# Advanced Constitutive Models as Precondition for an Accurate FEM-Simulation in Forming Applications

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ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

# Advanced Constitutive Models as Precondition for an Accurate FEM-Simulation in Forming Applications

Prof. P. Hora
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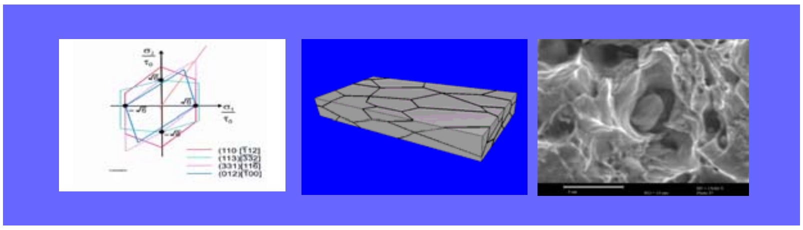
Keynote-Paper



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- **Introduction**
- **Advanced Methods in Constitutive Modeling of Materials**
  - Advanced methods in hardening description
    "Combined experimental and crystal plasticity methods in determination of hardening for large strains"
  - Advanced methods in yield locus description
    "Crystal plasticity methods in determination of non-quadratic yield locus shapes"
  - Advanced methods in failure modeling
    "Numerical methods in computational evaluation of FLCs with the enhanced Modified Maximum Force Criterion (eMMFC)"
- **Conclusions**

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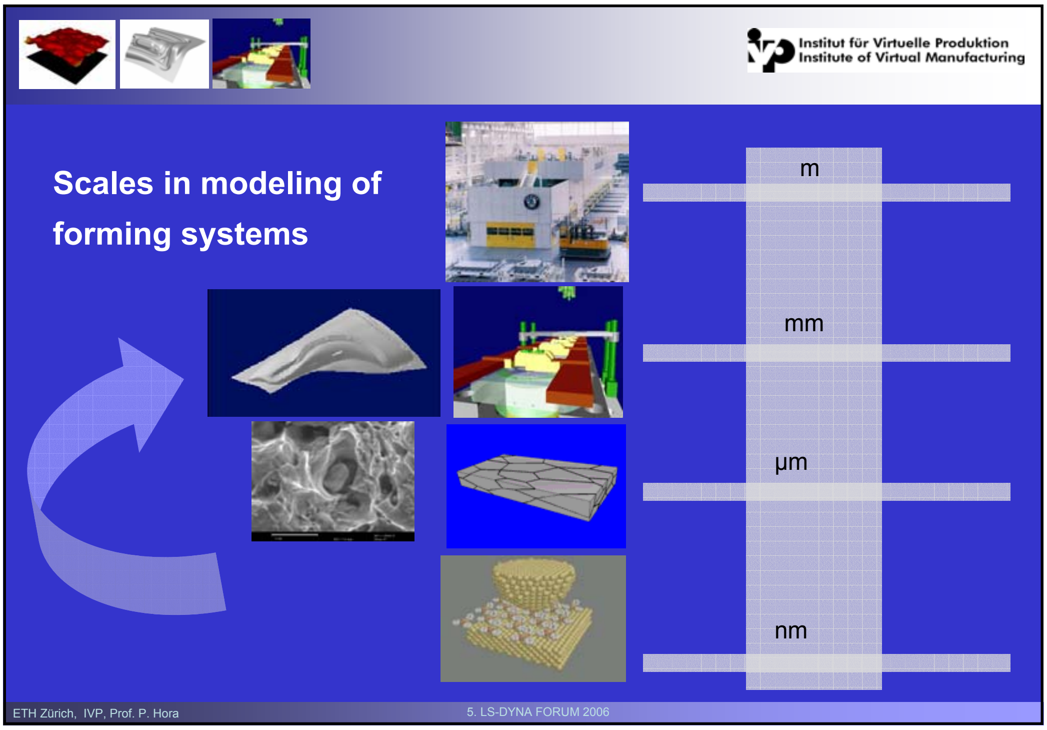
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Scales in modeling of forming systems
m
mm
µm
nm
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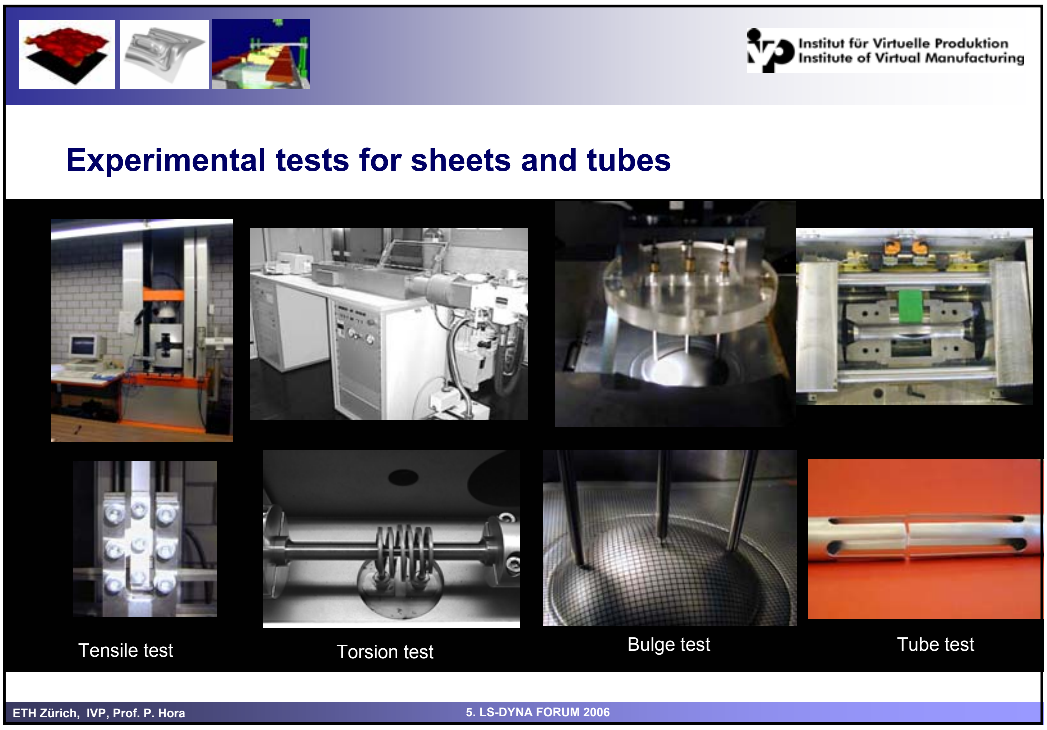
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Experimental tests for sheets and tubes
Tensile test
Torsion test
Bulge test
Tube test
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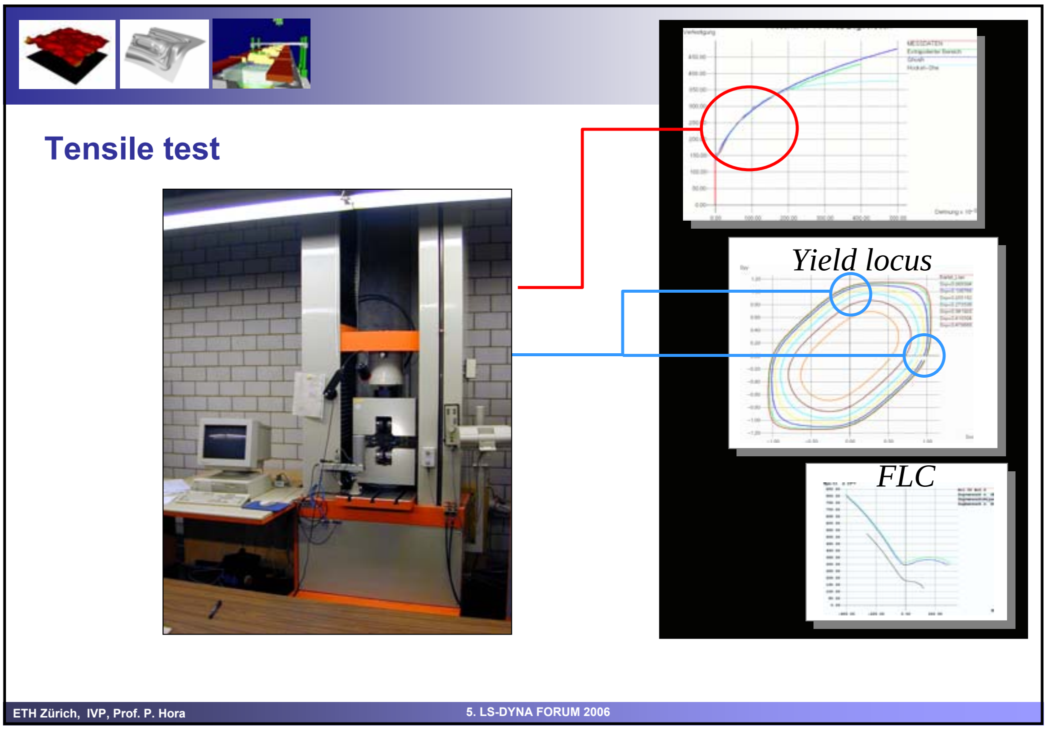
Tensile test
Yield locus
FLC
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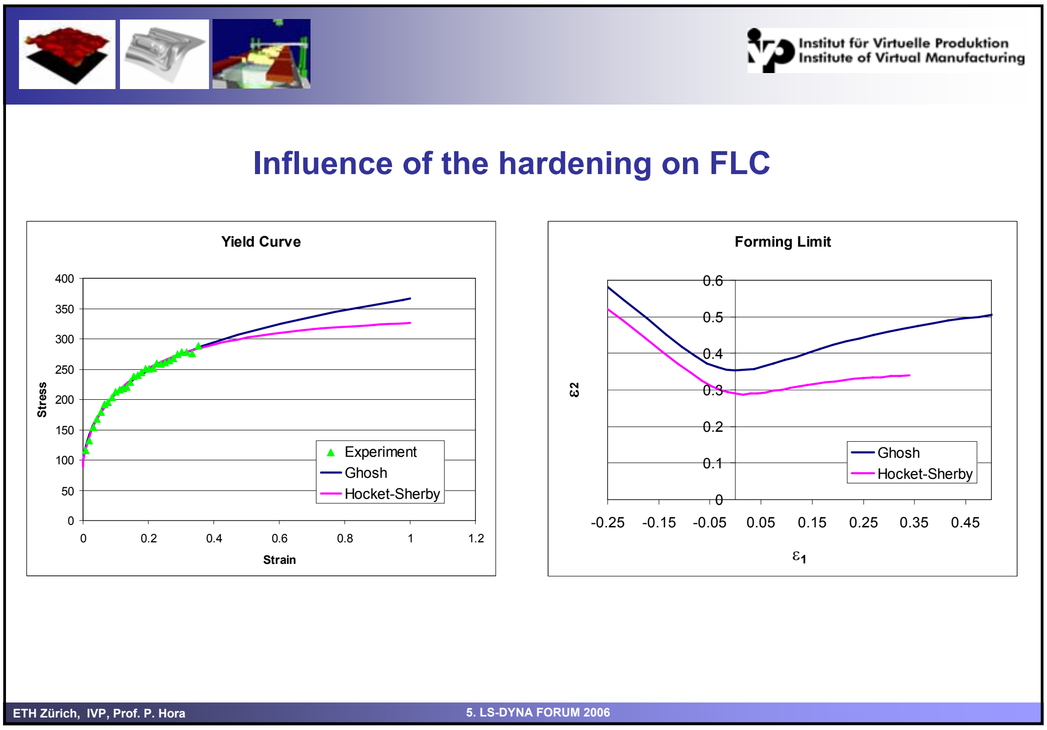
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Influence of the hardening on FLC
Yield Curve
Stress
Strain
Experiment
Ghosh
Hocket-Sherby
Forming Limit
ε2
ε1
Ghosh
Hocket-Sherby
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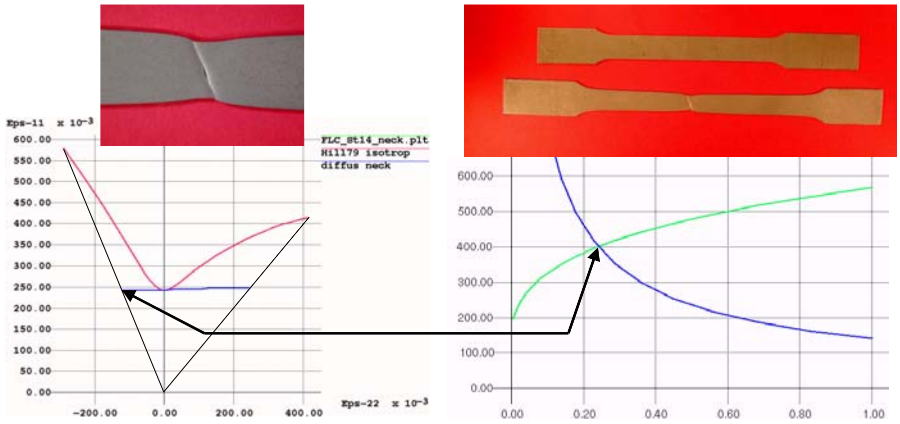
## Hardening & FLC specified by tensile test

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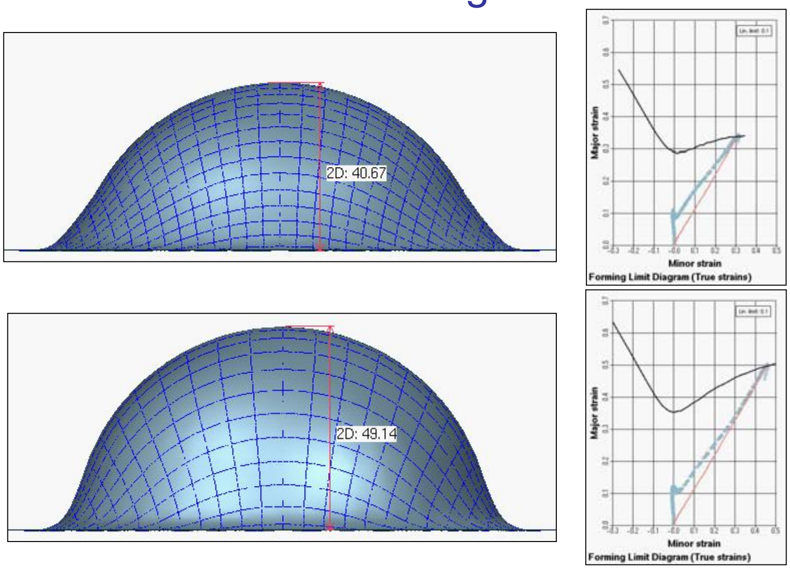
## Influence of the hardening on FLC

Hocket-Sherby

Ghosh

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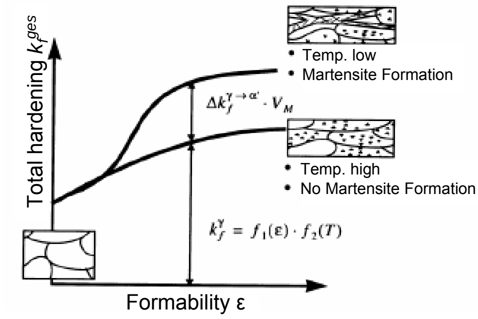
## Complex hardening behavior

- Stainless stees

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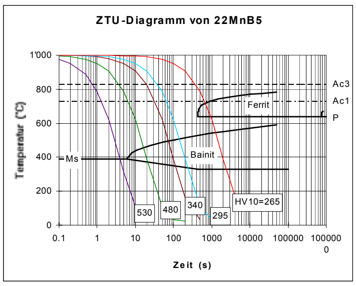
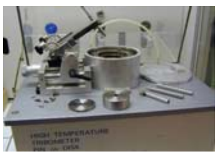
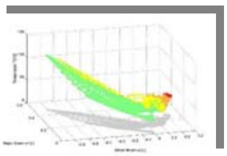
## Complex hardening behavior

- Press hardening





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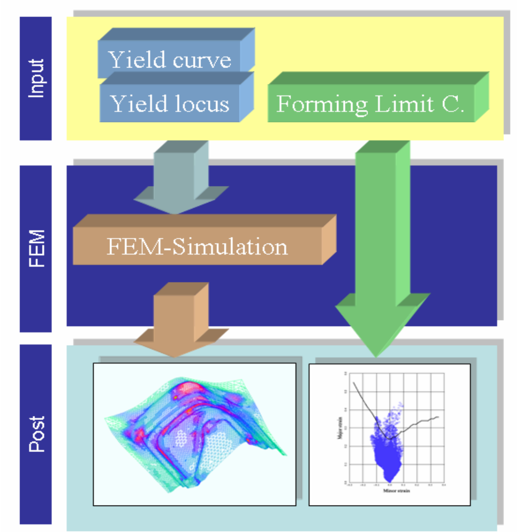
## Limitations of FLCs

- Only for linear strain paths
- Not applicable if thermal effects influence the hardening behavior
- Only post-processing
- FE mesh-size dependent

- Experimental procedure not (yet) standardised
- Experimental procedure is expensive

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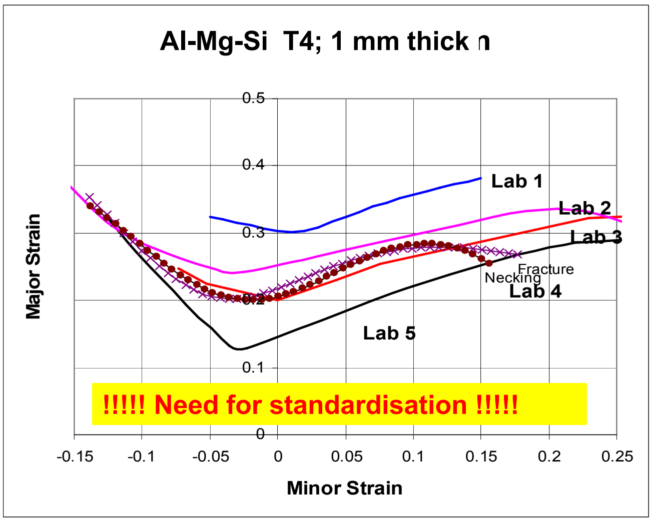
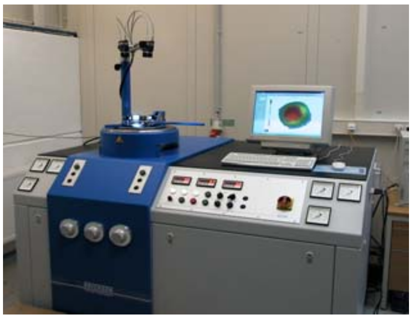
## Forming Limit Curve (FLC)

**Comparison FLC on same material determined by different labs**

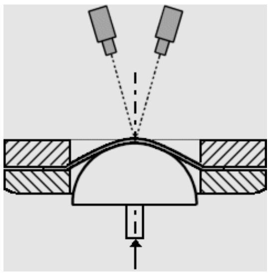



Novelis Technology AG W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006

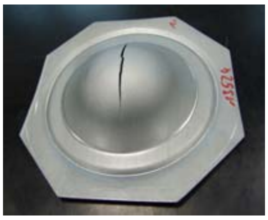
## FLC experimetal equipment



Nakajima testing machine BMW



Principle sketch



Quelle: W. Volk

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Part I

# Yield curve determination for large strains by combined experimental and crystal plasticity methods

Prof. P. Hora, J. Krauer, F. Vanini
Institute of Virtual Manufacturing
ETH Zurich, Switzerland

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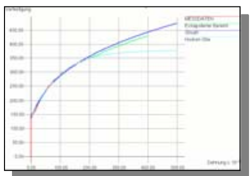
## Yield curve determination for large strains

- Methods
  - Extrapolation by equations
  - Combination of the tensile test with additional experimental tests
  - Application of the crystal plasticity



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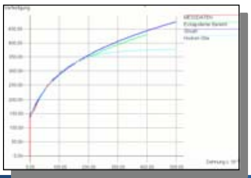

