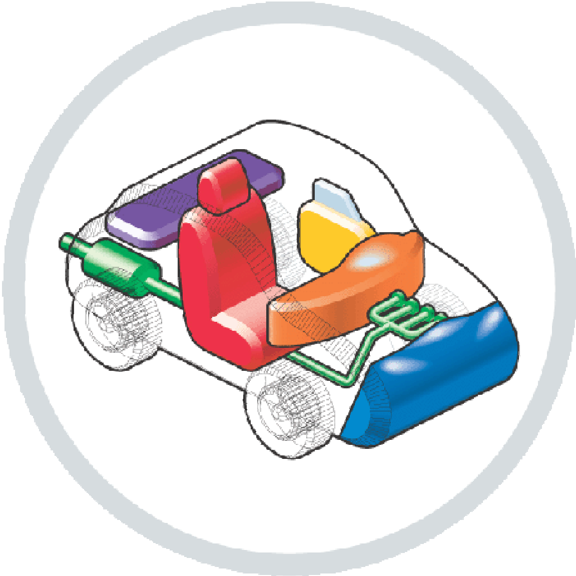
Technical perfection, automotive passion.

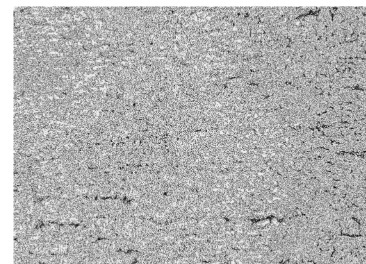
Cost-benefit conflict in material modeling

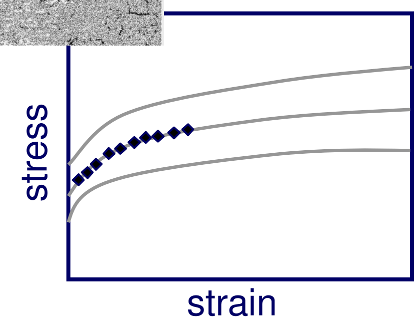


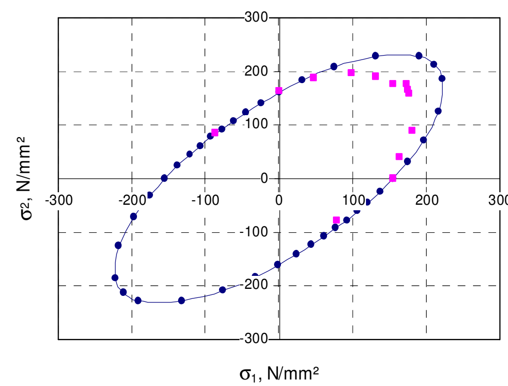
Dr.-Ing. Birgit Reichert

Content

- **Introduction**
- **Modelling philosophies**
- **Material testing for data input FEM**
- **Questions**



