90}, \sigma_b \]

Barlat 2000
Model calibration
(exponent \rightarrow parameter-fit)

Optimization

Generation of a new population

Strain rate (on/off)

Evaluation objective function

Validation experiment data
punch travel, strain state
Yield Locus Parameter Finding by Optimization

Material: DX 54

- With strain rate dependency
- Without strain rate dependency

Exponent $a$ for Barlat 2000

Objective function result (quality)

Criteria in RD, TD
- Drawing depth
- Strain state

better worse

best results
The modeling of material hardening effects the yield locus findings.
To identify areas with strong material model impact

- Standard simulation with Hill ´48 material model
- Simulation with advanced material model calibration
- Thickness distribution report
- Relative local change to Hill ´48

Material: DX 54
Comparison of Barlat 2000 to Hill ´48 Result

Material: DX 54

Side frame made of DX 54 with initial thickness = 0.75 mm

Difference thinning / mm to Hill ´48

-0.10
-0.06
-0.02
0.02
0.06
0.10

a) Barlat 2000, a=5.0, SR=on
b) Barlat 2000, a=5.0, SR=off

→ Complete change of the feasibility forecast by the parameter strain rate!
Different Results by Material Model Changes

Material: DX 54

Side frame initial thickness = 0.75 mm

<table>
<thead>
<tr>
<th>Difference thinning / mm to Hill ´48</th>
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</thead>
<tbody>
<tr>
<td>Hill ´48</td>
</tr>
<tr>
<td>minus (-)</td>
</tr>
<tr>
<td>Alternative model</td>
</tr>
<tr>
<td>equal (=)</td>
</tr>
<tr>
<td>Result a) to d)</td>
</tr>
</tbody>
</table>

Reference simulation with Hill ´48 (SR=off)
Here, comparison of other model results to the result of Hill ´48

There are multiple criteria for model acceptance and application in industry!

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Conclusion and Remarks

- Multi parameter yield loci allow to meet the experimentally measured material data in a better way
- Do not use general values from literature \((a, M=6)\) for steels untested
- In our studies with different steel grades the exponent of 6.0 never generated the best solution!
- Make a validation of all model parameters
- Optimization methods might be used effectively
- Finally: Identify your individual compromise of wishes for exactness and your willingness for expenses
Thank You for Attention