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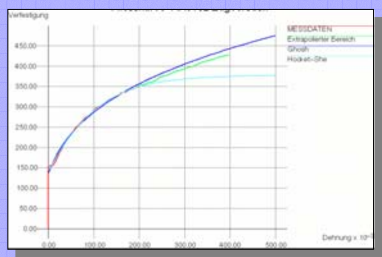
## Hardening extrapolation




Ghosh:

$$h = a(b+\varepsilon)^n - c$$

Hockett-Sherby:

$$h = S_{sat} - (S_{sat} - S_0)\exp(-m\varepsilon^n)$$

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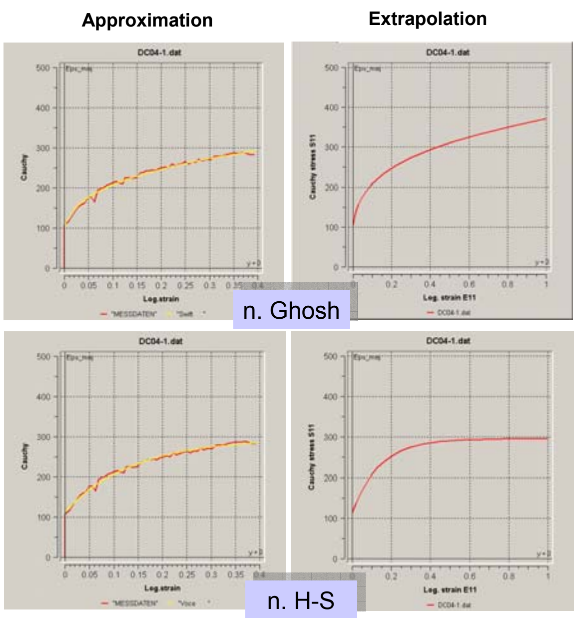
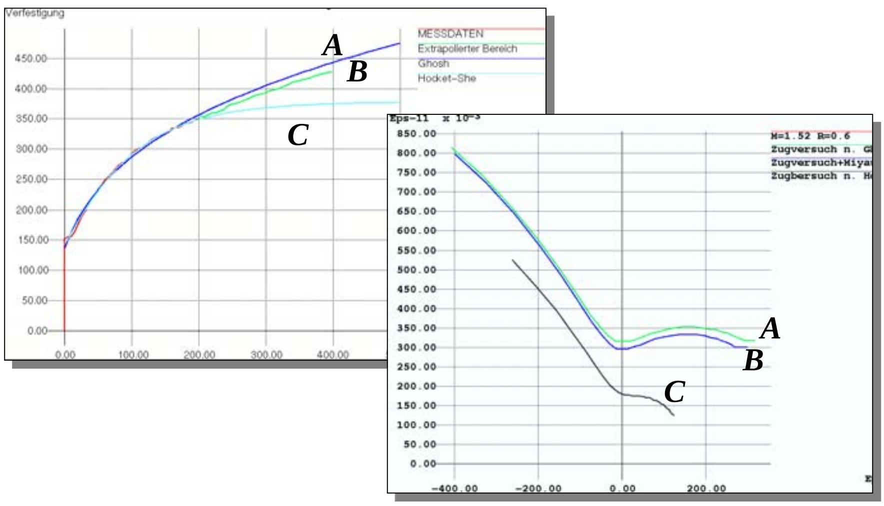
## Analytical Extrapolation Methods




Least square specified yield curve functions can be significantly wrong in the extrapolated area



## Influence of the hardening on FLC



## Yield curve determination for large strains

- Methods
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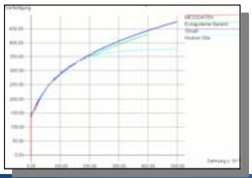

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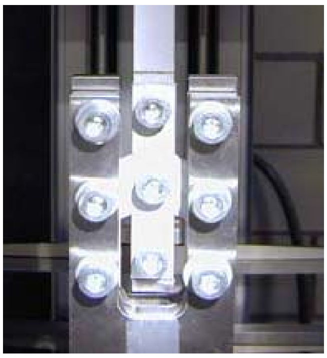
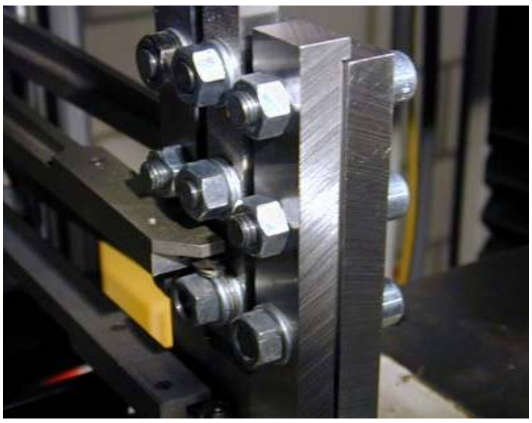
## Miyauchi Test





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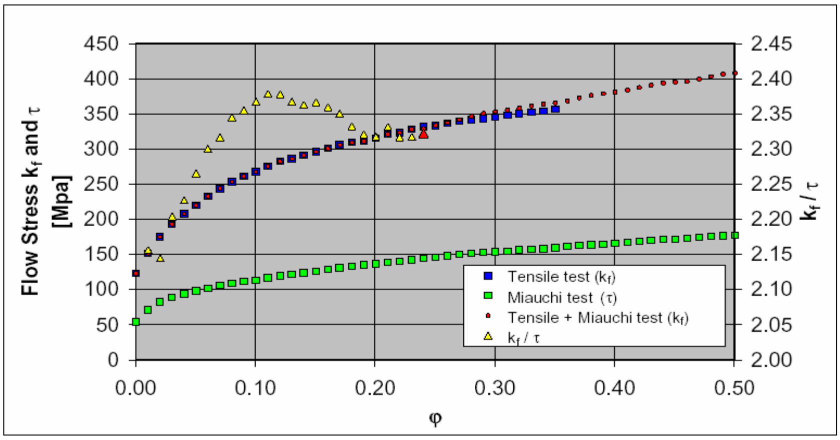
## Extrapolation of measured yield curves

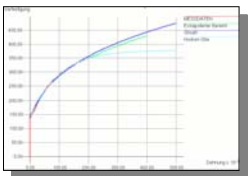



**Measured yield curves of DC04**



## Yield curve determination for large strains

- Methods
  - Extrapolation by equations
  - Combination of the tensile test with additional experimental tests
  - Application of the crystal plasticity

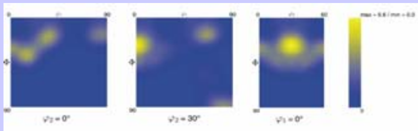


# FE-process modeling (1)

**Crystal plasticity**

**FEM Crystallographic constitutive modeling**

- Very expensiv
- Not very accurate



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# FE-process modeling (2)

**Experimental measurements** ⇄ **Crystal plasticity**

↓

**FEM: Phenomenological constitutive modeling**

Vanini F., Hora P., Plasticity 2003

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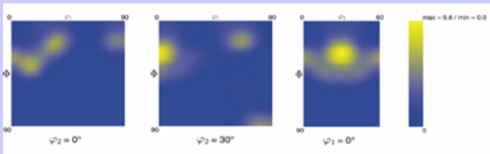
## Hardening evaluation



**Step 1**

Evaluation of the crystallographic model parameters using the experimental tensile test data

**Step 2**

Prediction of hardening for large strains

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## Material model

### Microstructure parameters

Obstacle density: $n_0$

Proportionality constants: $\sigma^{(\alpha)}$

Dislocation density: $\rho^{(\alpha)}$

Interaction coefficients: $a^{(\alpha\beta)}$

Dislocation creation rate: $\nu$

**Dislocation density increment:**

$$\delta\rho^{(\alpha)} = \nu \cdot \left(1 - \rho^{(\alpha)}\right) \cdot \delta\gamma^{(\alpha)}$$

**Critical resolved shear stress:**

$$\tau_c^{(\alpha)} = \sigma^{(\alpha)} \cdot \left(n_0 + \sum_\beta a^{(\alpha\beta)} \cdot \rho^{(\beta)}\right)^{1/2}$$

**Hardening coefficients:**

$$H^{(\alpha\beta)} = \nu \cdot \sigma^{(\alpha)2} \cdot \left(1 - \rho^{(\beta)}\right) \cdot a^{(\alpha\beta)} / \left(2 \cdot \tau_c^{(\alpha)}\right)$$

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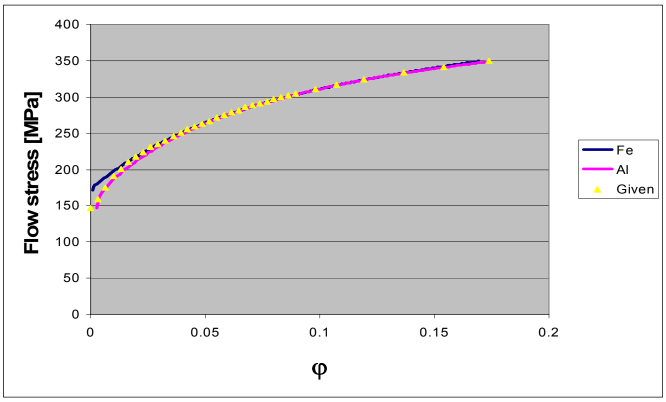
## Extrapolation of measured yield curves




Step 1

Fitted yield curves of Al (fcc) and Fe (bcc)

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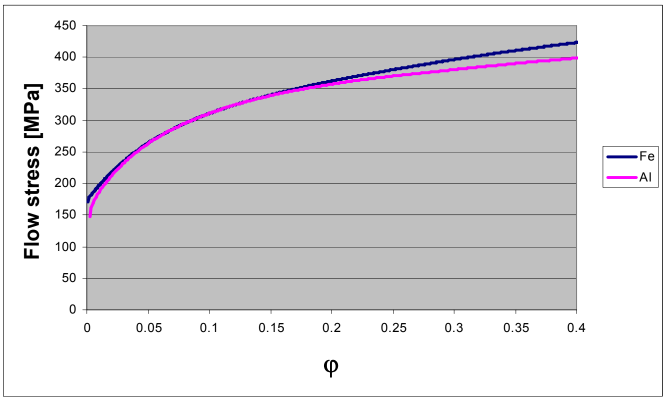
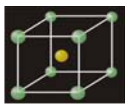
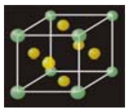
## Extrapolation of measured yield curves




Step 2





Calculated yield curve of Fe (bcc) and Al (fcc)

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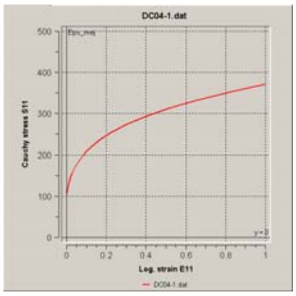
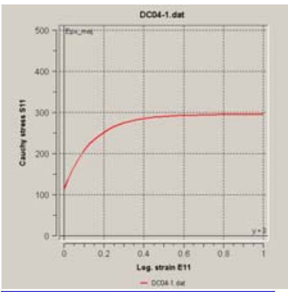
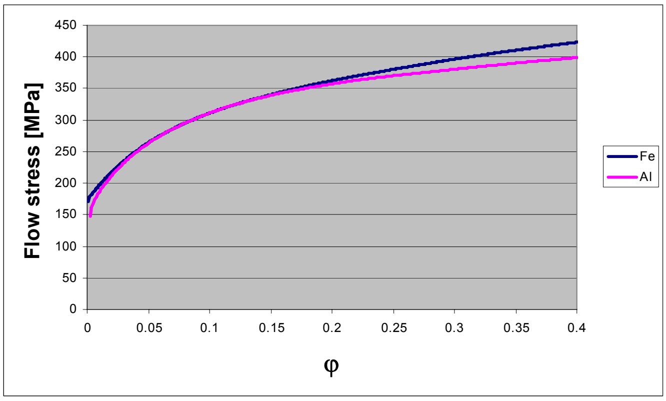
## Extrapolation of measured yield curves

Ghosh




Hockett-Sherby




Calculated yield curve of Al (fcc) and Fe (bcc)

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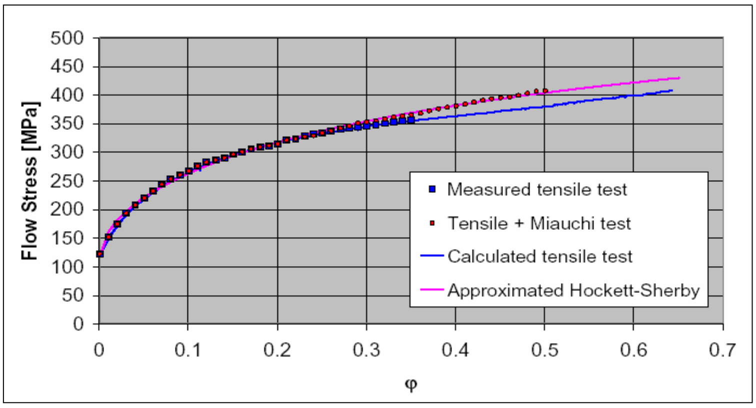
## Extrapolation of measured yield curves




Yield curves of DC04

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## Modified hardening laws

Ghosh

$$h = a(b+\varepsilon)^n - c$$

Ghosh inverse

$$h = c + \frac{a}{(b+\varepsilon)^n}$$

Hockett-Sherby

$$h = S_{sat} - (S_{sat} - S_0)\exp(-m\varepsilon^n)$$

Hockett-Sherby - 3 parameters

$$h = S_{sat} - (S_{sat} - S_0)\exp(-m_{MAT}\varepsilon^n)$$

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## Hockett-Sherby setup for material specific hardening

- 4 free parameter description

$$H = b - (b-a)\exp(-m\varphi^n)$$

- m: $M_{mater}$=const - material typical hardening behavior

$$H = b - (b-a)\exp(-M_{Mat}\varphi^n)$$

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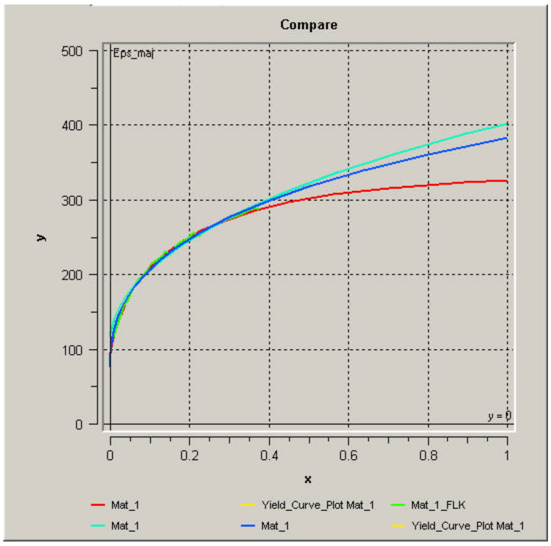


## Hockett-Sherby

M = 1.00

M = 1.50

M = 3.04

- *M* **describes the material specific hardening**
- **It can can be assumed as constant for the different material types: $M_{al}$, $M_{CrNi}$, $M_{Mg}$**

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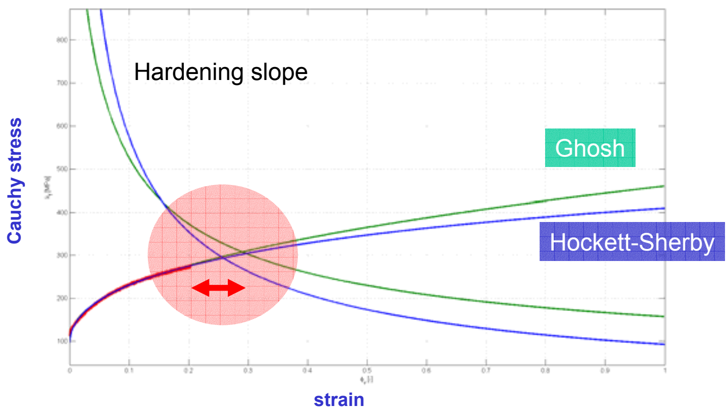
# Least square fit of the yield curve

Deviation between the predicted and the experimetal diffuse necking point

$$p_j \Rightarrow \sum_k \left(h_n(p_j) - \hat{h}_n\right)^2 = Min$$

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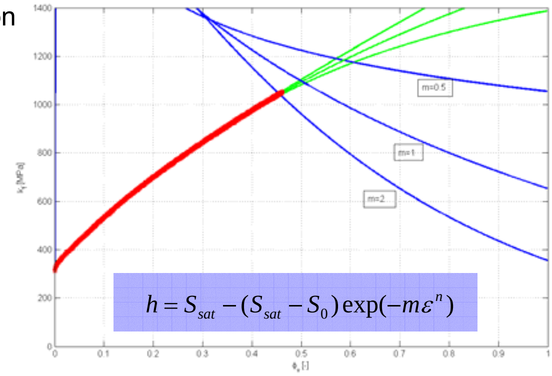
## Yield curve approximation with additional constraint at the diffuse necking point

- Least square approximation

$$\sum_n \left( h_n(p_j) - \hat{h}_n \right)^2 = Min$$

- Constraint:

$$\hat{\varepsilon}_{eq\_\exp} \stackrel{!}{=} \varepsilon_{eq}(h = h')$$




Influence of the variation of ***m*** on the location of the diffuse necking point



## Conclusions hardening curves

- ***Voce*** and ***Hockett-Sherby*** extrapolation functions usually underestimate the hardening even for Al-materials
- Combination of polycrystalline methods in combination with experimental data seems to be a helpful method for the determination of constitutive behaviour for large strains

**Modified H-S approach**

- The H-S approximation gives much better results, when the ***m***-parameter is prescribed as a material constant
- The ***m***-parameter can be specified using the strain value of the diffused necking point as an additional constraint

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  - "Hardening determination for metastable materials with temperature and strain induced martensite transformation"
  - Advanced methods in yield locus description
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- **NUMISHEET'08**

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Part I / b

## Hardening behavior of metastable materials with temperature and strain induced martensite transformation

Prof. P. Hora, J. Krauer, B. Hochholdinger
A.Hänsel*, G. Heinemann*

Institute of Virtual Manufacturing
ETH Zurich, Switzerland

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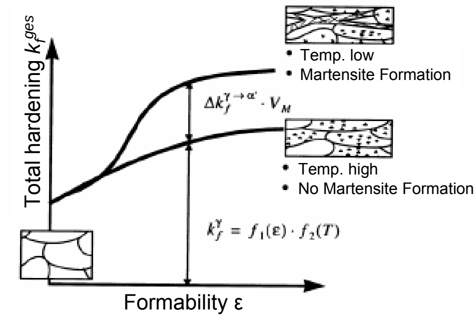
## Complex hardening behavior

- **Stainless steels**

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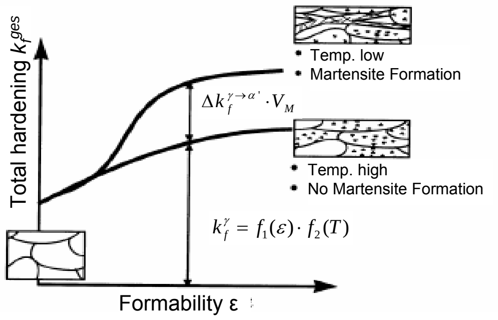
## Hardening

The hardening behavior depends on the formability and the temperature:

Total Hardening:

$$k_f^{ges} = k_f^{\gamma} + \Delta k_f^{\gamma \to \alpha'} \cdot V_M$$

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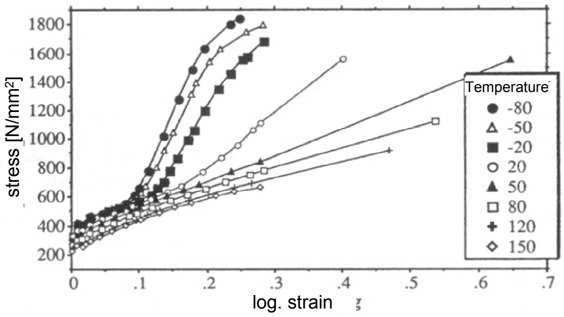
# Hardening