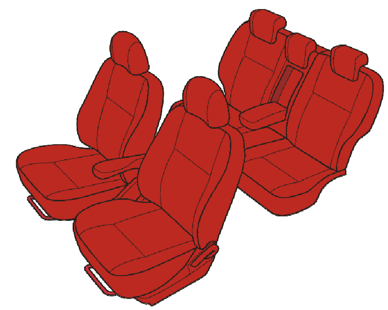




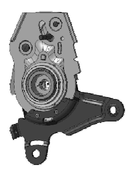
Faurecia Seating Group

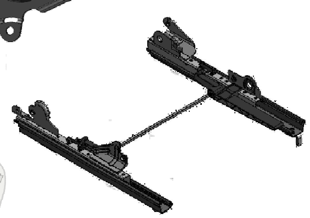
Frames

Complete seat

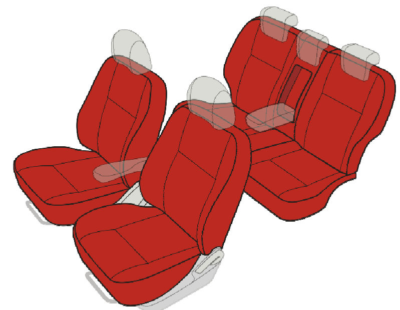


Mechanisms

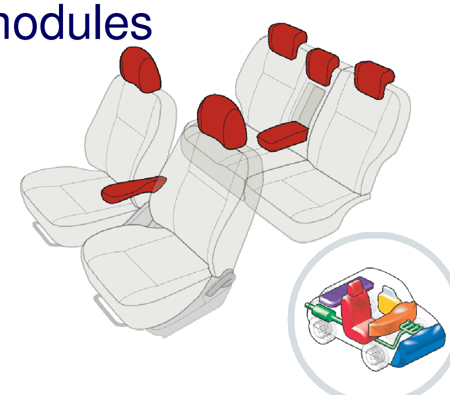




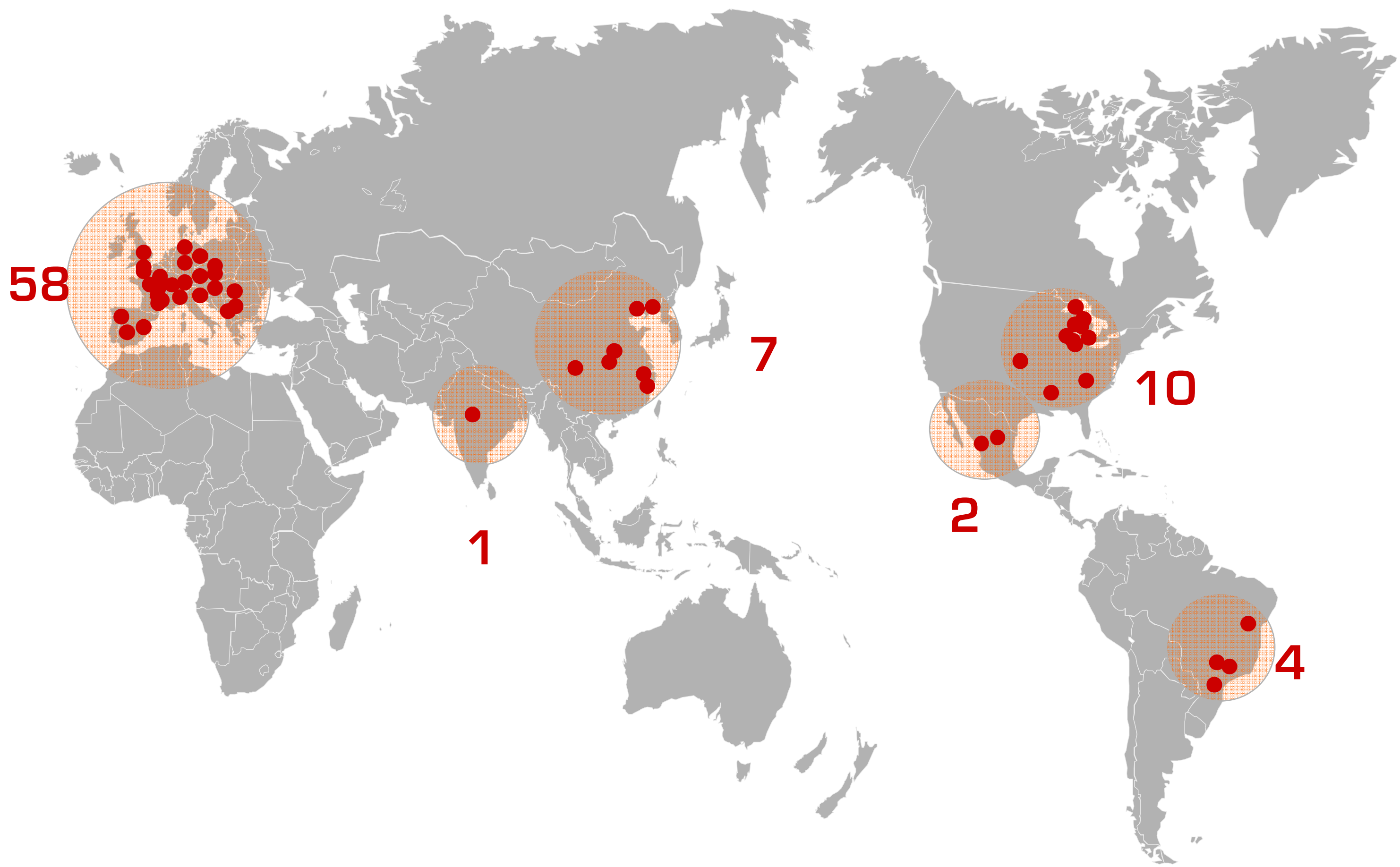
Foam and covers