Isothermal hardening behavior depending on temperature:
(Tensile test, material: 1.4301)

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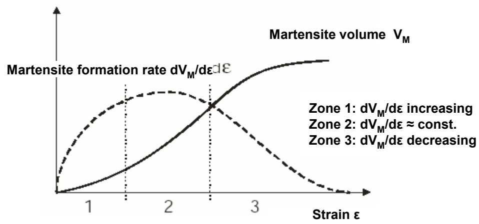
# Isothermal material models

- The martensite formation rate can be split into three parts (***Angel***):




- ***Ludwigson et. al:*** Martensite formation rate:

$$V_M = \left(1 + \frac{\varepsilon^{-B}}{a}\right)^{-1}$$

**Extended by temperature**

- ***Tsuta et. al:*** Martensite formation rate:

$$V_M = \left[1 + \left(\frac{\varepsilon}{A \cdot e^{\frac{-Q}{T}}}\right)^{-B}\right]^{-1}$$

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## Isothermal material models

- ***Olsen and Cohen*** considered the formation of shear bands crossing as the decisive effect for strain induced martensite formation:

$$V_M = 1-\exp\left\{-\beta\left[1-\exp\left(-\alpha\cdot\varepsilon\right)\right]^n\right\}$$

- ***Groth*** describes the martensite formation as a function of deformation energy end temperature:

$$V_M = 1-\exp\left\{-N\left(T\right)\cdot\left[w_A\left(T\right)-E_0\left(T\right)\right]^p\right\}$$

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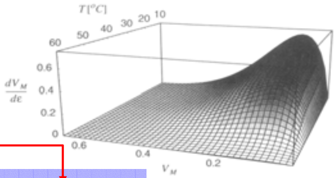
## Non-isothermal material models

- According to ***Hänsel***, the martensite formation rate is a function of temperature and the actual martensite volume:
  Hänsel-model: Martensite formation rate:

$$\frac{V_M}{d\varepsilon} = \frac{B}{A}\cdot e^{\frac{Q}{T}}\cdot\left(\frac{1-V_M}{V_M}\right)^{\frac{1+B}{B}}\cdot {V_M}^p\cdot\left[0.5\cdot\left(1-\tanh\left(C+D\cdot T\right)\right)\right]$$

- ***Heinemann*** was able to reduce the number of parameters:

$$\frac{V_M}{d\varepsilon} = \frac{B}{A}\cdot e^{\frac{Q}{T}}\cdot\left(\frac{1-V_M}{V_M}\right)^{\frac{1+B}{B}}\cdot {V_M}^p\cdot C$$




$$k_f^{ges} = \left[B_{HS}-\left(B_{HS}-A_{HS}\right)\cdot\exp\left(-m\cdot\varepsilon^n\right)\right]\cdot f_2(T)+\Delta k_f^{\gamma\to\alpha'}\cdot V_M$$

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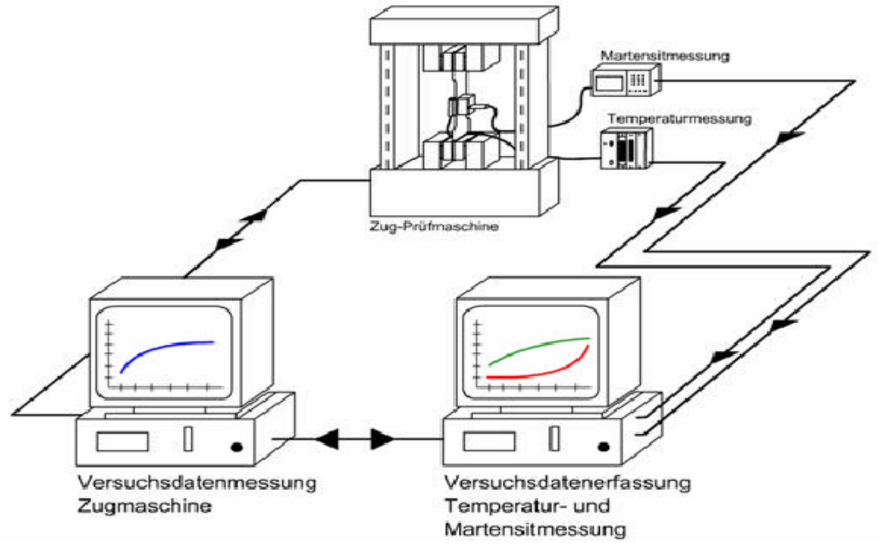
## Determination of the Hänsel-Parameters

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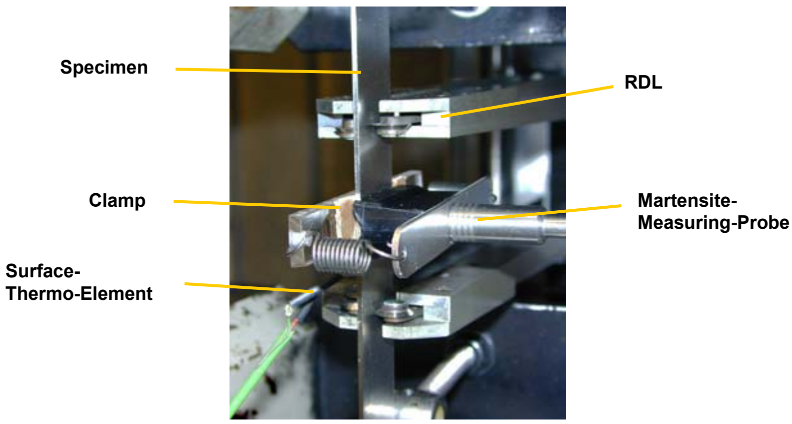
## Determination of the Hänsel-Parameters

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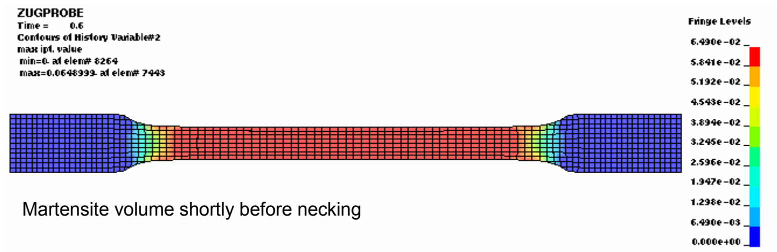
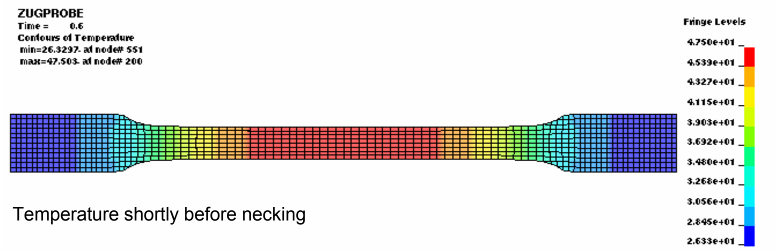
## Example: Tensile Test (material: 1.4301)




Martensite volume shortly before necking




Temperature shortly before necking

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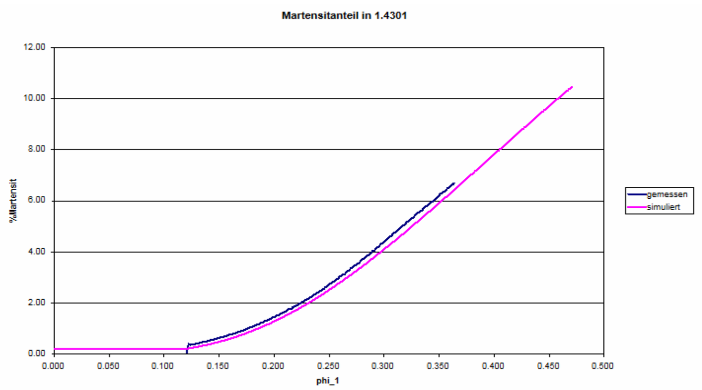
## Example: Tensile Test

- Material 1.4301

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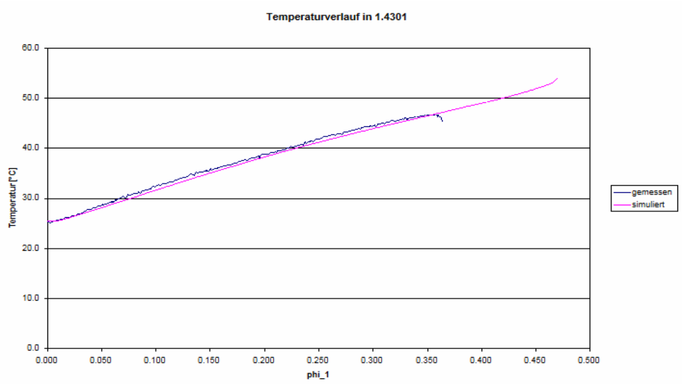
## Example: Tensile Test

- Material 1.4301

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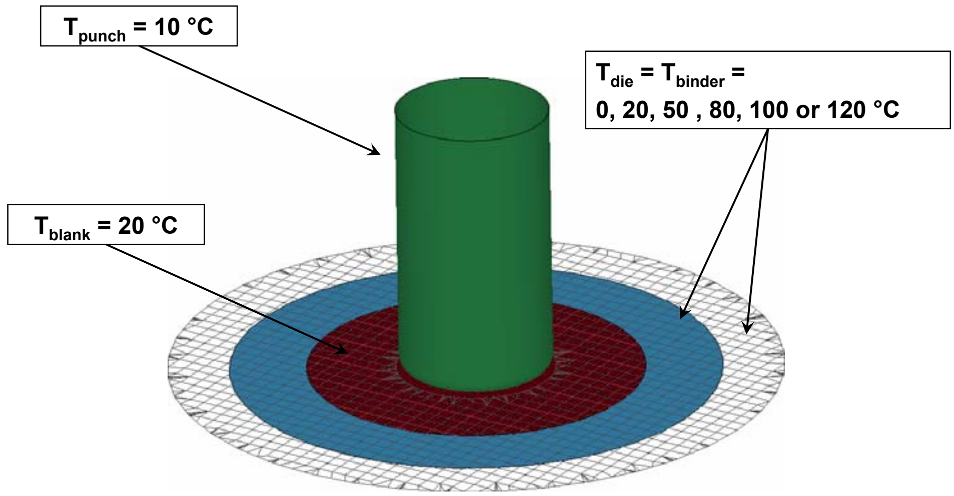
## Example: Model for Cup Drawing

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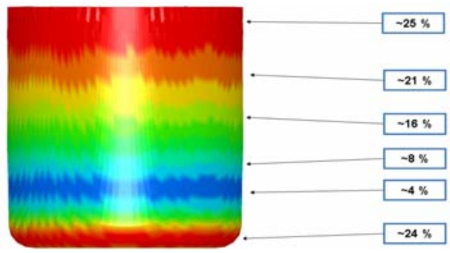
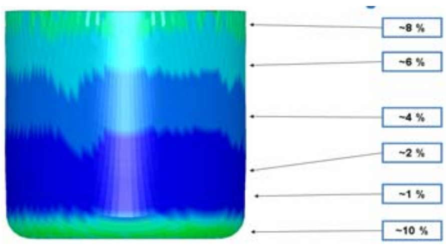
$T_{die} = T_{binder} = 20\ °C$




$T_{die} = T_{binder} = 100\ °C$

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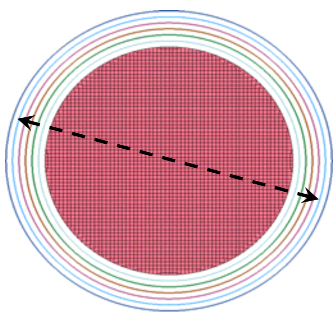
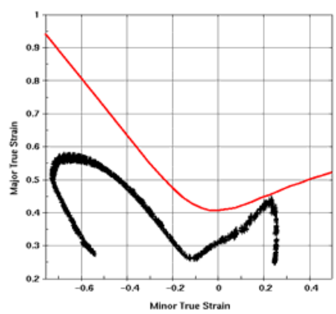
## Determination of Limit Drawing Ratio

- Simple optimization procedure with LS-OPT for each chosen temperature:
  - objective function: **“maximize blank diameter”**
  - strict constraint: **”preserve FLC”**



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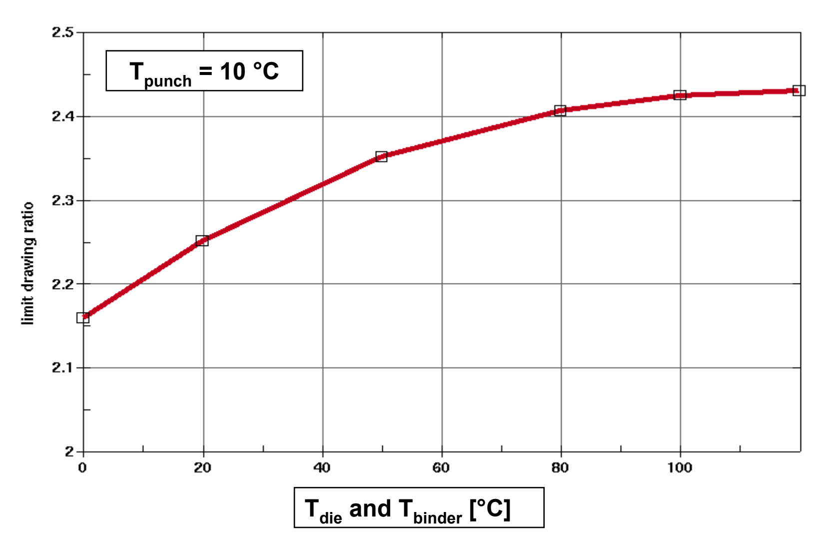
## Result: Limit Drawing Ratio

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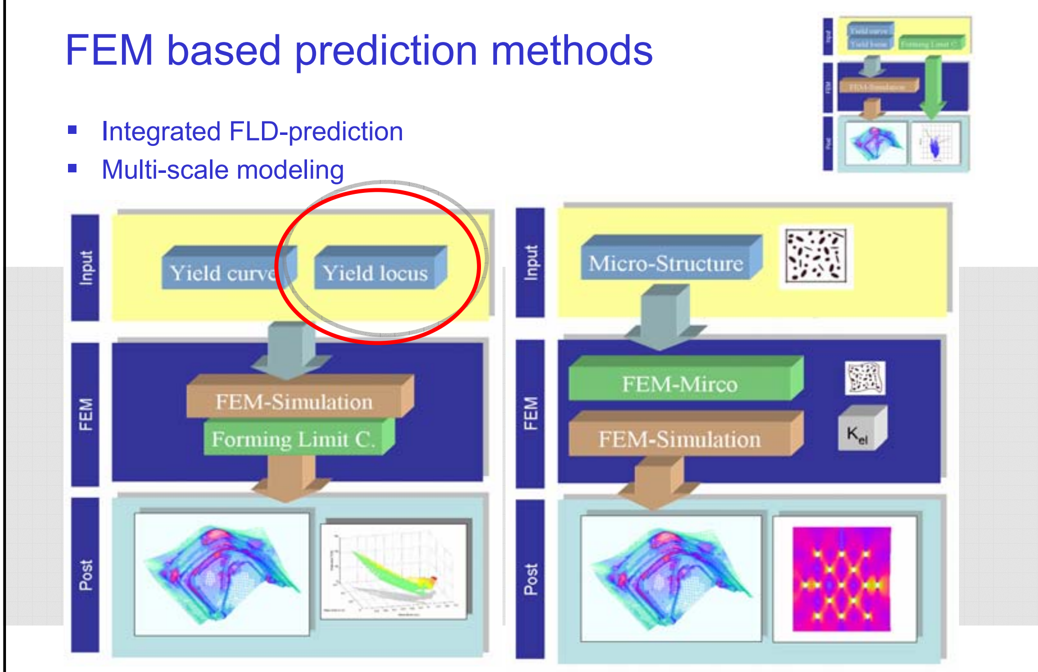
## FEM based prediction methods

- Integrated FLD-prediction
- Multi-scale modeling

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## Content

- **Introduction**
- **Advanced Methods in Constitutive Modeling of Materials**
  - Advanced methods in hardening description
    “Combined experimental and crystal plasticity methods in determination of hardening for large strains”
  - Advanced methods in yield locus description
    “Crystal plasticity methods in determination of non-quadratic yield locus shapes”
  - Advanced methods in failure modeling
    “Numerical methods in computational evaluation of FLCs with the enhanced Modified Maximum Force Criterion (eMMFC)”
- **Conclusions**

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- **NUMISHEET‘08**

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ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Part II

# Crystal plasticity methods for determination of the non-quadratic yield locus shapes

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Institute of Virtual Manufacturing
ETH Zurich, Switzerland

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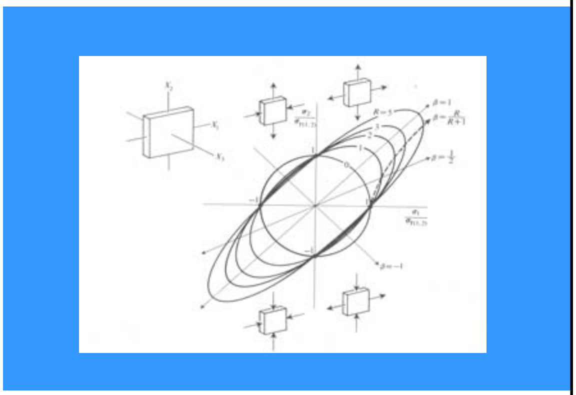
## Influence on forming behavior



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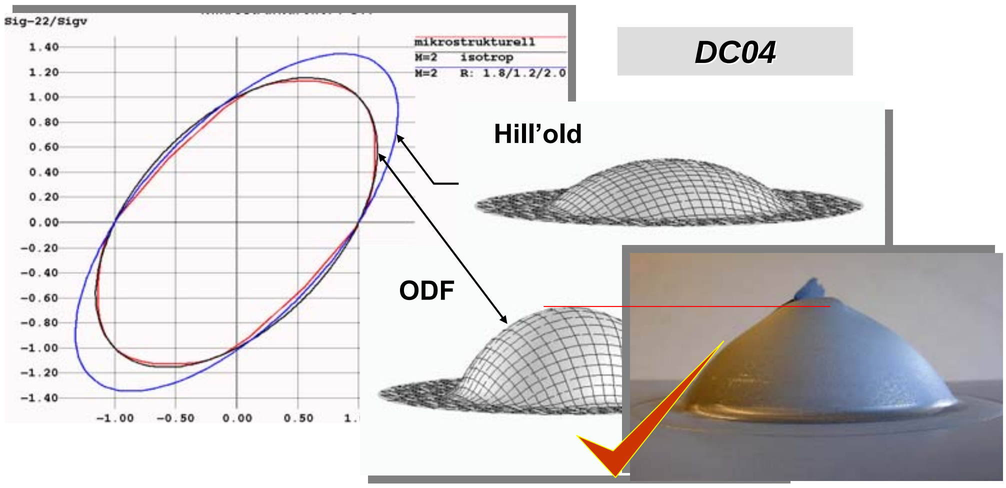
## Influence on the part shape in pressure driven processes