Safety and comfort modules

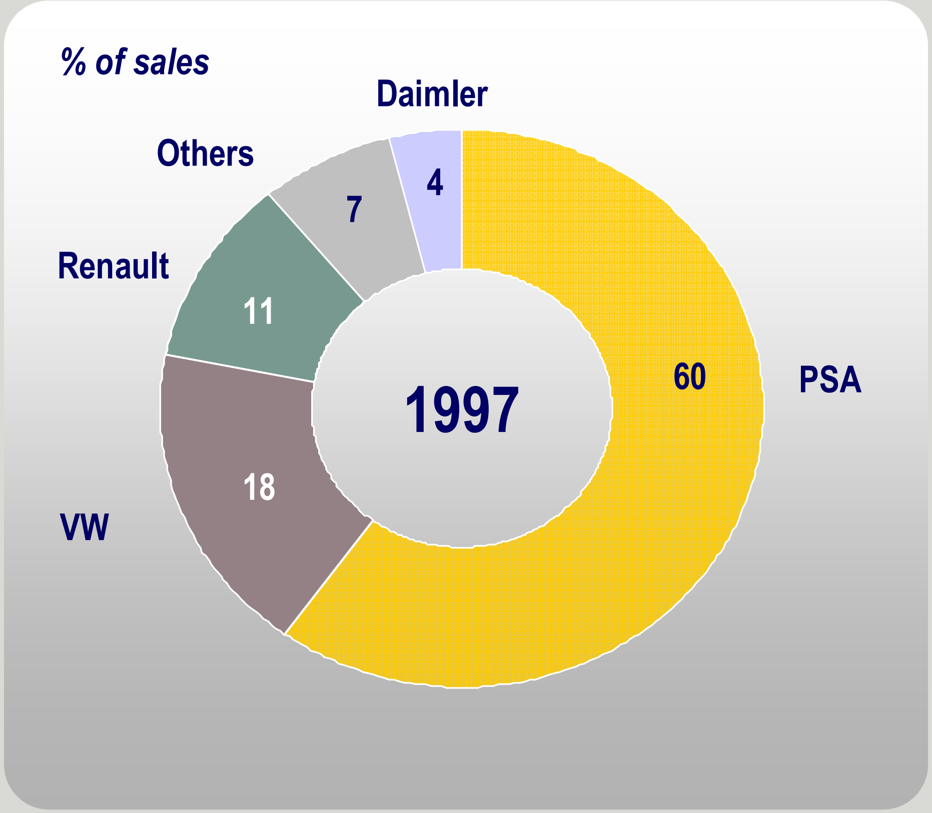


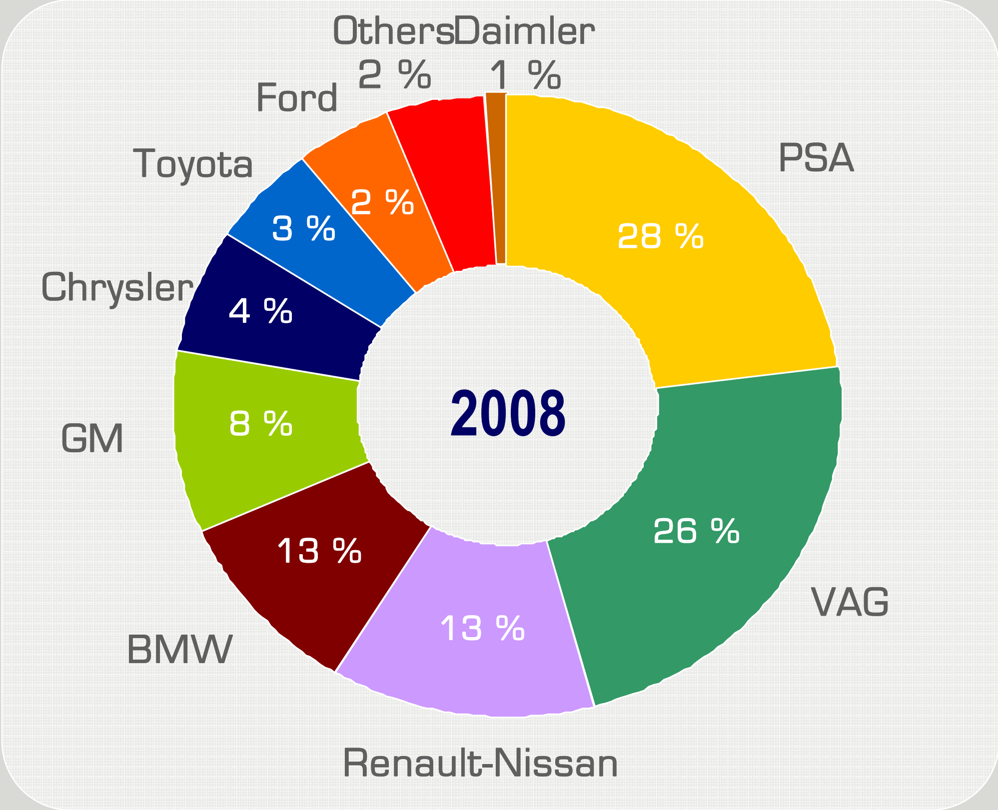
Faurecia as global player



2 Leading commercial position & successful customer diversification

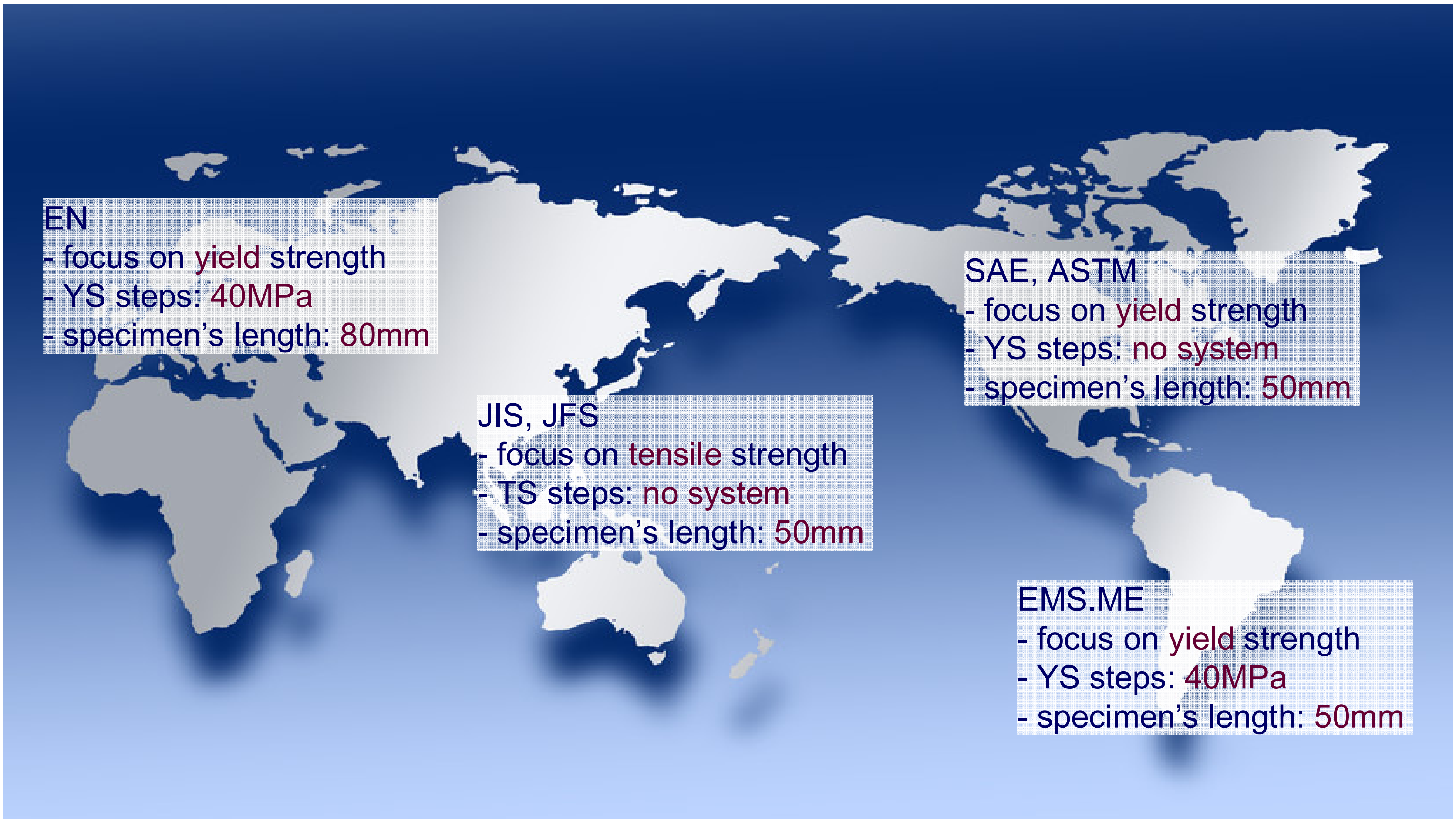
faurecia





* Excluding monoliths

The complex material landscape (steel sheet)



Best equivalence of sheet steel by norms

Grade classes Europe	Europe	America		Japan		China	India
Deep drawing steel grades	**EN 10130**	**SAE J2329**	**ASTM A 1008M-07a**	**JIS G 3141**	**JFS A 2001**	**GB/T 5213**	**IS 513**
cold rolled	DC01	-	CS	SPCC	JSC270C	DC01	CR1
cold rolled	DC03	CR3	DS	SPCD	JSC270D	DC03	CR3
cold rolled	DC04	CR4	DDS	SPCE	JSC270E	DC04	CR4
cold rolled	DC06	CR5	EDDS	SPCG	JSC260G	DC06	CR5
Deep drawing steel grades	**EN 10111**	**SAE J2329**	**ASTM 1011M-07**	**JIS G 3131**	**JFS A 1001**	**GB 710-91/ GB 711-88**	**IS 1079**
hot rolled	DD11	-	-	SPHC	-	08	D
hot rolled	DD12	HR2	HR CS Type B	SPHD	JSH270C	-	DD
hot rolled	DD13	-	-	SPHE	JSH270D	08A1	EDD
hot rolled	DD14	HR3	HR DS Type B	SPHF	JSH270E	-	-
High strength IF steel grades	**EN 10268**	**SAE J2340**	**ASTM A 1008M-07**	**JIS G 3135**	**JFS A 2001**	**GB/T 20564-3**	**India**
cold rolled	HC180Y	CR 180AT	-	SPFC340	JSC340W	CR180IF	
	HC260Y	CR 280AT	-	SPFC390	JSC390W	CR260IF	
Microalloyed steel grades	**EN 10268**	**SAE J2340**	**ASTM A 1008M-07a**	**JIS G 3135**	**JFS A 2001**	**China**	**IS 14491**
cold rolled	HC260LA	-	CR SS275	-	-		260Y
	HC300LA	CR 300XF	CR HSLAS310 Class 2	-	-		300Y
	HC340LA	CR 340XF	CR HSLAS340 Class 2	-	JSC440R		340Y
	HC380LA	CR 380XF	CR HSLAS380 Class 2	-	-		380Y
	HC420LA	CR 420XF	CR HSLAS410 Class 2	-	-		420Y
Microalloyed steel grades	**EN 10149**	**SAE J2340**	**ASTM 1011M-07**	**JIS G 3134**	**JFS A 1001**	**GB/T 20887-1**	**IS 5986**
hot rolled	S315MC	HR 300XF	HR HSLAS310 Class 2	-	JSH440R	HR315F	-
	S355MC	HR 340XF	HR HSLAS340 Class 2	-	JSH490R	HR355F	Fe 490
	S420MC	HR 420XF	HR HSLAS410 Class 2	-	JSH540R	HR420F	-
	S460MC	-	HR HSLAS450 Class 2	-	JSH590R	HR460F	-
	S500MC	HR 490XF	HR HSLAS480 Class 2	-	-	HR500F	-
	S550MC	HR 550XF	HR HSLAS-F550	-	-	HR550F	-
	S600MC	-	HR UHSS 620	-	-	HR600F	-
	S650MC	-	-	-	-	HR650F	-
	S700MC	-	HR UHSS 690	-	-	HR700F	-
Dual phase steel grades	**draft EN 10338**	**SAE J2745**	**ASTM A 1008M-07a**	**JIS G 3135**	**JFS A 2001**	**GB/T 20564-2**	**India**
cold rolled	HCT450X	CR DP440T/250Y	-	SPFC440	JSC440W	CR260/450DP	-
	HCT500X	CR DP490T/290Y	-	SPFC490	-	CR300/500DP	-
	HCT600X	CR DP590T/340Y	-	SPFC590	JSC590Y	CR340/590DP	-
	HCT780X	CR DP780T/420Y	-	SPFC780Y	JSC780Y	CR420/780DP	-
	HCT980X	CR DP980T/550Y	-	SPFC980Y	JSC980Y	CR550/980DP	-
Dual phase steel grades	**draft EN 10338**	**SAE J2745**	-	**JIS G 3134**	**JFS A 1001**	**China**	-
hot rolled	HDT580X	HR DP590T/300Y	-	SPFH590Y	JSH590Y	-	-
Complex phase steel grades	**draft EN 10338**	**SAE J2745**	**ASTM A 1008M-007a**	**JIS G 3135**	**JFS A 2001**	**China**	**India**
cold rolled	HCT600C	-	-	-	-	-	-
	HCT780C	-	-	-	-	-	-
	HCT980C	-	-	-	-	-	-
Complex phase steel grades	**draft EN 10338**	**SAE J2745**	**ASTM 1011M-07**	**JIS G 3134**	**JFS A 1001**	**China**	**India**
hot rolled	HDT750C	-	-	-	-	-	-
	HDT780C	-	-	-	JSH780R	-	-
	HDT950C	-	-	-	-	-	-
Martensite phase steel grades	**draft EN 10338**	**SAE J2745**	**ASTM 1011M-07**	**JIS G 3134**	**JFS A 1001**	**China**	**India**
hot rolled	HDT1200M	-	-	-	-	-	-

- Often old short names in use
- In Europe EN standards obligatory
- In general only ‘best equivalence’ to other standards possible (JIS, SAE, ASTM, JFS,…)
- For the newest steel developments standards do not exist, only companies’ information can be cited

Modeling philosophies

Experimental data
- using the unprocessed experimental data (materials database)
- extrapolation by mathematical trend

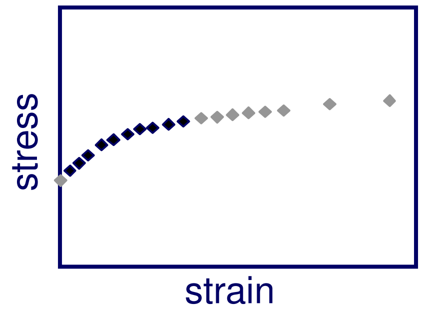
Empirical derived models
- e.g. flow stress functions
- parameter without physical meaning
- determination of parameters by fitting to experimental data of material

Continuum mechanics models
- physical interpretable parameters
- fitting of model parameters to experimental data of material

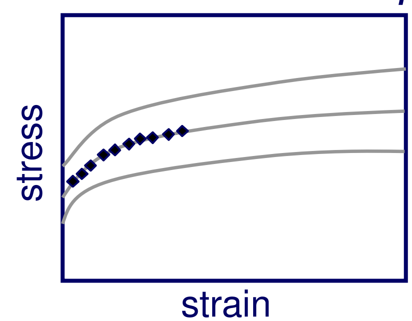
Microstructurally based models
- involving microstructure-related internal variables.
- determination of model parameter by certain set of experiments

Ab initio modeling
- applying quantum mechanics
- parameter-free determination

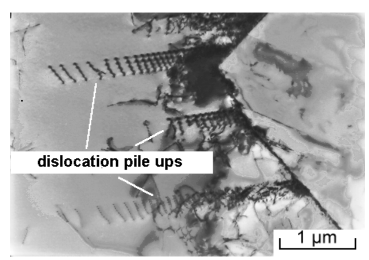
DATEN			
ZEIT <s>;	KRAFT <N>;	WEG <mm>;	BREITENAENDERU
0.0;	1.062636e+002;	0.0;	0.0
0.0;	1.015853e+002;	0.0;	0.0
0.0;	1.015853e+002;	0.0;	0.0
0.0;	1.973226e+002;	0.0;	0.0
0.0;	1.916418e+002;	0.0;	0.0
0.0;	1.857940e+002;	0.0;	0.0
1.953125e-002;	1.849586e+002;	4.952637e-005;	3.607978e-004
5.953125e-002;	1.839561e+002;	1.481264e-004;	-6.943555e-005
9.595312e-001;	1.904723e+002;	-7.475736e-004;	-4.480221e-005
1.059531e+000;	1.914748e+002;	-8.966403e-004;	3.460645e-004
1.679531e+000;	1.948164e+002;	-1.920274e-003;	2.654394e-004



Models represent macroscopic behaviour



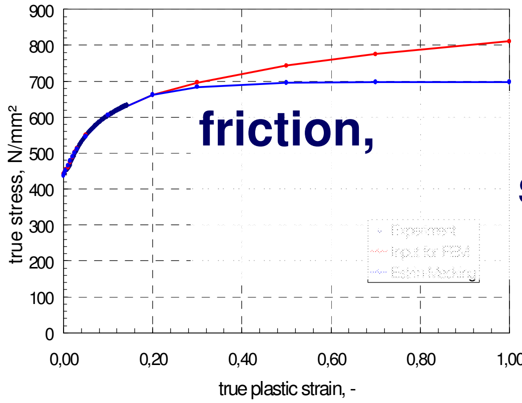
Models represent metal-physical mechanisms