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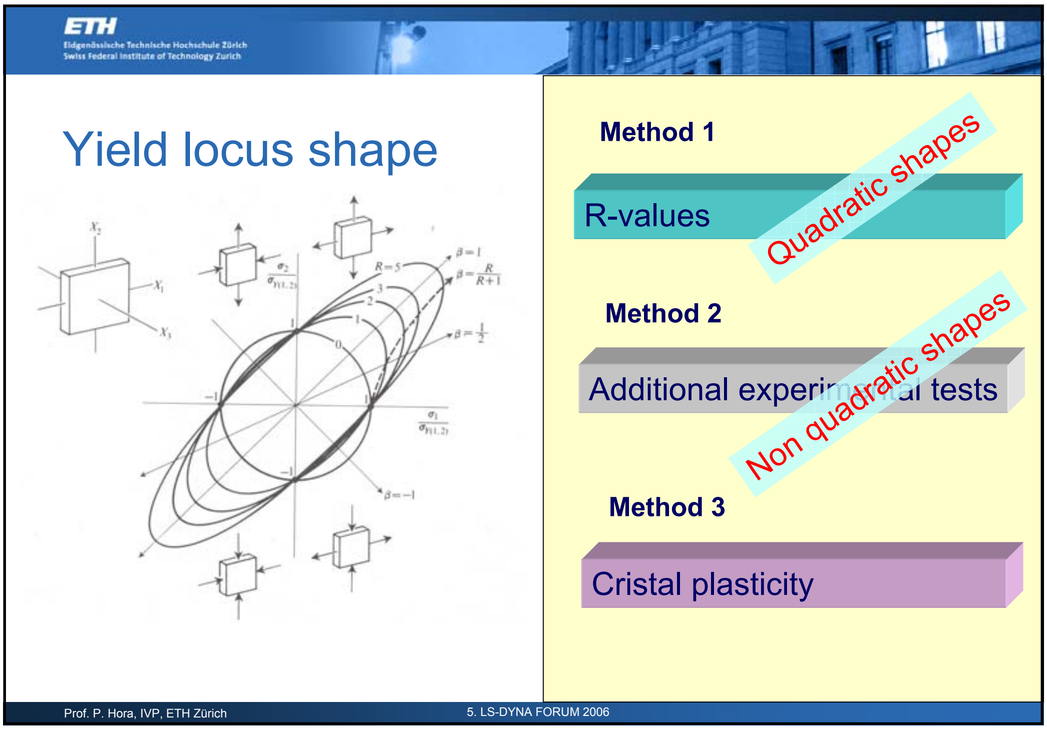
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Yield locus shape
Method 1
R-values
Quadratic shapes
Method 2
Additional experimental tests
Non quadratic shapes
Method 3
Cristal plasticity
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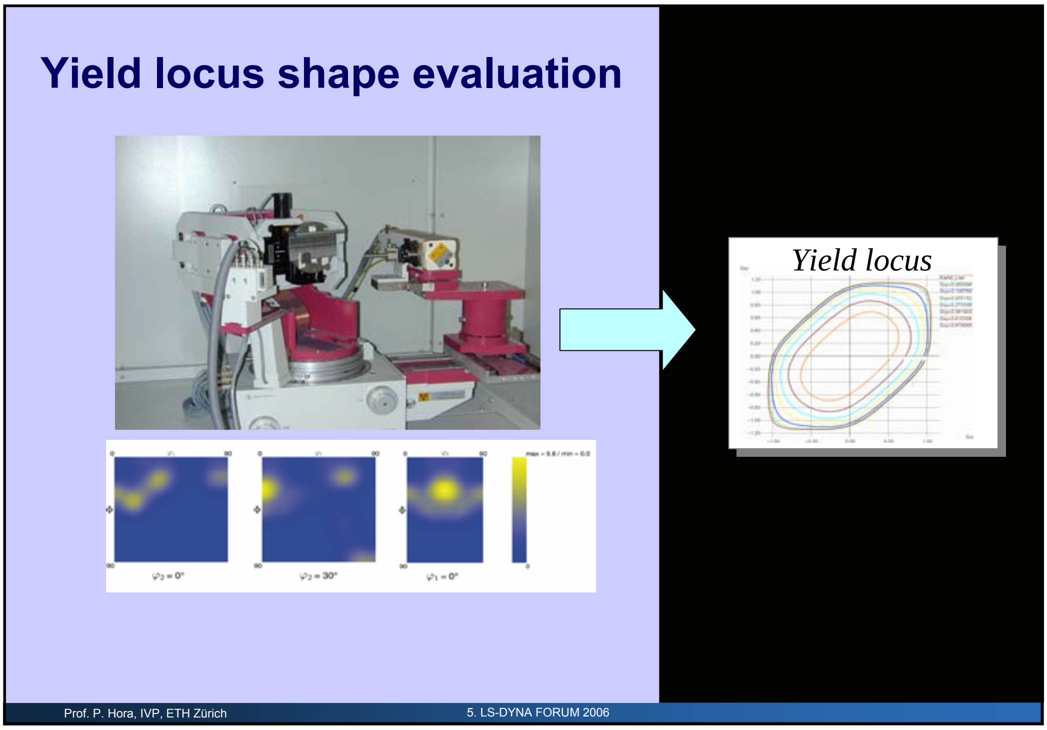
Yield locus shape evaluation
Yield locus
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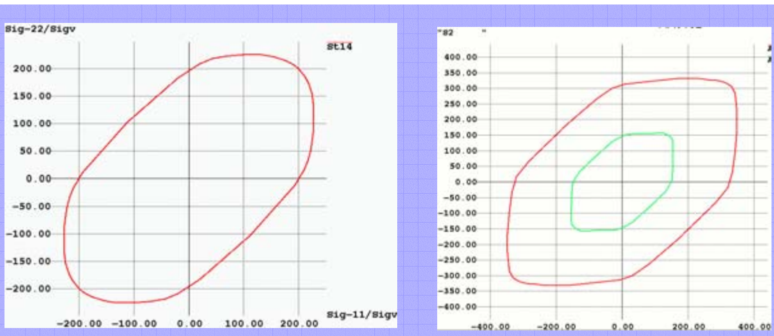
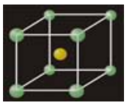
## Examples



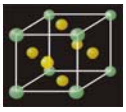

l.c. steel (DC04) AA5182

Non-quadratic exponents

BCC: m ≈ 6



FCC: m ≈ 8



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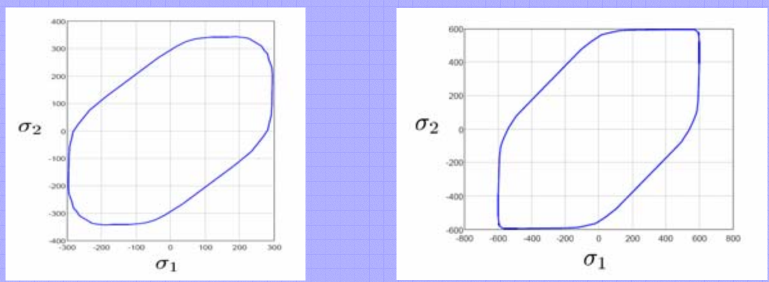
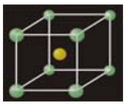
## Examples CrNi-steels



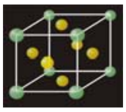

Ferrite Austenite

Non-quadratic exponents

BCC: m ≈ 5



FCC: m ≈ 9



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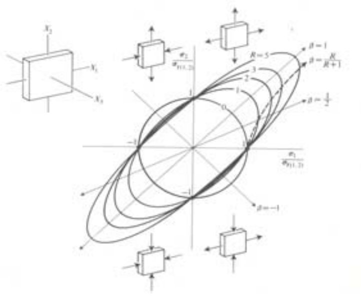
## Yld_Hill'48

$$\Phi = a_1(\sigma_{22}-\sigma_{33})^2 + a_2(\sigma_{33}-\sigma_{11})^2 + a_3(\sigma_{11}-\sigma_{22})^2 + \\ + 3\,a_4\,\tau_{23}2 + 3\,a_5\,\tau_{31}2 + 3\,a_6\,\tau_{12}2 = 2\,\sigma_y^2$$

**Disadvantages:**

- Real, non-quadratic shape can't be described
- „anomalos behavior for al-alloys for r < 1 : $\sigma_b / \sigma_0 > 1$
- „anomalos behavior of 2nd order“ $r_{90} = r_0$ then $\sigma_{90} = \sigma_0$



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## Different yield functions

**Hill-Family**
- Hill 1948
- Hill 1979
- Hill 1990
- Hill 1993
- Chu 1995
- Lin&Ding 1996

**Hosford-Family**
- Hosford 1979
- Barlat-Lian 1989
- Barlat et al. 1991
- Karafillis-Boyce 1993
- Barlat et al 1994
- Barlat el al 1996

- Barlat 2000
- Barlat 2005

Skip theory

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## Yld_Hill'79

$$f\,|\sigma_2-\sigma_3|^m + g\,|\sigma_3-\sigma_1|^m + h\,|\sigma_1-\sigma_2|^m +$$
$$+ a\,|2\sigma_1-\sigma_2-\sigma_3|^m + b\,|2\sigma_2-\sigma_1-\sigma_3|^m + c\,|2\sigma_3-\sigma_1-\sigma_2|^m$$
$$= \sigma_y^m$$

Case 1: a=b=h=0; f=g $\quad c|\sigma_1+\sigma_2|^m + f\left(|\sigma_1|^m + |\sigma_2|^m\right) = \sigma_y^m$

Case 2: a=b; c=f=g=0 $\quad a\left(|2\sigma_1-\sigma_2|^m + |2\sigma_2-\sigma_1|^m\right) + h|\sigma_1-\sigma_2|^m = \sigma_y^m$

Case 3: a=b; f=g; c=h=0 $\quad a\left(|2\sigma_1-\sigma_2|^m + |2\sigma_2-\sigma_1|^m\right) + f\left(|\sigma_1|^m + |\sigma_2|^m\right) = \sigma_y^m$

Case 4: a=b=f=g=0 $\quad c|\sigma_1+\sigma_2|^m + h|\sigma_1-\sigma_2|^m = \sigma_y^m$

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## Yld_Hill'79

$$\underbrace{f\,|\sigma_2-\sigma_3|^m + g\,|\sigma_3-\sigma_1|^m + h\,|\sigma_1-\sigma_2|^m}_{\Phi_1} +$$
$$\underbrace{+ a\,|2\sigma_1-\sigma_2-\sigma_3|^m + b\,|2\sigma_2-\sigma_1-\sigma_3|^m + c\,|2\sigma_3-\sigma_1-\sigma_2|^m}_{\approx \Phi_2}$$
$$= \sigma_y^m$$

## Yld_Karafillis-Boyce '93

$$\Phi_1 = |S_1-S_2|^m + |S_2-S_3|^m + |S_3-S_1|^m = 2\sigma_y^m$$

$$\Phi_2 = |S_1|^m + |S_2|^m + |S_3|^m = \frac{2^m+2}{3^m}\sigma_y^m$$

$$\Rightarrow \quad \Phi = (1-c)\Phi_1 + c\frac{3^m}{2^{m-1}+1}\Phi_2$$

$S_k$: Deviatoric stress

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## Barlat yld94 and yld96

$$\Phi_1 = \alpha_x |S_1 - S_2|^m + \alpha_y |S_2 - S_3|^m + \alpha_z |S_3 - S_1|^m = 2\sigma_y^m$$

Yld_94: $a_k$ constat

Yld_96: $a_k$ functions of $\beta_k$

$\beta_k$: angels between the principal directions of the stress tensor and the anisotroic axes

$$\alpha_x = \alpha_{x0} \cos^2(2\beta_1) + \alpha_{x1} \sin^2(2\beta_1)$$

$$\alpha_y = \alpha_{y0} \cos^2(2\beta_2) + \alpha_{y1} \sin^2(2\beta_2)$$

$$\alpha_z = \alpha_{z0} \cos^2(2\beta_3) + \alpha_{z1} \sin^2(2\beta_3)$$

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## Barlat yld94 and yld96

$$\Phi_1 = \alpha_x |S_1 - S_2|^m + \alpha_y |S_2 - S_3|^m + \alpha_z |S_3 - S_1|^m = 2\sigma_y^m$$

**Advantages** Barlat-YLD96 (6 parameters)

- Possible to describe the yield surface

**Disadvantages:**

- No proof of convexity, important for uniqiness of the solution
- Difficult to obtain derivatives, inconvenient for FE simulations

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## Barlat yld94 and yld96

$$\Phi_1 = \alpha_x |S_1 - S_2|^m + \alpha_y |S_2 - S_3|^m + \alpha_z |S_3 - S_1|^m = 2\sigma_y^m$$

## Barlat yld2000

$$\Phi_1 = |\tilde{S}_1 - \tilde{S}_2|^m + |\tilde{S}_2 - \tilde{S}_3|^m + |\tilde{S}_3 - \tilde{S}_1|^m = 2\sigma_y^m$$

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## Barlat YLD2000 2D-case

- Istropic case

$$\Phi' = |S_1 - S_2|^m = 2\sigma_y^m$$

$$\Phi'' = |2S_2 + S_1|^m + |2S_1 + S_2|^m$$

$$\Rightarrow \quad \Phi_1 = \Phi' + \Phi''$$

- Anisotropic case

$$\Phi_1 = |\alpha_1 s_x - \alpha_2 s_y|^m + |2\alpha_4 s_y + \alpha_3 s_x|^m + |2\alpha_5 s_x + \alpha_6 s_y|^m$$

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## Barlat YLD2000

$$\Phi_1 = \left|\alpha_1 s_x - \alpha_2 s_y\right|^m + \left|2\alpha_4 s_y + \alpha_3 s_x\right|^m + \left|2\alpha_5 s_x + \alpha_6 s_y\right|^m$$

$$\Phi' = \left|\tilde{S}'_1 - \tilde{S}'_2\right|^m \qquad \Phi'' = \left|2\tilde{S}''_2 + \tilde{S}''_1\right|^m + \left|2\tilde{S}''_1 + \tilde{S}''_2\right|^m$$

$\tilde{S}'; \tilde{S}''$ : Linearly transformation stress tensor

$$\tilde{S}' = C' \cdot s = C' \cdot T \cdot \sigma = L' \cdot \sigma$$

$$\tilde{S}'' = C'' \cdot s = C'' \cdot T \cdot \sigma = L'' \cdot \sigma$$

$$\Phi_1 = \left|\tilde{S}'_1 - \tilde{S}'_2\right|^m + \left|2\tilde{S}''_2 + \tilde{S}''_1\right|^m + \left|2\tilde{S}''_1 + \tilde{S}''_2\right|^m$$

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## Barlat YLD2000

$\tilde{s}'_{ij}; \tilde{s}''_{ij}$ : Linearly transformation of Cauchy stress tensor σ

$$\tilde{s}' = C' \cdot s = C' \cdot T \cdot \sigma = L' \cdot \sigma$$

$$\tilde{s}'' = C'' \cdot s = C'' \cdot T \cdot \sigma = L'' \cdot \sigma$$

$$C' = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_7 \end{bmatrix} \quad C'' = \begin{bmatrix} 4\alpha_5 - \alpha_3 & 2\alpha_6 - 2\alpha_4 & 0 \\ 2\alpha_3 - 2\alpha_5 & 4\alpha_4 - \alpha_6 & 0 \\ 0 & 0 & 3\alpha_8 \end{bmatrix} \quad T = \begin{bmatrix} 2/3 & -1/3 & 0 \\ -1/3 & 2/3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\tilde{S}'_k; \tilde{S}''_k$ : Principal values of linearly transformed Cauchy stress tensor σ

$$\Phi_1 = \left|\tilde{S}'_1 - \tilde{S}'_2\right|^m + \left|2\tilde{S}''_2 + \tilde{S}''_1\right|^m + \left|2\tilde{S}''_1 + \tilde{S}''_2\right|^m$$

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# Barlat YLD2000

$$\Phi_1 = \left|\tilde{S}_1^{'} - \tilde{S}_2^{'}\right|^m + \left|2\tilde{S}_2^{''} + \tilde{S}_1^{''}\right|^m + \left|2\tilde{S}_1^{''} + \tilde{S}_2^{''}\right|^m$$

**Advantages** Barlat-YLD2000 (8 parameters)

- New plane stress yield function particularly suitable for FE
- 8 material parameters (better fit to test data then with 6 parameters)
- Convex yield surface assures unique stress state
- More efficient than YLD96 due to the relative simplicity in its mathematical form

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## Experimental data required for the formulation of various criteria

| | $\sigma_0$ | $\sigma_{45}$ | $\sigma_{90}$ | $\sigma_b$ | $\tau$ | $r_0$ | $r_{45}$ | $r_{90}$ | $r_b$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| **Hill 1948** | x | | | | | x | | x | |
| **Hill 1979** | x | | | x | | x | | | |
| **Hill 1990** | x | x | x | x | x | | x | | |
| **Hill 1993** | x | | x | x | | x | | x | |
| **Chu 1995** | x | | | x | | | | | |
| **Lin, Ding 1996** | x | | x | x | | x | x | x | |
| | | | | | | | | | |
| **Hosford** | X | | | | | X | | x | |
| **Barlat et al. 1989** | X | | | | X | X | | x | |
| **Barlat et al. 1991** | 4 Parameters | | | | | | | | |
| **Karafillis-Boyce 93** | 6 Parameters | | | | | | | | |
| **Barlat 1994** | 6 Parameters | | | | | | | | |
| **Barlat 1996** | X | X | X | X | | X | X | x | |
| **Barlat 2000** | X | X | X | X | | X | X | X | x |

***Banabic et al. Formability of Metallic Materials***

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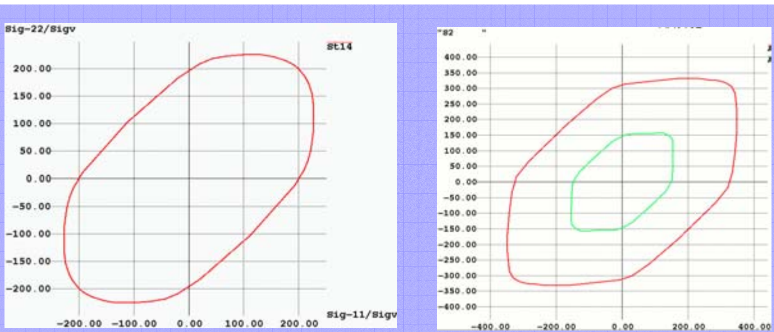
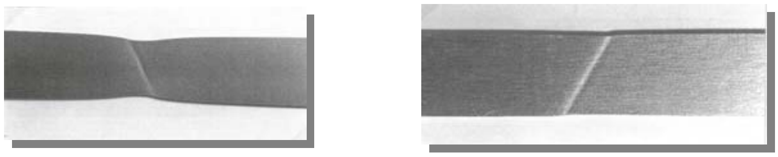
## Influence of the YL type on the localization behavior

l.c. steel (DC04) AA5182



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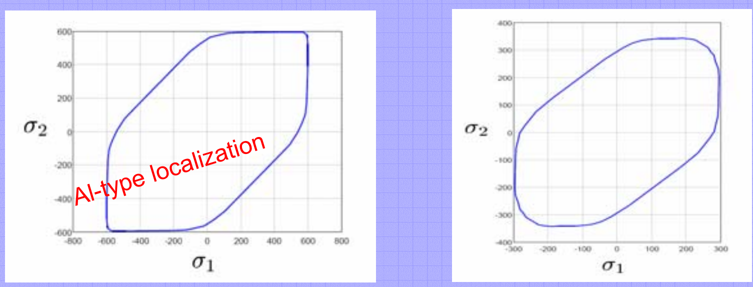
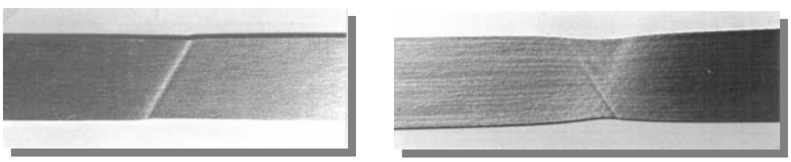
## Examples CrNi-steels

Austenite Ferrite



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    "Combined experimental and crystal plasticity methods in determination of hardening for large strains"
  - Advanced methods in yield locus description
    "Crystal plasticity methods in determination of non-quadratic yield locus shapes"
  - Advanced methods in failure modeling
    "Numerical methods in computational evaluation of FLCs with the enhanced Modified Maximum Force Criterion (eMMFC)"
- **Conclusions**