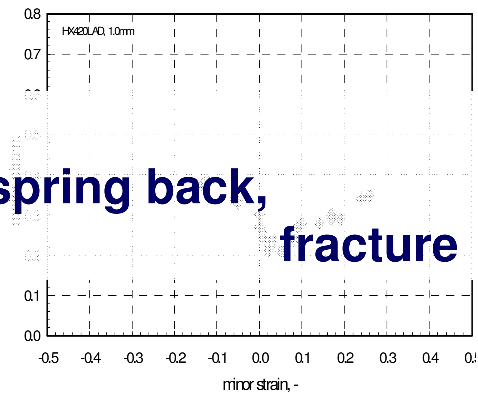


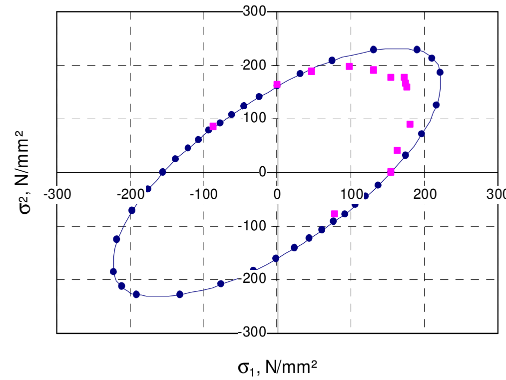
Cost-benefit conflict in material modeling

Forming

flow curve (quasi-static)
forming limit diagram
yield locus







friction,

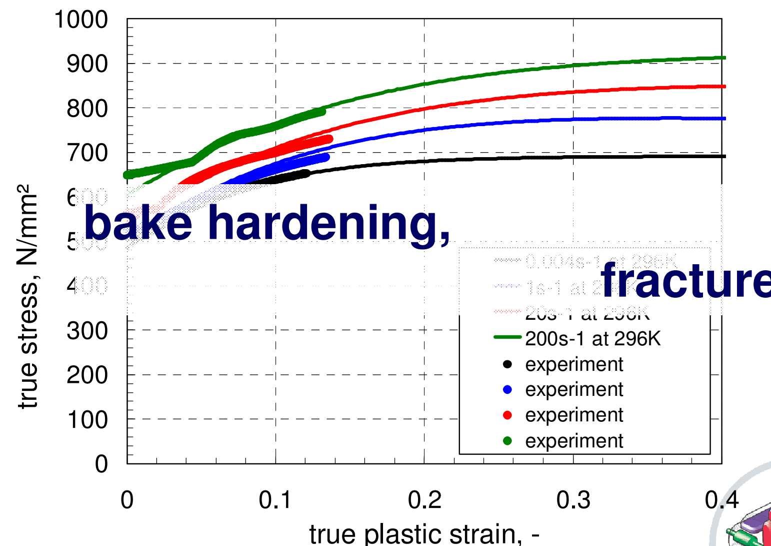
spring back,

fracture

Youngs-Modulus
Poisson ratio
anisotropy coefficient
friction coefficient
specific weight
specific heat capacity
...

Crash

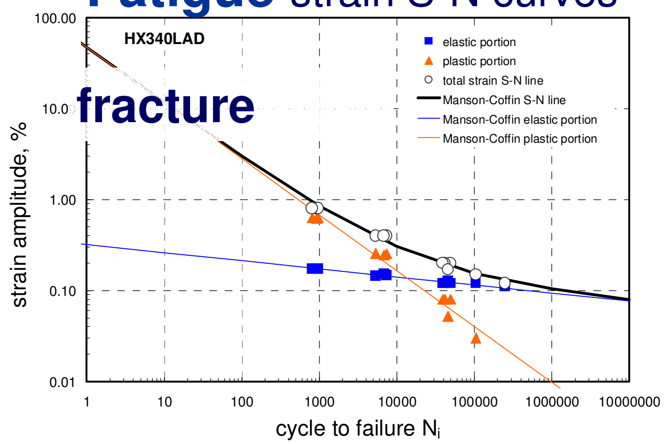
flow curves
(dynamic)



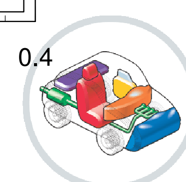
bake hardening,

fracture

Fatigue strain S-N curves

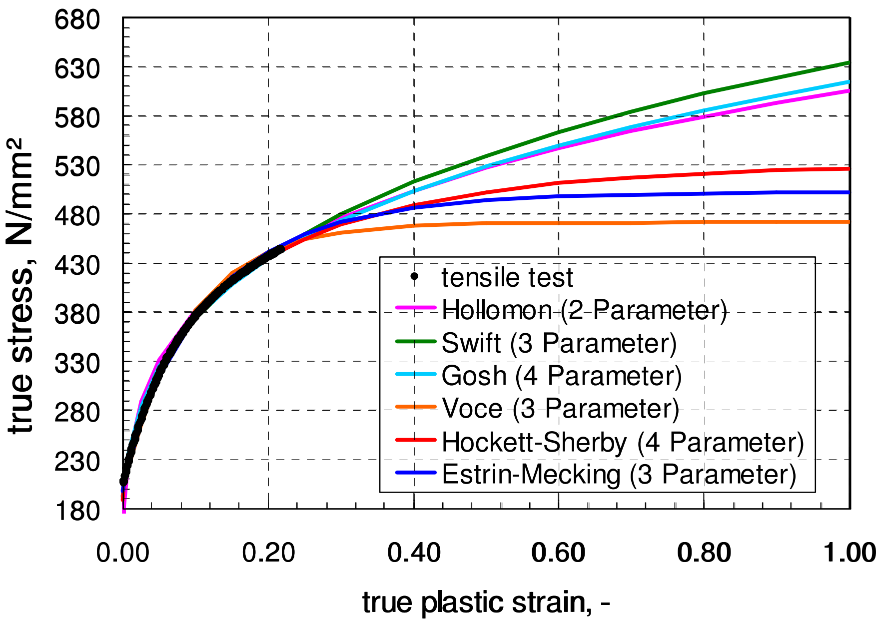


fracture



Empirical derived models for flow curves

tensile test quasi-static



$$Ludwik: k_f(\varphi) = \sigma_0 + C_L \cdot \varphi^{n_L}$$ (1909)

$$Hollomon: k_f(\varphi) = C_H \cdot \varphi^{n_H}$$ (1945)

$$Swift: k_f(\varphi) = C_S(\varphi_i + \varphi)^{n_S}$$ (1952)

$$Gosh: k_f(\varphi) = C_S(\varphi_i + \varphi)^{n_S} - D$$ (1977)

$$Voce: k_f(\varphi) = \sigma_S + (\sigma_i - \sigma_S) \cdot \exp\left(-\frac{\varphi}{\varphi_r}\right)$$ (1948)

microstructurally interpreted by Kocks-Mecking for coarse grain and single phase microstructure (1981)