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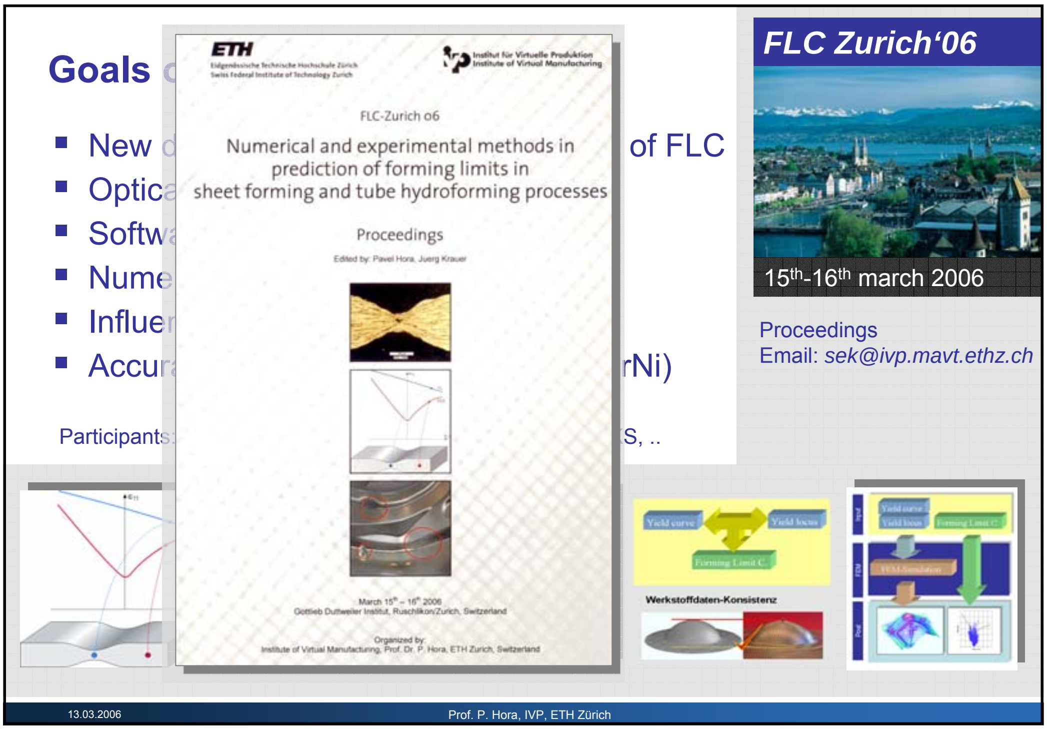
- **NUMISHEET'08**

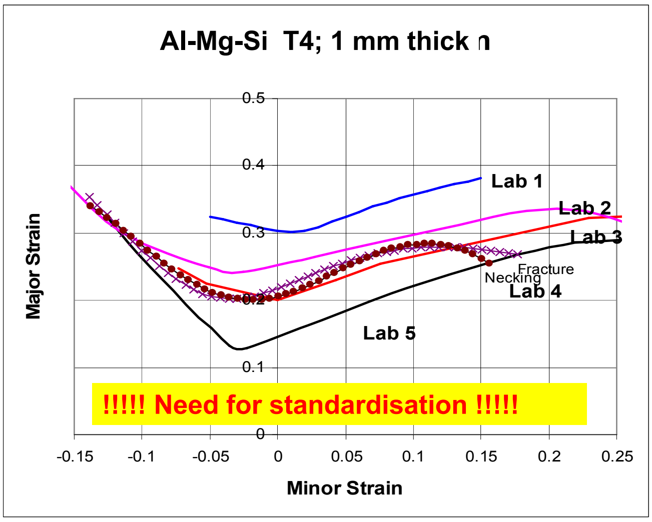
ETH Zürich, IVP, Prof. P. Hora 5. LS-DYNA FORUM 2006



## Forming Limit Curve (FLC)

Novelis

Comparison FLC on same material determined by different labs




Novelis Technology AG W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006

Novelis

# European Efforts in Standardization of FLC

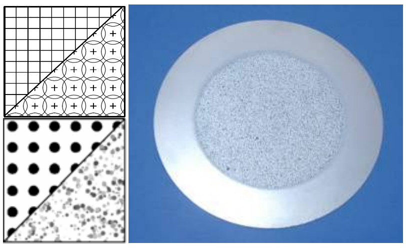
Walter Hotz, Novelis, Neuhausen

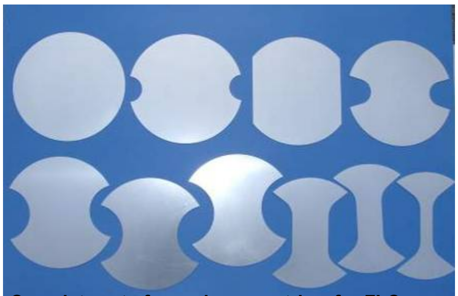
Novelis Technology AG W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006

## Specimen Preparation: Geometries

Novelis

- application of a deterministic grid or of a stochastic pattern
- rectangular stripes or circular blanks with cut outs
- In tension area (minor true strain < 0) parallel shafts



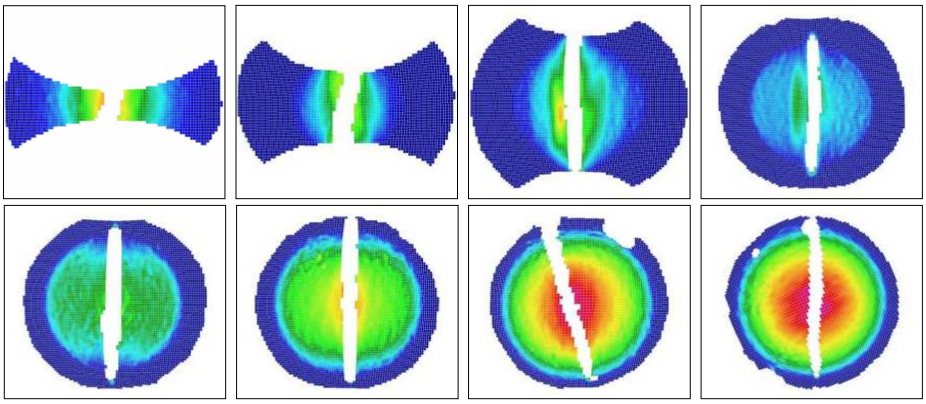


Complete set of sample geometries for FLC

Novelis Technology AG W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006

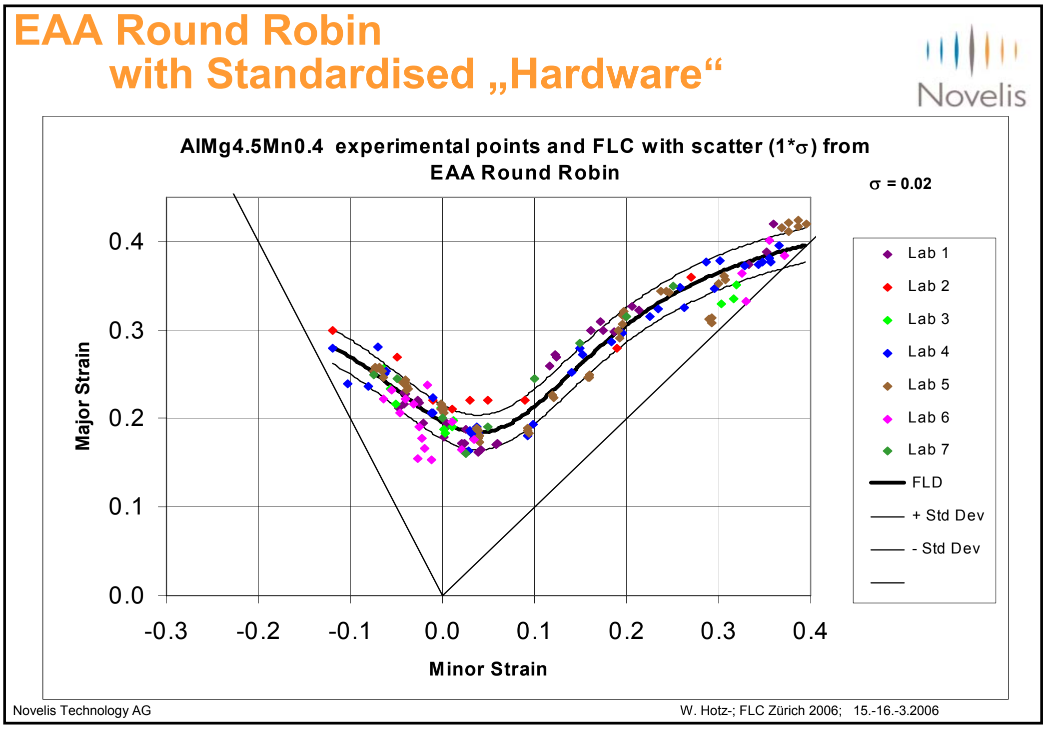
## Nearly Frictionless State in Nakajima Test using a Suitable Tribological System

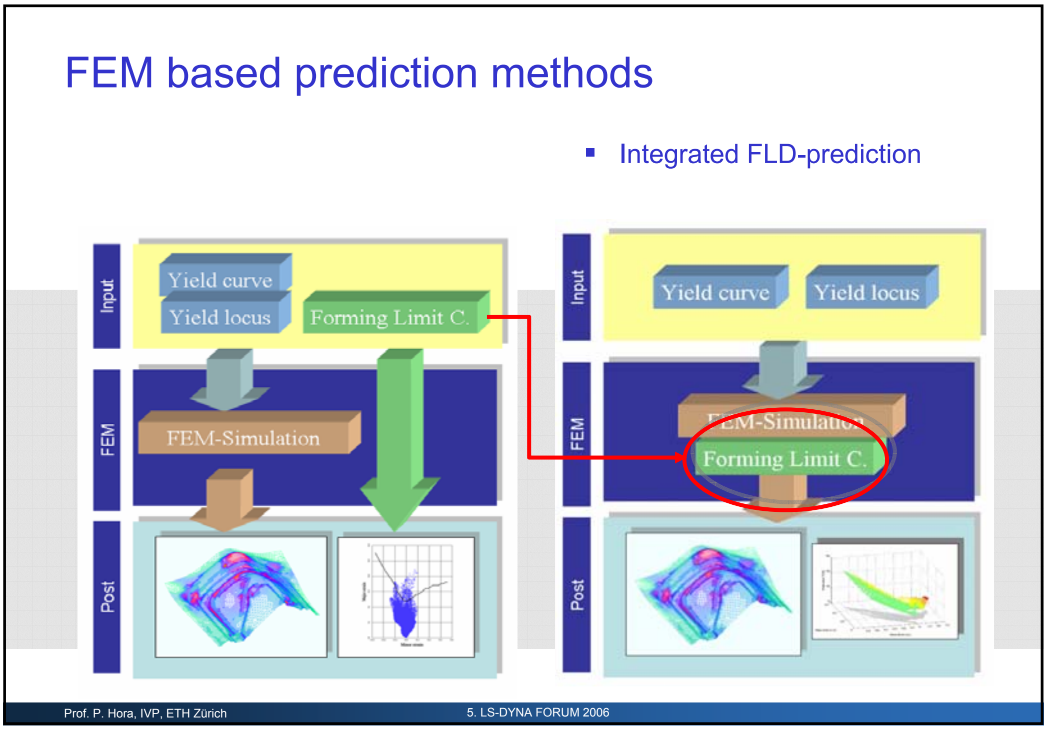
Novelis



Recommended tribological systems leading to a fracture in the centre (+- 15 mm) e.g. :
Grease / Teflon® / Grease, or Grease / Mipolan® / Grease.

Novelis Technology AG W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006


EAA Round Robin
with Standardised „Hardware“
Novelis
AlMg4.5Mn0.4 experimental points and FLC with scatter (1*σ) from
EAA Round Robin
σ = 0.02
Major Strain
Minor Strain
0.4
0.3
0.2
0.1
0.0
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
Lab 1
Lab 2
Lab 3
Lab 4
Lab 5
Lab 6
Lab 7
FLD
+ Std Dev
- Std Dev
Novelis Technology AG
W. Hotz-; FLC Zürich 2006; 15.-16.-3.2006


FEM based prediction methods
Integrated FLD-prediction
Input
FEM
Post
Yield curve
Yield locus
Forming Limit C.
FEM-Simulation
Yield curve
Yield locus
Forming Limit C.
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## Theoretical models in failure predictions

- Marciniak
- Rice
- Hutchinson
- Ghosh
- Needleman
- Stören
- Keeler
- Miyauchi
- Budianski
- Kobayashi
- Koistinen


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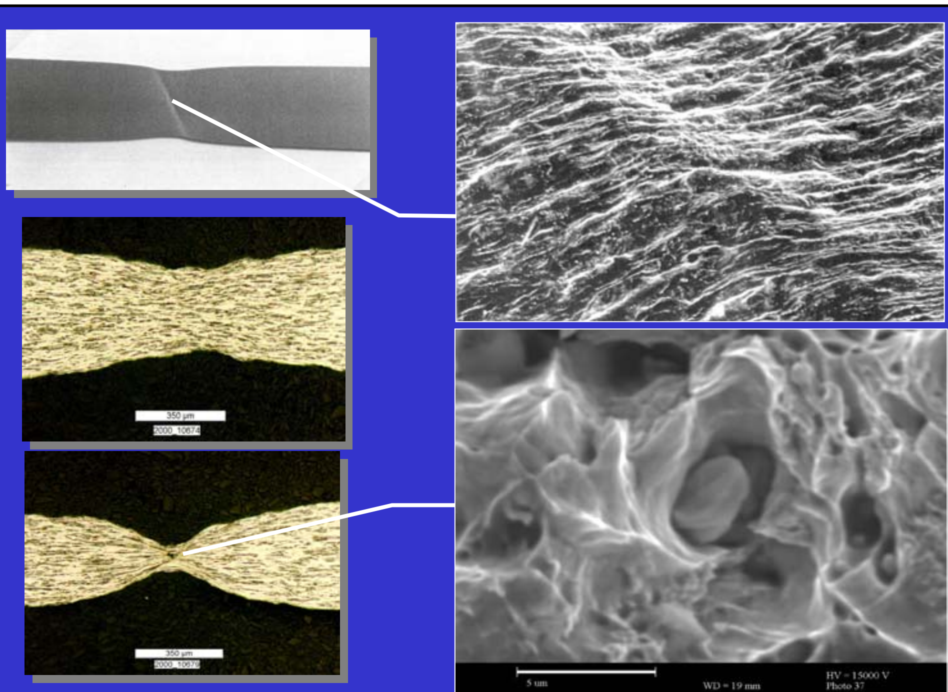

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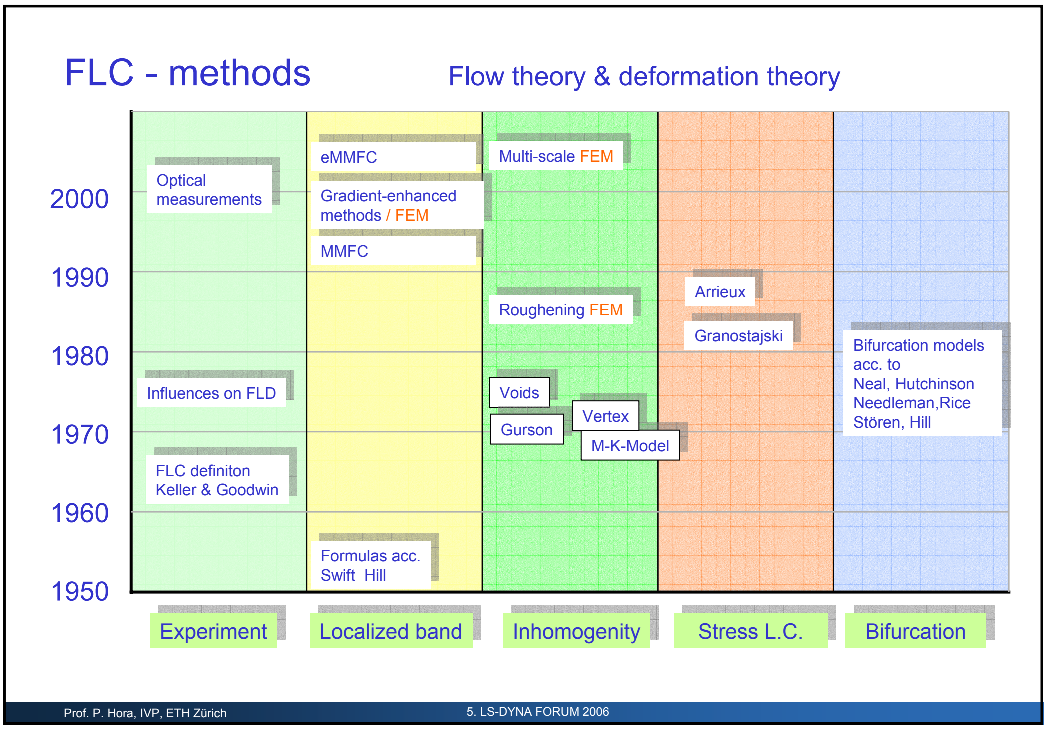
FLC - methods
Flow theory & deformation theory
2000
1990
1980
1970
1960
1950
Optical measurements
Influences on FLD
FLC definiton Keller & Goodwin
eMMFC
Gradient-enhanced methods / FEM
MMFC
Formulas acc. Swift Hill
Multi-scale FEM
Roughening FEM
Voids
Gurson
Vertex
M-K-Model
Arrieux
Granostajski
Bifurcation models acc. to Neal, Hutchinson Needleman,Rice Stören, Hill
Experiment
Localized band
Inhomogenity
Stress L.C.
Bifurcation
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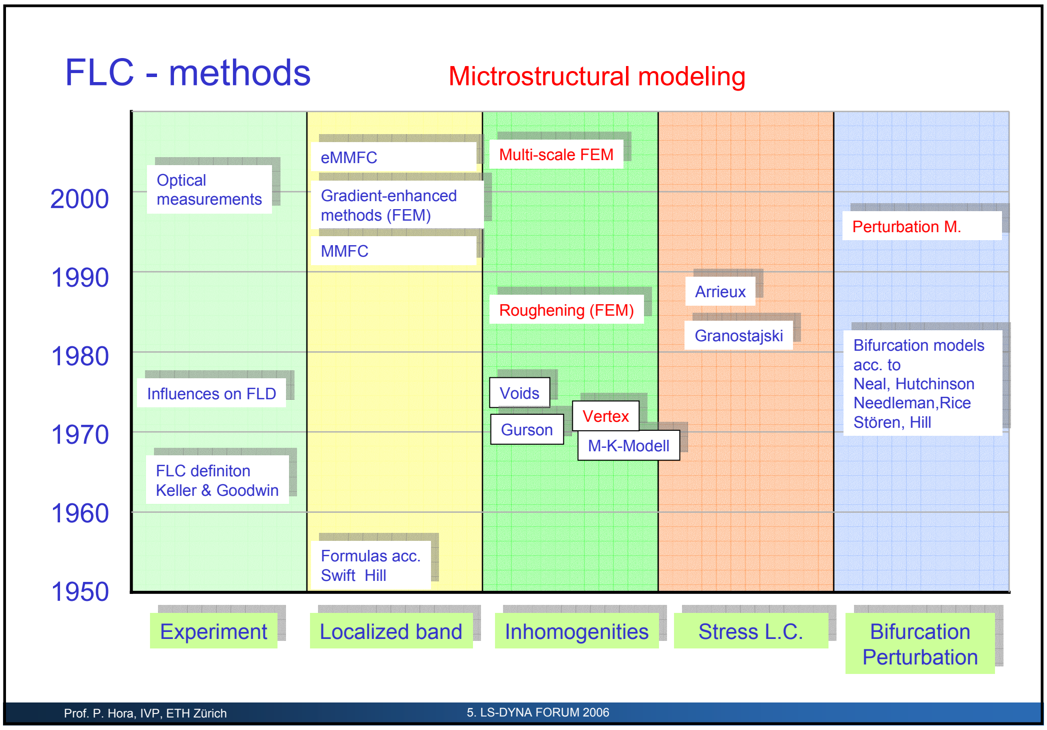
FLC - methods
Mictrostructural modeling
2000
1990
1980
1970
1960
1950
Optical measurements
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eMMFC
Gradient-enhanced methods (FEM)
MMFC
Formulas acc. Swift Hill
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Voids
Gurson
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M-K-Modell
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Granostajski
Perturbation M.
Bifurcation models acc. to Neal, Hutchinson Needleman,Rice Stören, Hill
Experiment
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Stress L.C.
Bifurcation Perturbation
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## Possible combination in modeling of failure phenomena

| Principals | Methods | Plasticity | Materials |
|---|---|---|---|
| Diffused Necking | Hill's model | J2-Flow theory | Strain hardening |
| Localized Necking | M-K-Type<br>▪ t-Inhomogenity | Deformation theory | Strain rate h. |
| Roughness | Stress Limit C. | Gradient-enhanced plasticity | Yield Locus<br>▪ quadratic<br>▪ non-quadratic<br>– Hill<br>– Barlat et al.<br>– Karafillis-Boyce<br>– ….. |
| | Bifurcation | Crystal plasticity | Slip system behavior and ODF |
| | Perturbation | Voids | |
| | FEM | Vertex | |
| | Finite Discrete | | |
| | Smeared Structures | | |
| | Multi-scale FEM | | |

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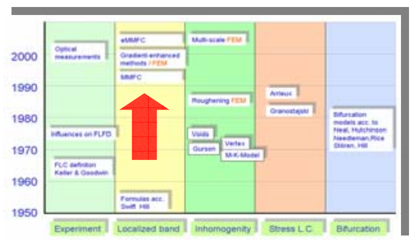
## MMFC-Kriterium

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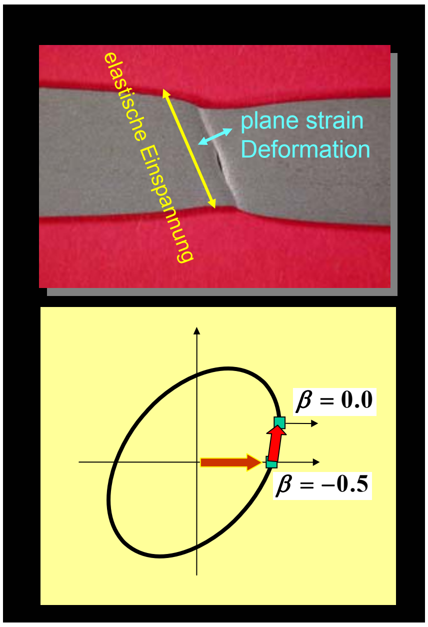
# *Modified Maximum Force Criterion - MMFC*

*Hora-Tong IDDRG 1994*

**Basic relation**

$$\sigma_{11} \geq \frac{\partial \sigma_{11}}{\partial \varepsilon_{11}} + \frac{\partial \sigma_{11}}{\partial \beta} \frac{\partial \beta}{\partial \varepsilon_{11}}$$

Maximum force criterion

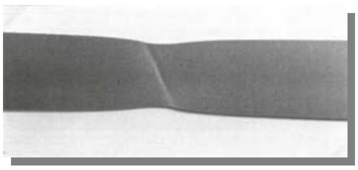




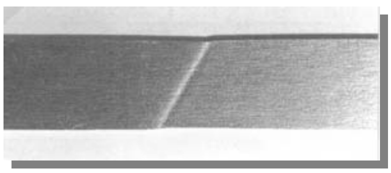

# Advantages

- No assumption of inhomogenities
- Transparent influence of the yield locus shape
- Reduced influence of anisotropy on the FLD for low r-values (Al-behaviour)

Ductile steel-type yield locus

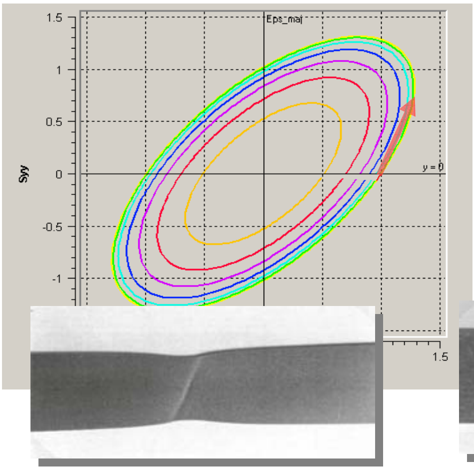


Al-type yield locus

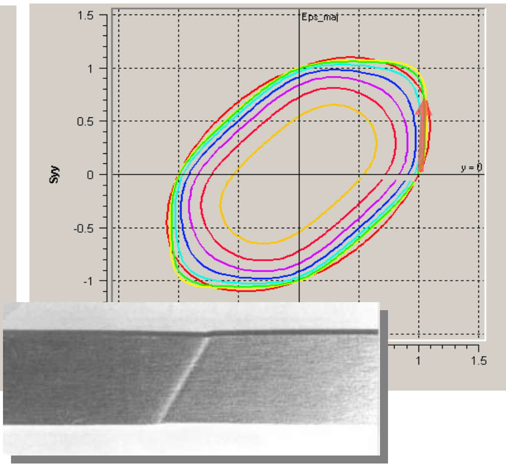


## LN dependence on yield locus shape

Ductile steel-type yield locus




Al-type yield locus






## *MMFC*

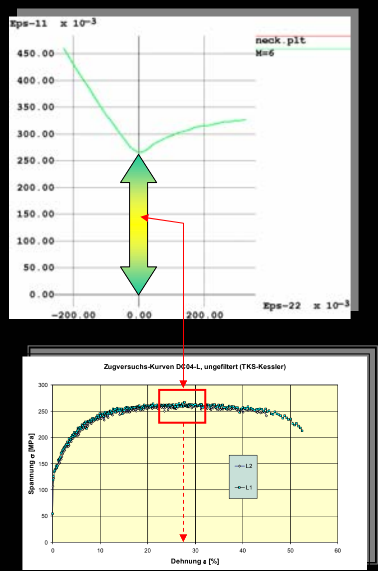
## *Modified Maximum Force Criterion*

*Hora-Tong IDDRG 1994*

**Yield locus: v. Mises**

$$H' = \left\{ \frac{\beta}{\varepsilon_V} \left[ \frac{1}{(2+\beta)} - \frac{(1+2\beta)}{2\alpha} \right] + \frac{\sqrt{3}}{2\sqrt{\alpha}} \right\} H$$

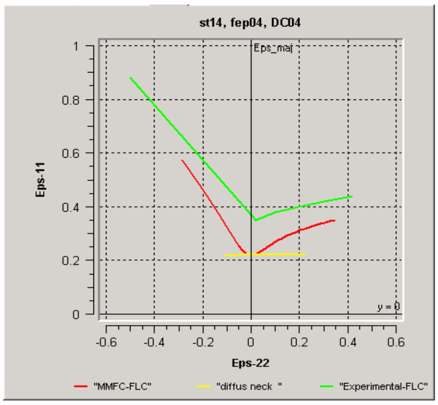
$$\beta = \frac{\Delta\varepsilon_{22}}{\Delta\varepsilon_{11}} \qquad \alpha = (1+\beta+\beta^2)$$





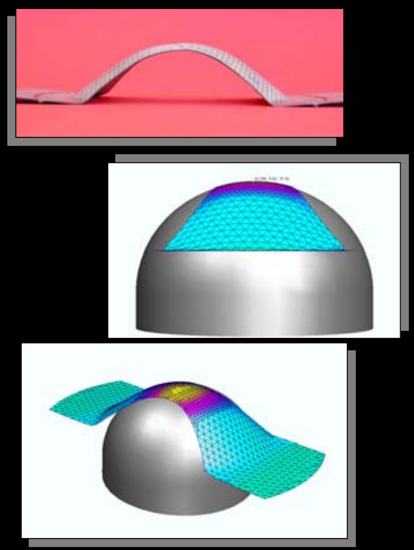

 

## DC04 - MMFC




**MMFC:** *t = 0.*

**Nakazima-Versuch** n. Hasek



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Institute of Virtual Manufacturing

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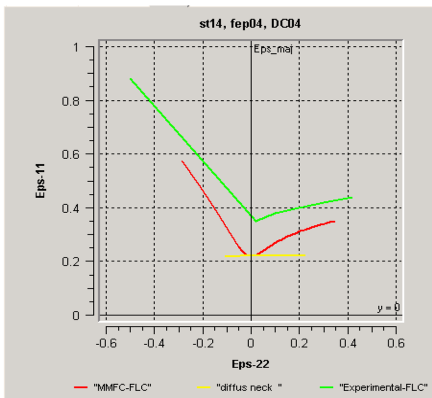
## DC04 - theoretical determination of FLC

**MMFC:** *t = 0.*




Underestimation of the FLC for the most steel materials

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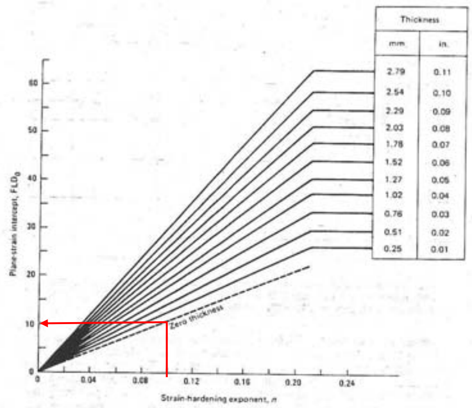
# Influence of sheet thickness

Dependency of FLD on thickness and n-value

$FLD_0 = n \quad \text{if} \quad t = 0$

2-25. Low-Carbon Steel Sheet




**Dependence of FLD on thickness and *n*:** Relationship between plane-strain intercept on FLD ($FLD_0$) and strain-hardening exponent as a function of thickness. $FLD_0$ depends only on thickness for values of *n* greater than 0.21.

**Source:**
**Quality Control Source Book, A.K. Hingwe, Ed. Amer. Soc. For Metals, Metals Park OH, 1982**

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# Content - MMFC

- Modified Maximum Force Criterion - MMFC, *IDDRG 1994*
  - Basic model
- **Enhanced MMFC - eMMFC, *Plasticity 2003***
  - Principal - Influence of the thickness and the crack propagation
- Parameter study
  - Comparison with experimental data
  - Influence of yield locus shape
  - Application for non linear FLC
  - Application for stainless steels

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## Enhanced MMFC

$$\frac{\partial \sigma_{11}}{\partial \varepsilon_{11}}\left[1+\frac{t}{2\rho}+e(E,t)\right]+\frac{\partial \sigma_{11}}{\partial \beta}\frac{\partial \beta}{\partial \varepsilon_{11}} \geq \sigma_{11}$$

Influence of thickness

Empirical assumption

$$e(E,t)=E_0\left(\frac{t}{t_o}\right)^n$$

E: Young modulus
t: Thickness

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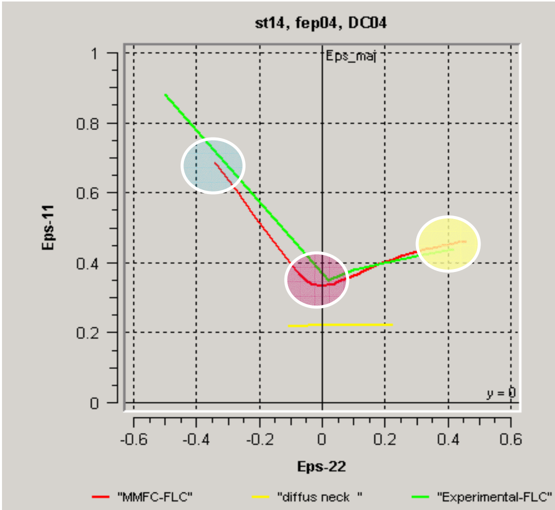
## Comparison with experimental FLCs

Evaluated points

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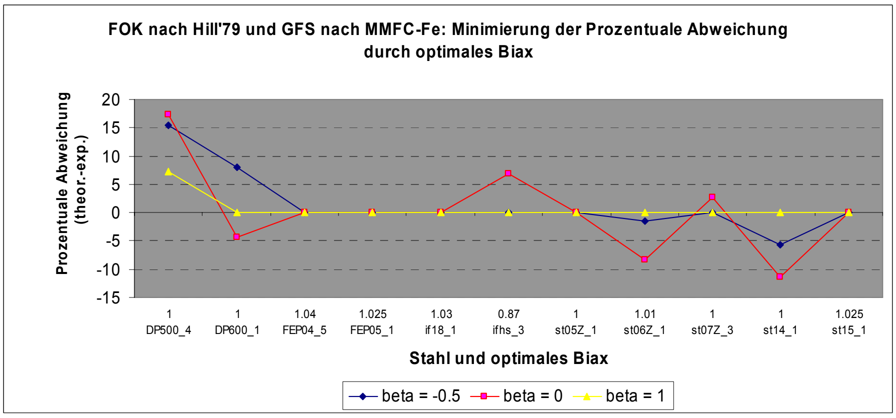
## $E_o$ Verification with experimental data

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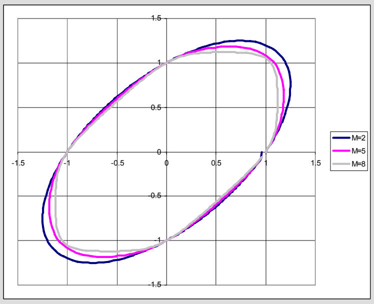
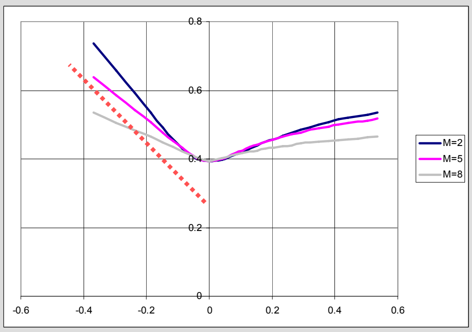
# Influence of yield locus shape




Hardening: $\sigma_y=600\varphi^{0.27}$ Hill's formula

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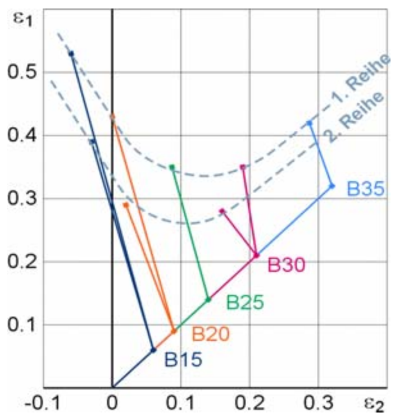
## *Experimental verification for non-linear strain paths*




1) Prestrained in biaxial tension

2) Cutted

3) Deformed in 2nd step

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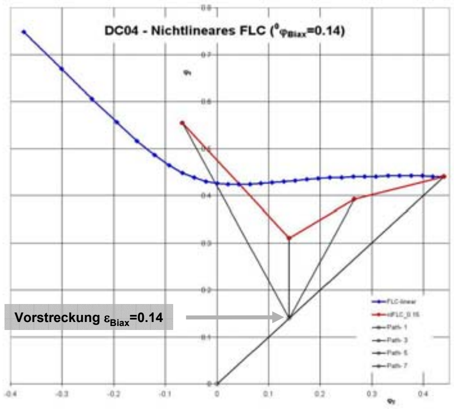
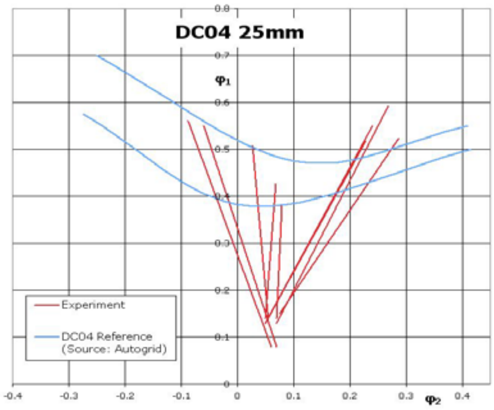
## Theoretische Voraussage der Pfadabhängigkeit n. eMMFC vs. Experiment beim DC04

**Lineare Vorstreckung $\varepsilon_{Biax}$ = 0.14 ~ 25 mm Bulgehöhe**




eMMFC | Experiment

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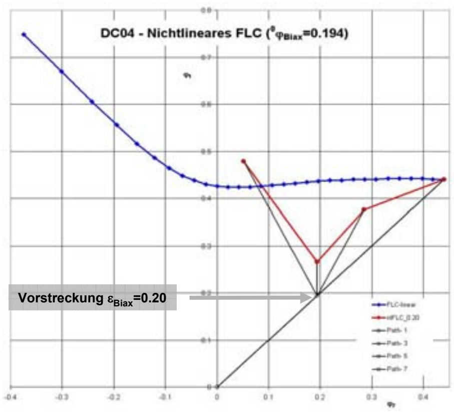
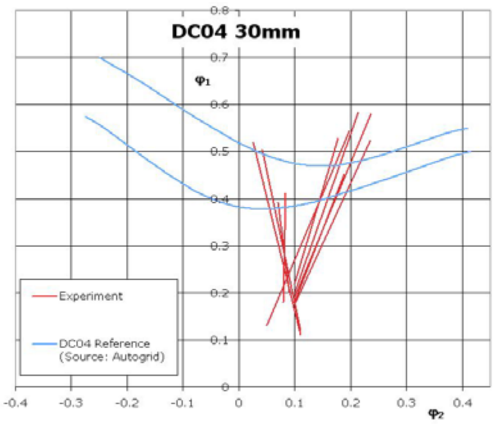
## Theoretische Voraussage der Pfadabhängigkeit n. eMMFC vs. Experiment beim DC04

**Lineare Vorstreckung $\varepsilon_{Biax}$ = 0.20 ~ 30 mm Bulgehöhe**




eMMFC | Experiment

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# Enhanced MMFC

$$\frac{\partial \sigma_{11}}{\partial \varepsilon_{11}}\left[1+\frac{t}{2\rho}+e(E,t)\right]+\frac{\partial \sigma_{11}}{\partial \beta}\frac{\partial \beta}{\partial \varepsilon_{11}} \geq \sigma_{11}$$

+ Influence of temperature and martensite

$$\frac{\partial \sigma_{11}}{\partial \varepsilon_{11}}\left[1+\frac{t}{2\rho}+e(E,t)\right]+\frac{\partial \sigma_{11}}{\partial T}\frac{\partial T}{\partial \varepsilon_{11}}+\frac{\partial \sigma_{11}}{\partial V_M}\frac{\partial V_M}{\partial \varepsilon_{11}}+\frac{\partial \sigma_{11}}{\partial \beta}\frac{\partial \beta}{\partial \varepsilon_{11}} \geq \sigma_{11}$$

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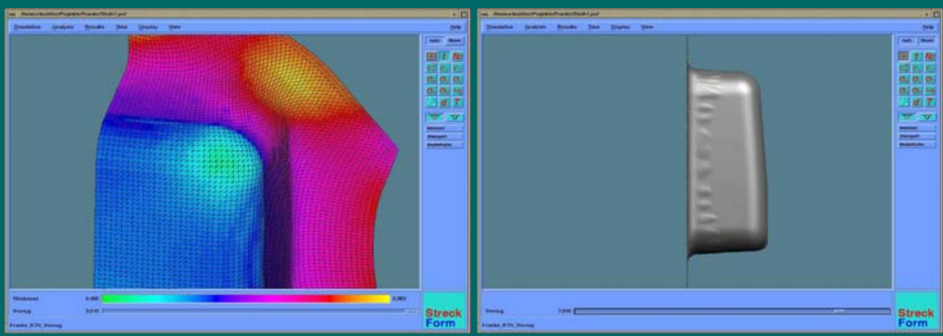
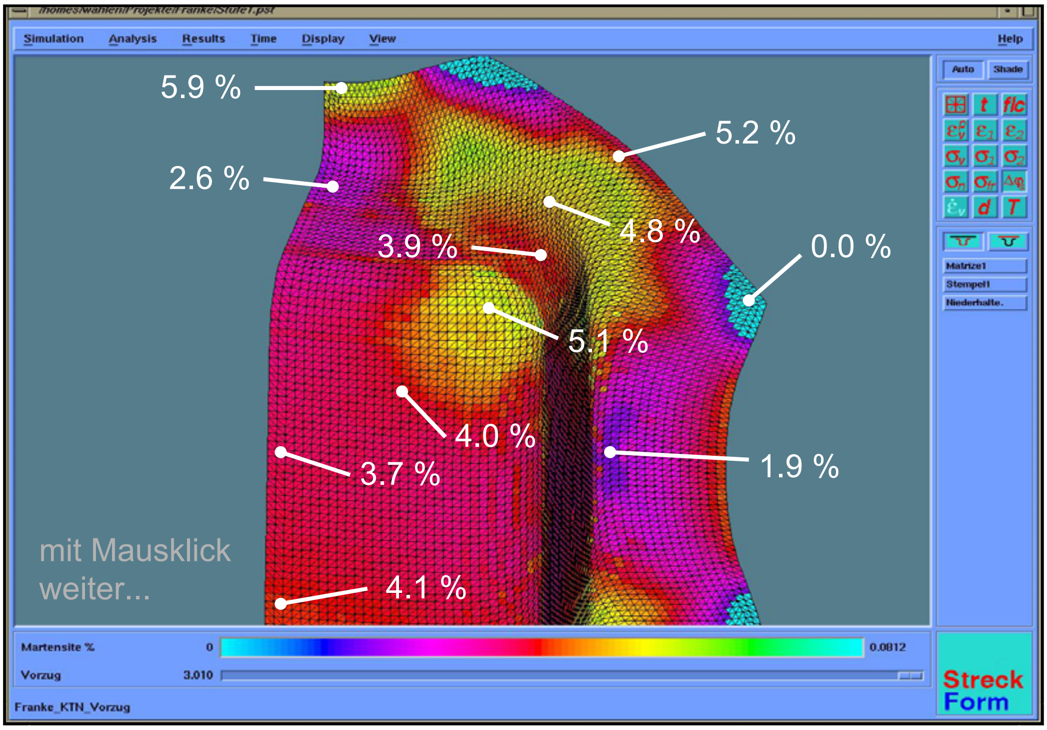
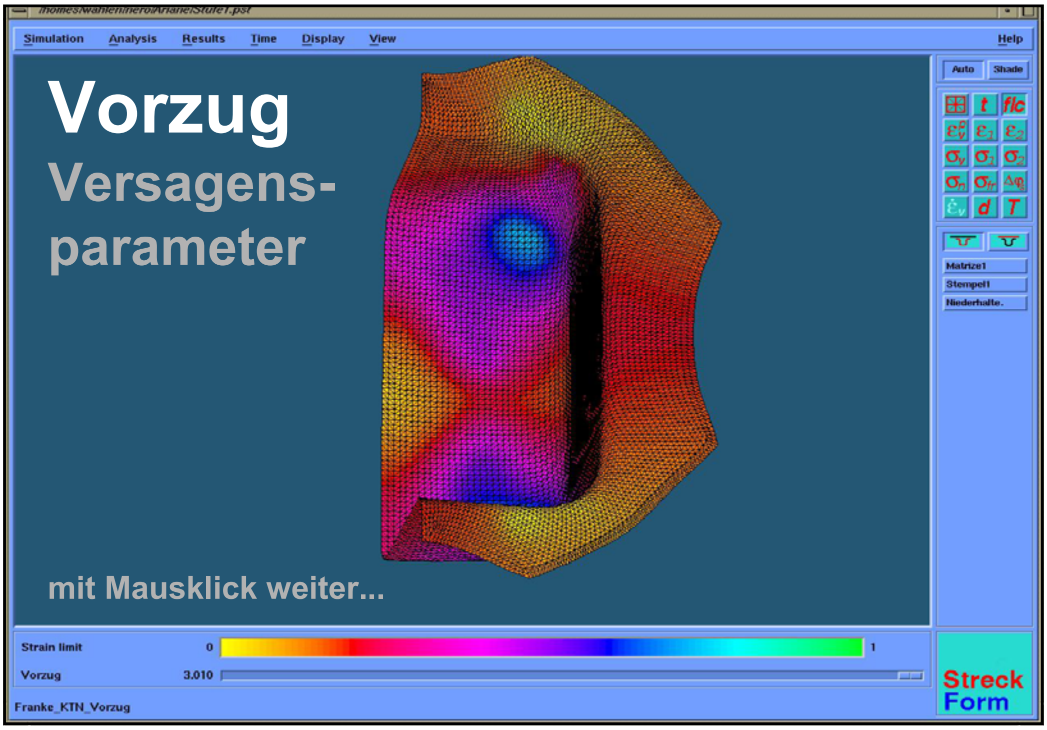
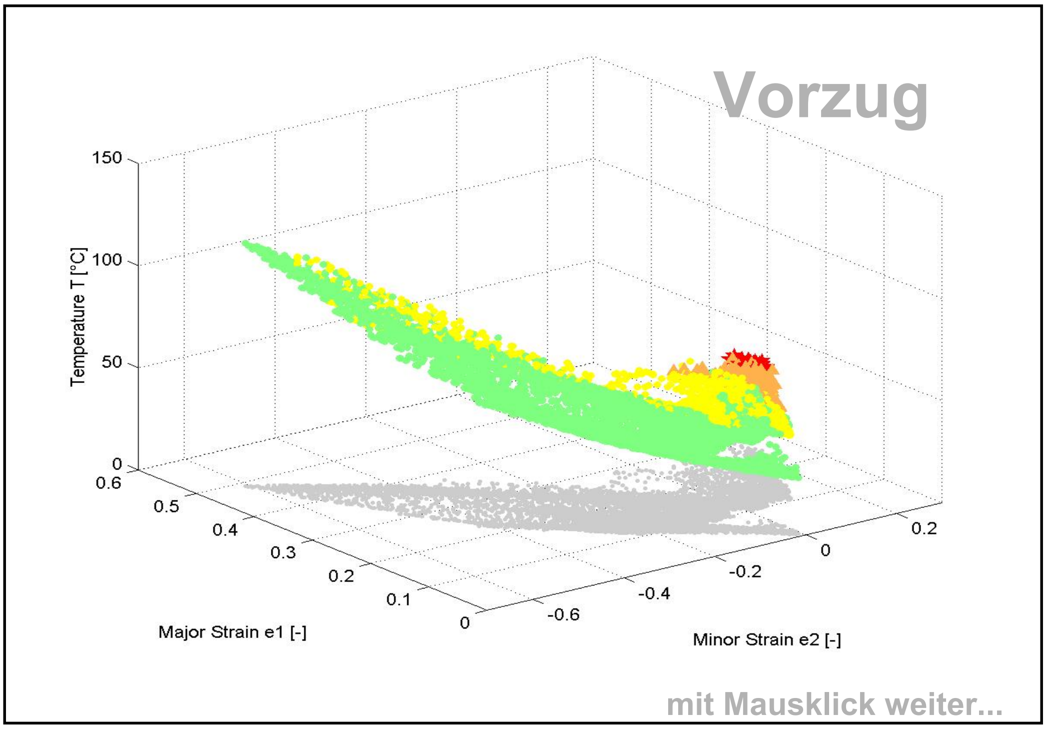
# Tiefziehsimulation Becken ARX 35/43



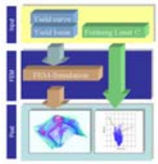

**Projektpartner: FRANKE Küchentechnik AG**
**Institut für Umformtechnik: Dr. L. Tong, A. Wahlen**
**Zürich, 11. Juli 2000** 5. LS-DYNA FORUM 2006



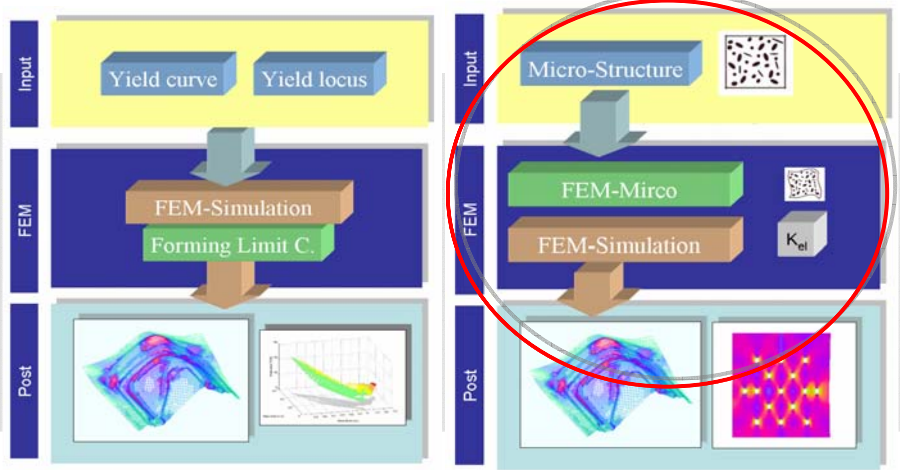

Simulation
Analysis
Results
Time
Display
View
Help
Vorzug
Versagens-
parameter
mit Mausklick weiter...
Auto
Shade
Matrize1
Stempel1
Niederhalte.
Strain limit
0
1
Vorzug
3.010
Franke_KTN_Vorzug
Streck
Form


Vorzug
150
100
50
0
Temperature T [°C]
0.6
0.5
0.4
0.3
0.2
0.1
0
Major Strain e1 [-]
-0.6
-0.4
-0.2
0
0.2
Minor Strain e2 [-]
mit Mausklick weiter...

## FEM based prediction methods



- Integrated FLD-prediction
- Multi-scale modeling

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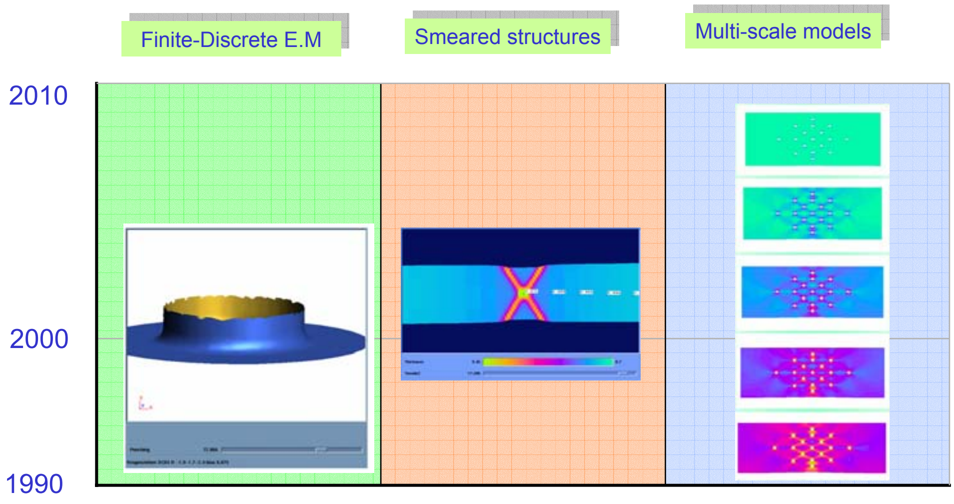
## FEM - methods

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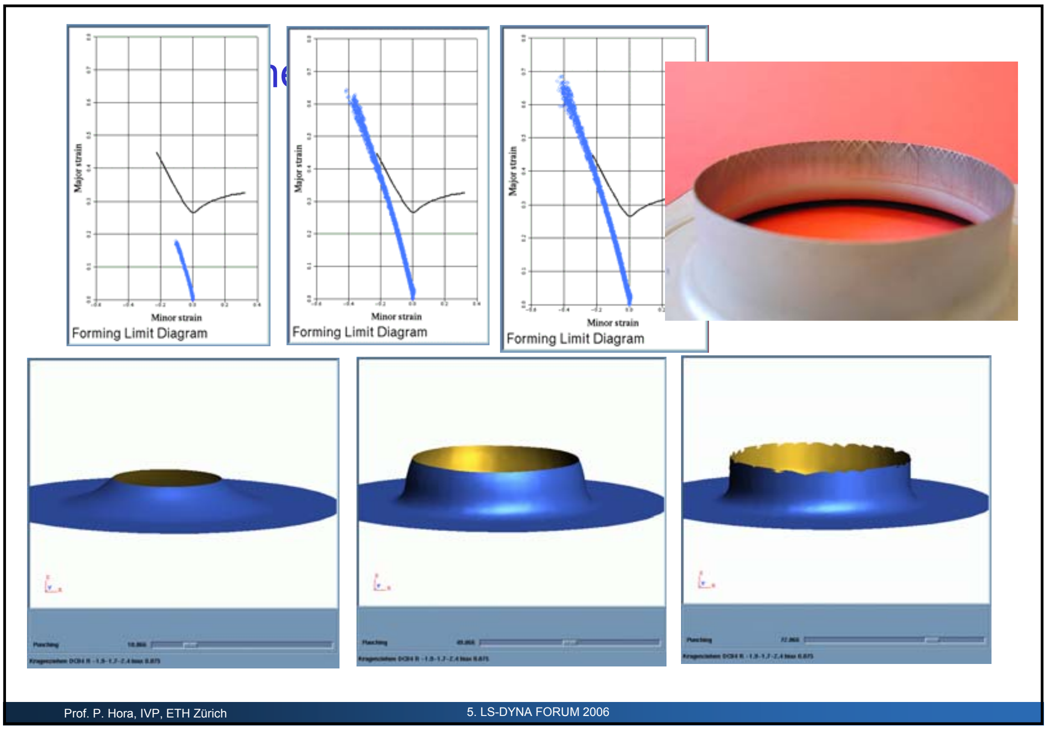
Major strain
Minor strain
Forming Limit Diagram
Major strain
Minor strain
Forming Limit Diagram
Major strain
Minor strain
Forming Limit Diagram
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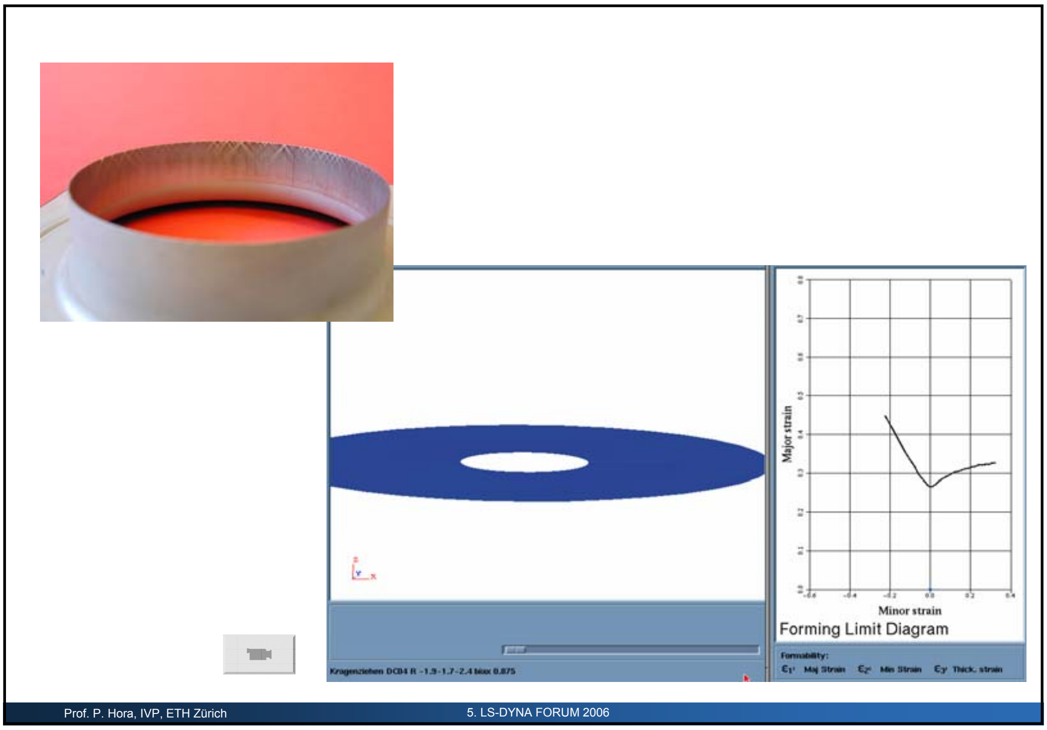
Major strain
Minor strain
Forming Limit Diagram
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## Smeared structures

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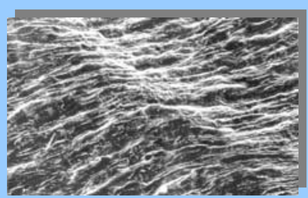
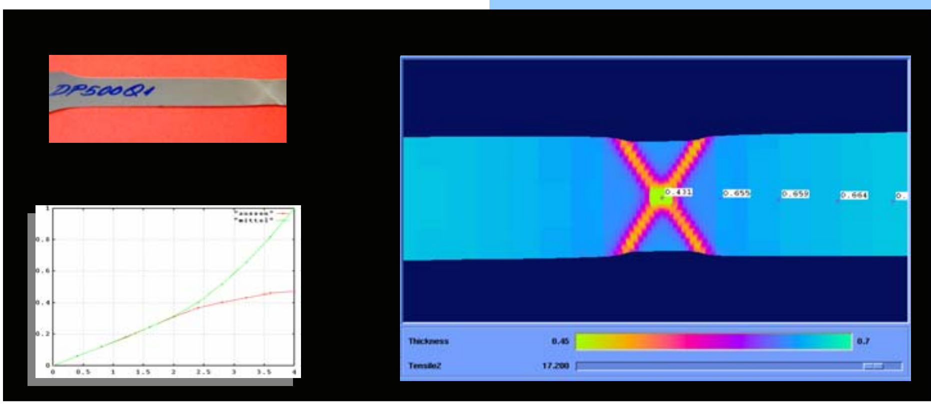
## *FEM-basierte Bestimmung der FLC*

- Simulation Zugversuch



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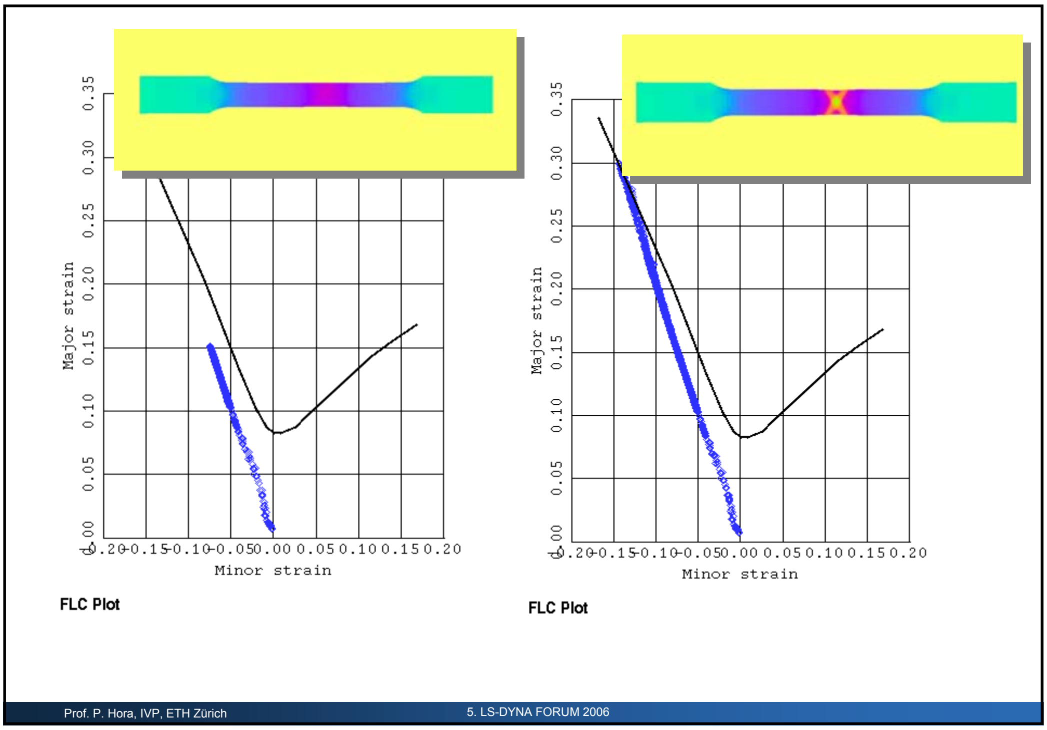
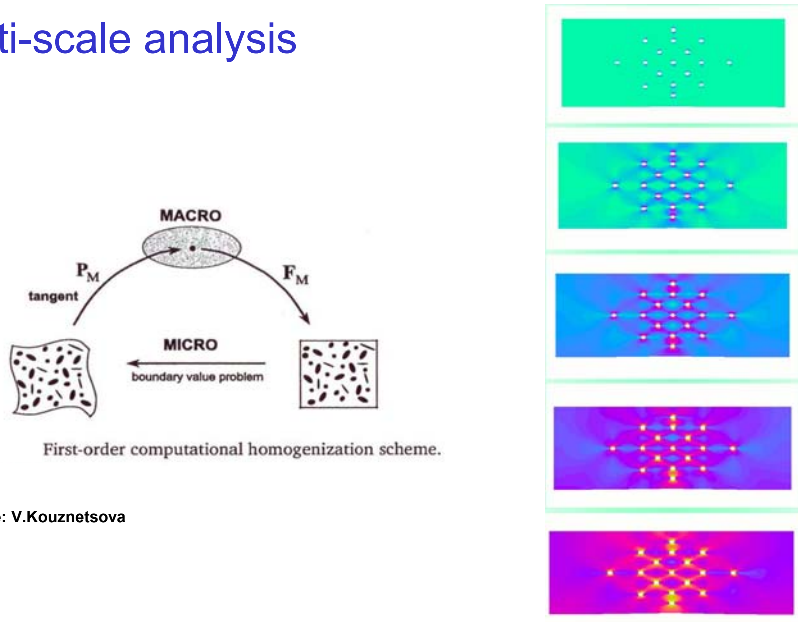



## Multi-scale analysis




Source: V.Kouznetsova

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## Multi-scale analysis

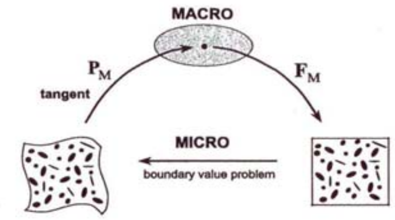
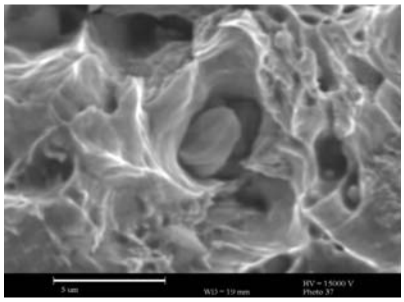
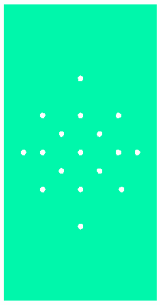



**Figure 2.3:** First-order computational homogenization scheme.

Source Picture: V.Kouznetsova





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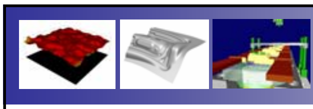

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## Content

- **Introduction**
- **Advanced Methods in Constitutive Modeling of Materials**
  - Advanced methods in hardening description
    "Combined experimental and crystal plasticity methods in determination of hardening for large strains"
  - Advanced methods in yield locus description
    "Crystal plasticity methods in determination of non-quadratic yield locus shapes"
  - Advanced methods in failure modeling
    "Numerical methods in computational evaluation of FLCs with the enhanced Modified Maximum Force Criterion (eMMFC)"
- **Conclusions**

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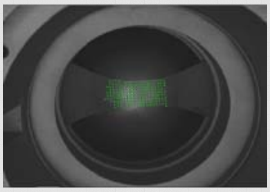
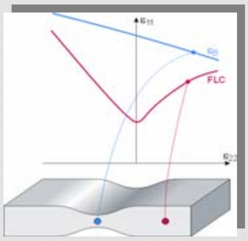
# Experimental methods

- International standards for the evaluation of experimental FLC
- Better methods for the numerical evaluation procedures



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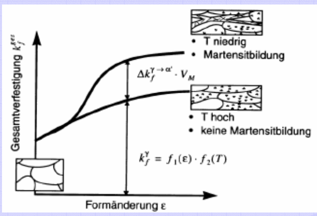
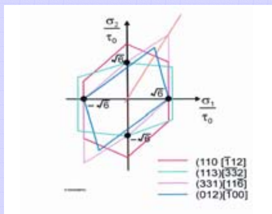
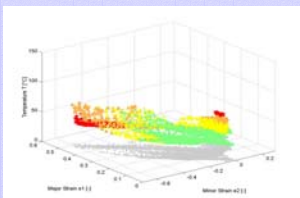
# "Consistent" material inputs




Hardening



Yield Locus



Failure modeling

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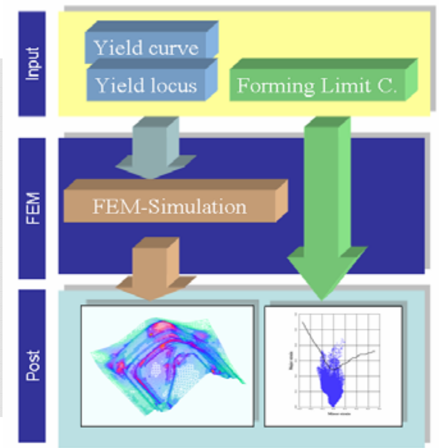
# FEM based prediction methods

- Nowadays approach

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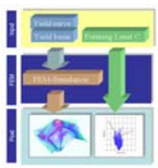
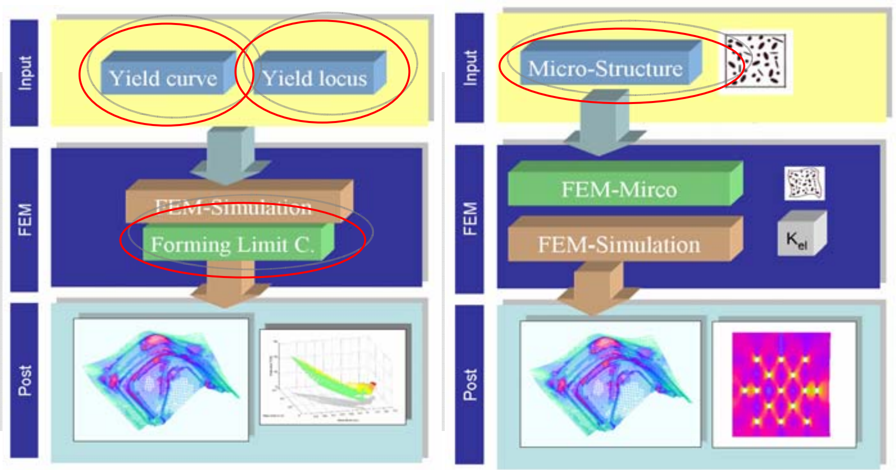
# FEM based prediction methods



Future approach

- Integrated FLD-prediction
- Multi-scale modeling

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# *Numisheet'08*

## Zurich-Munich-Stuttgart

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

BMW Group

DAIMLERCHRYSLER

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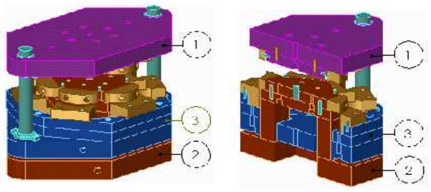
## NUMISHEET'08

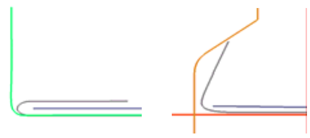
BM-08-1

# Modeling of flanging and hemming operations

- **Task 1.1:** prediction of spring back
- **Task 1.2:** prediction of flange shortage




*By courtesy of DaimlerChrysler*



Organizer: DaCh, Prof. K. Roll

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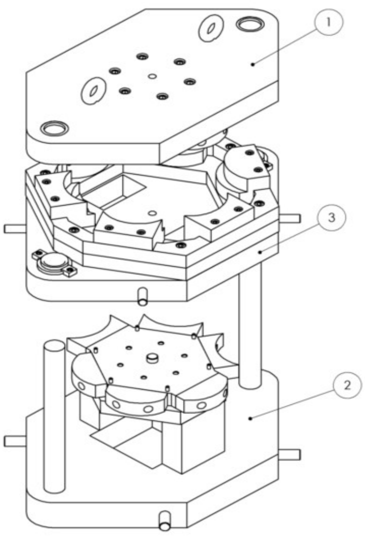


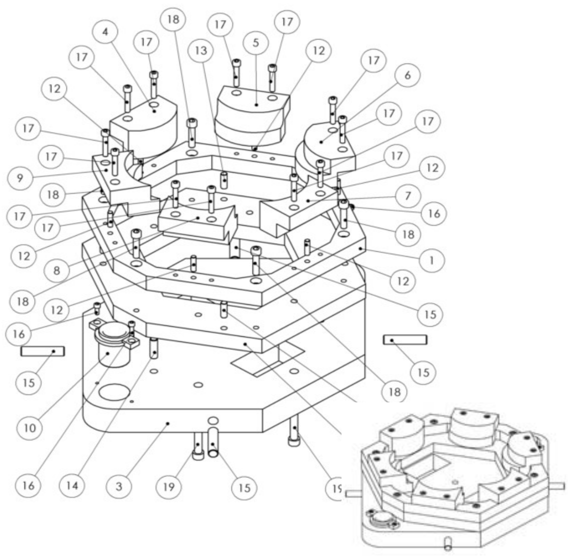

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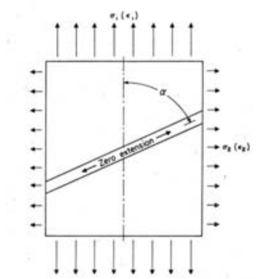
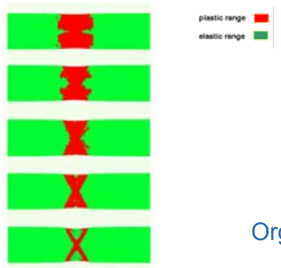
## NUMISHEET‘08

BM 08-2

# Theoretical and semi-analytical prediction of FLC

- **Task 2.1:** Prediction of FLCs




Organizer: BMW, Dr.W.Volk

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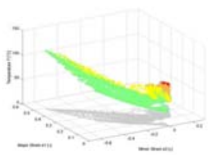
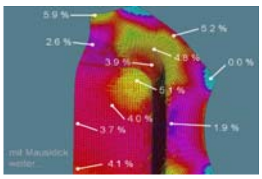
## NUMISHEET‘08

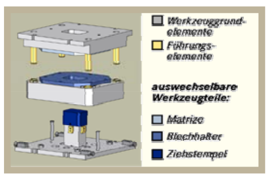
BM 08-3

# Modeling of thermal induced processes with meta-stable stainless steels

- **Task 3.1:** Modeling of a deep drawing process with stainless steels
  - Prediction of the critical deformation state
  - Prediction of the martensite
  - Prediction of failure








*By courtesy of DaimlerChrysler*

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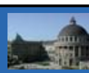


Neighbourhood to the most famous european car makers

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## Technical tour program

- Visit to BMW in Munich
- Visit to DaimlerChrysler in Stuttgart

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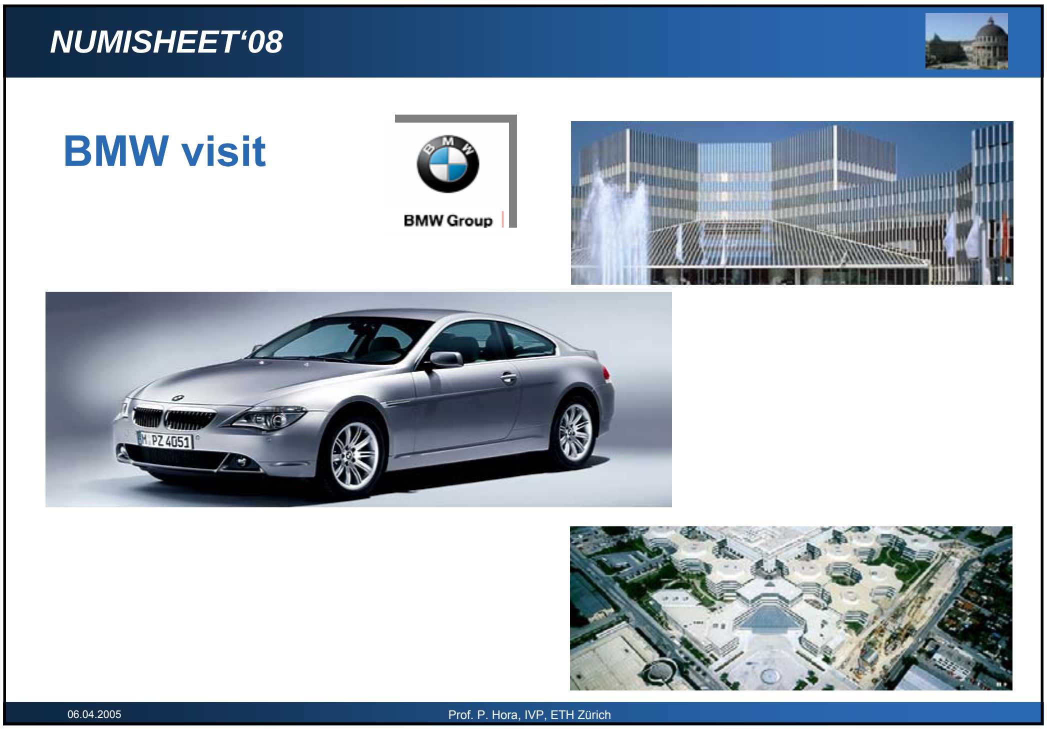
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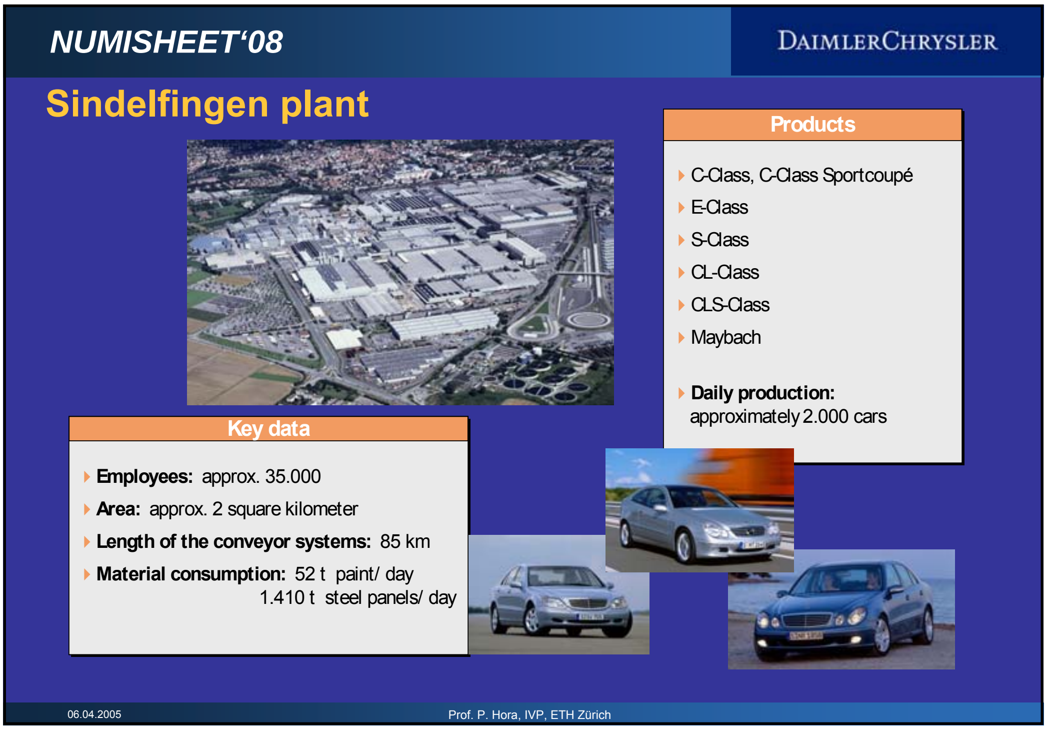
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DAIMLERCHRYSLER
Sindelfingen plant
Products
C-Class, C-Class Sportcoupé
E-Class
S-Class
CL-Class
CLS-Class
Maybach
Daily production: approximately 2.000 cars
Key data
Employees: approx. 35.000
Area: approx. 2 square kilometer
Length of the conveyor systems: 85 km
Material consumption: 52 t paint/ day
1.410 t steel panels/ day
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NUMISHEET'08
DAIMLERCHRYSLER
Mercedes-Benz
Technology Center
Key data
Employees: approx. 9.200
Start of new car series:
1985-1995: 10
1995-2005: 27
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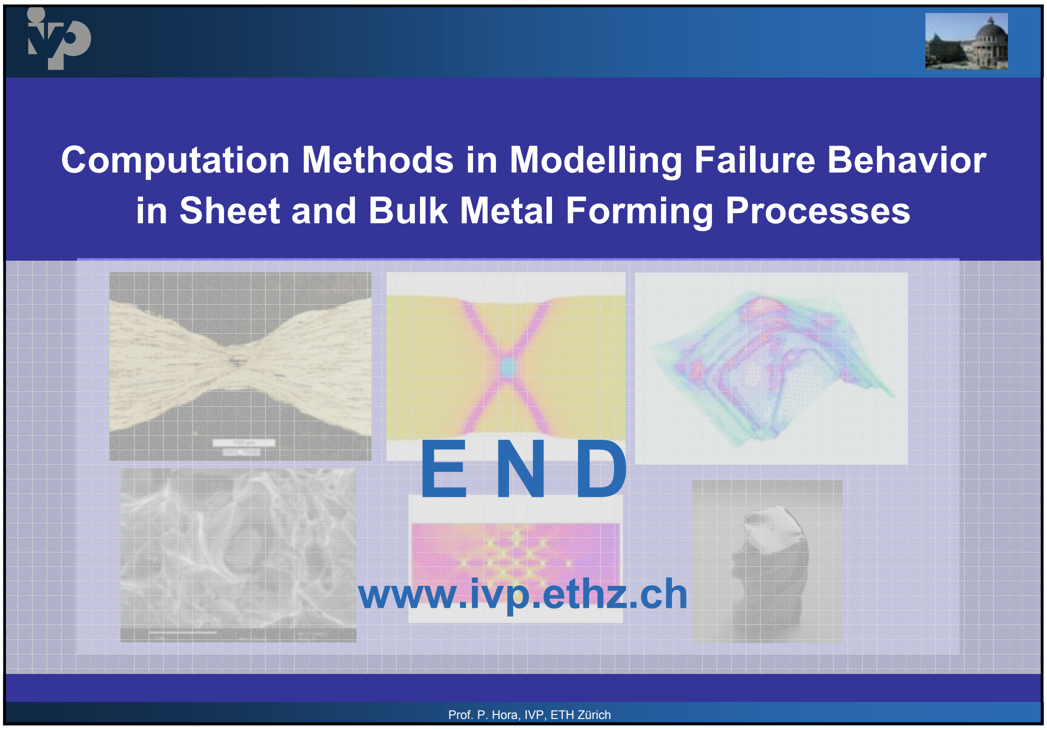
Computation Methods in Modelling Failure Behavior in Sheet and Bulk Metal Forming Processes
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