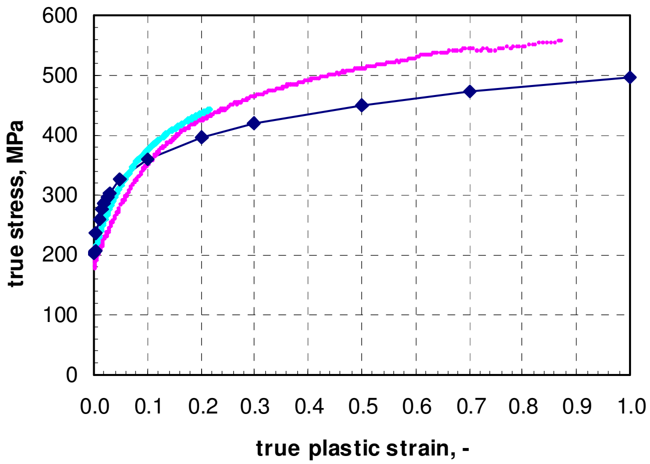
$$Hockett-Sherby: k_f(\varphi) = C_2 - (C_2 - C_1) \cdot \exp\left(-\frac{m_{HS} \cdot \varphi}{n_{HS}}\right)$$ (1975)

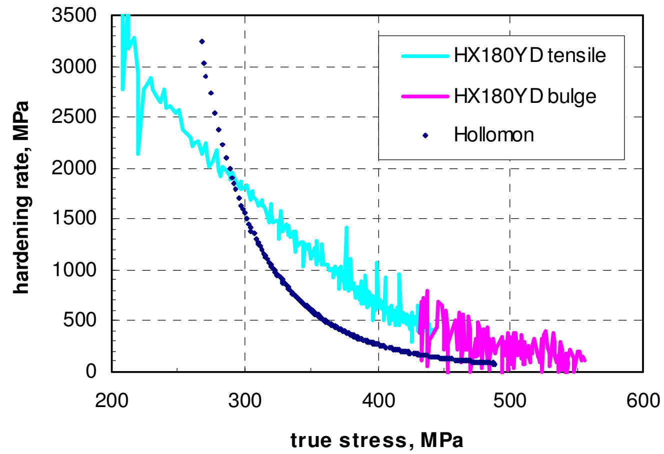
$$Estrin-Mecking: k_f(\varphi) = \sqrt{\sigma_S^2 + (\sigma_i^2 - \sigma_S^2) \cdot \exp\left(-\frac{\varphi}{\varphi_{r^*}}\right)}$$ (1984)

microstructural interpretation of Voce for fine grain or precipitation hardened single phase microstructure

Kocks-Mecking (Voce) and Estrin-Mecking are presented currently as modules of the One Internal Variable Model (OIVM)

Application of fitting functions to HX180YD

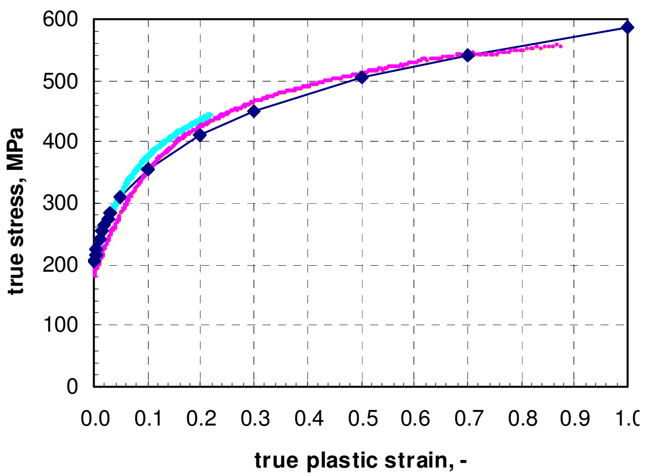


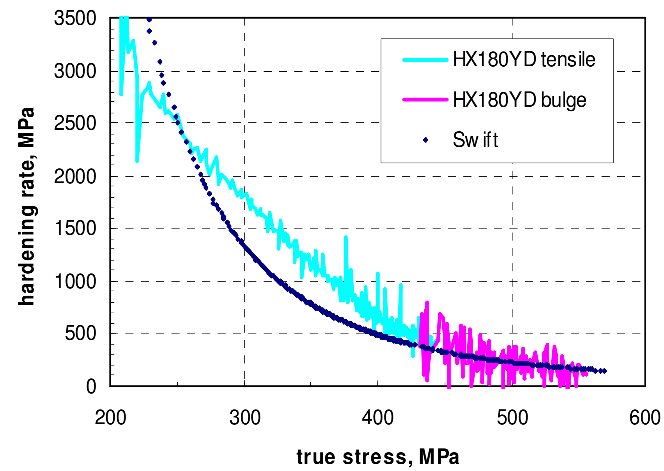


Differential quotient of tensile flow curve *dσ/dε versus σ*

Minimising sum of flow curve and hardening rate:

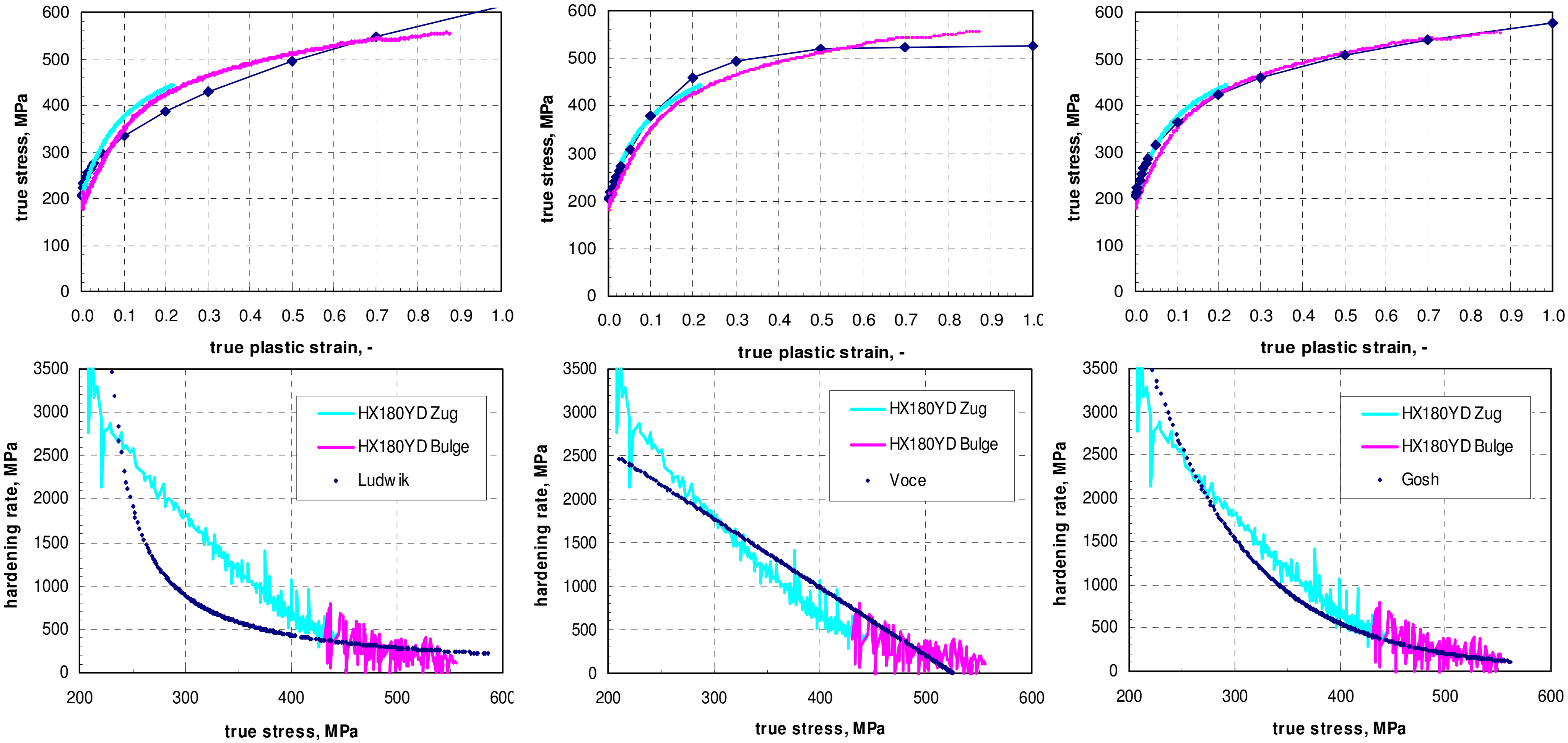
$$\sum_{i=1}^{n}(y_{i\_Experiment} - y_{i\_Modell})^2$$



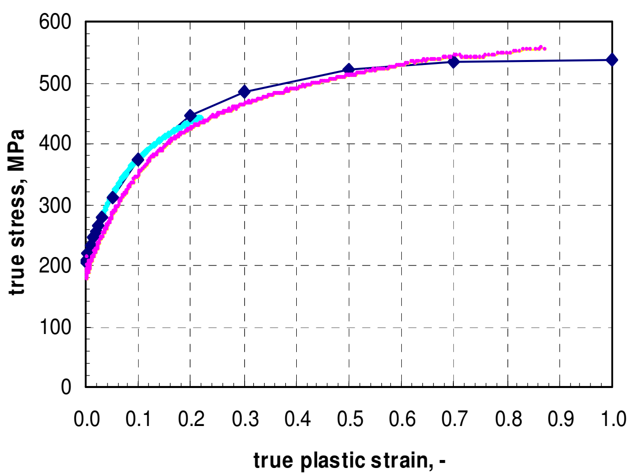


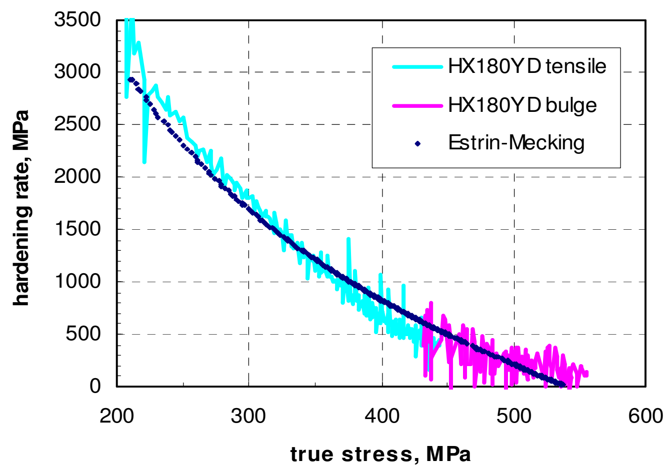
Constraints:
- experimental tensile curve is of priority
- stress at true plastic strain 0 is not lower than $R_{p0.2}$ (205MPa)

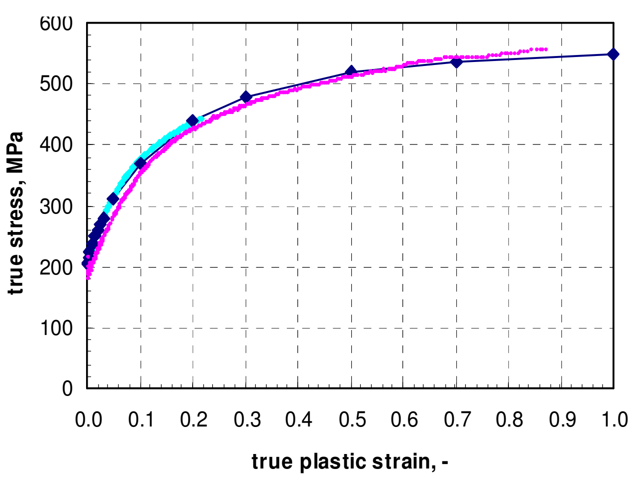
Application of fitting functions to HX180YD

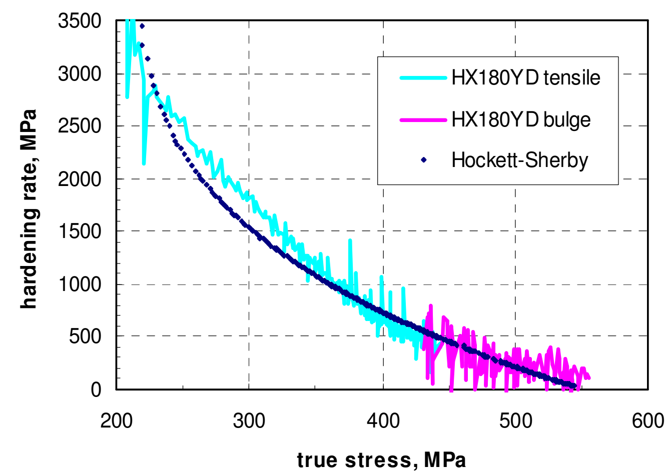


Application of fitting functions to HX180YD









Comments:

- best simultaneous fit to flow curve and hardening rate for models with 4 parameters (Hockett-Sherby or Gosh)
- best model working with 3 parameters is Estrin-Mecking; superior to Swift or Ludwik and similar to Gosh due to minimising criteria
- application of model using two parameters is difficult (Hollomon)
- if it comes to parameterise models for application of stochastic analysis then one may care for as less model parameters as possible

Cost assessment for basic testing

- **Chemical composition**
- **Metallography**
- **Tensile tests on sheet specimens**
  - longitudinal, transversal, diagonal
  - statistically reliable (e.g. according to SEP 1240)
- **Flow curve up to high strains**

⇒ 1000 - 1250€ for one material

Yield criteria families

Yield criteria

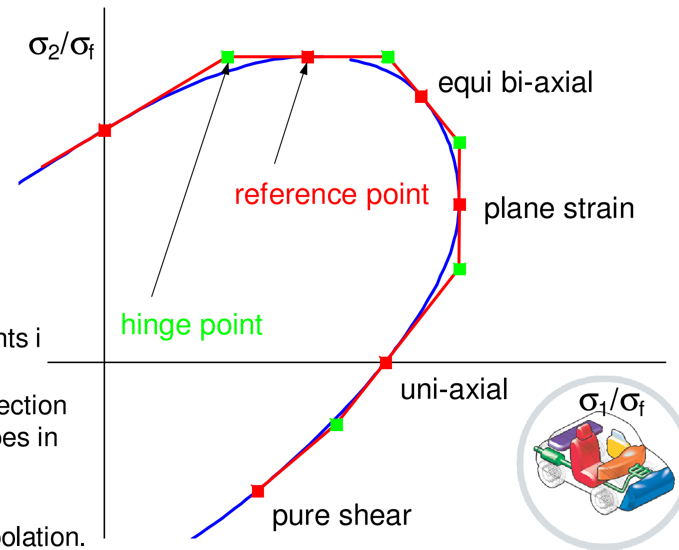
Hill's family	σ_0	σ_{30}	σ_{45}	σ_{75}	σ_{90}	σ_b	τ	r_0	r_{30}	r_{45}	r_{75}	r_{90}	r_b	A1	A2
Hill48	X							X		X		X			
Hill79	X					X		X						X	
Hill90	X		X		X	X				X				X	
Hill93	X				X	X	X	X				X		X	X
Chu95	X					X		X		X		X		X	
Lin, Ding96	X				X	X	X	X		X		X			X
Hu2005	X		X		X	X		X		X		X			X
Hosford's family	σ_0	σ_{30}	σ_{45}	σ_{75}	σ_{90}	σ_b	τ	r_0	r_{30}	r_{45}	r_{75}	r_{90}	r_b	A1	A2
Hosford79	X							X				X		X	
Barlat89	X						X	X				X		X	
Barlat91	X		X		X	X								X	
Karafillis, Boyce93	X		X		X			X		X		X		X	X
Barlat96	X		X		X	X		X		X		X		X	X
BBC2000	X		X		X	X		X		X		X		X	X
Bron-Besson2003	X		X		X	X		X		X		X		X	X
Barlat2003	X		X		X	X		X		X		X	X	X	X
BBC2003	X		X		X	X		X		X		X	X	X	X
Aretz-Barlat2004	X		X		X	X		X		X		X	X	X	X

A1: anomalous behavior of first kind
A2: anomalous behavior of second kind

Other yield criteria approaches

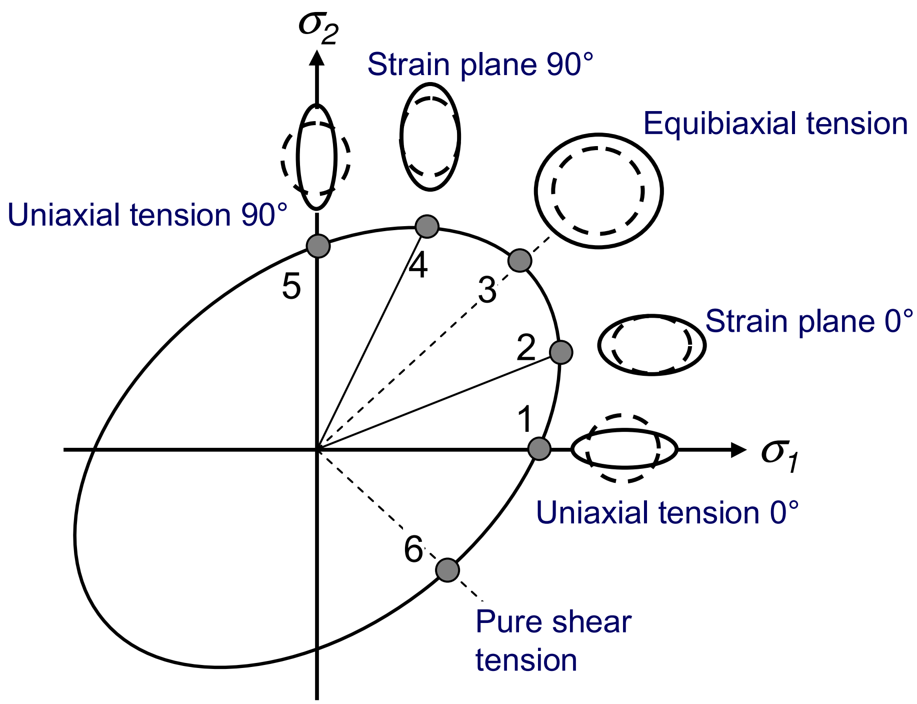
- **Budiansky (polar coordinates)**
- **Ferron (polar coordinates)**
- **Vegter (Bézier interpolation)**
- **...**

$$\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix} = (1-\lambda)^2 \cdot \begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_i^r + 2\cdot\lambda\cdot(1-\lambda)\cdot\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_i^h + \lambda^2\cdot\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_{i+1}^r$$



Second order interpolation between the reference points i and i+1 (here i= 1, 2, 3, 4).
Hinge points are the intersection points from the known slopes in these reference points.
Orientation dependency described via cosine interpolation.

Experimental data for describing yield loci



Point 1: σ_0

Point 2: $\sigma_1 = 2\sigma_2$ ($\varepsilon_2 = 0$)

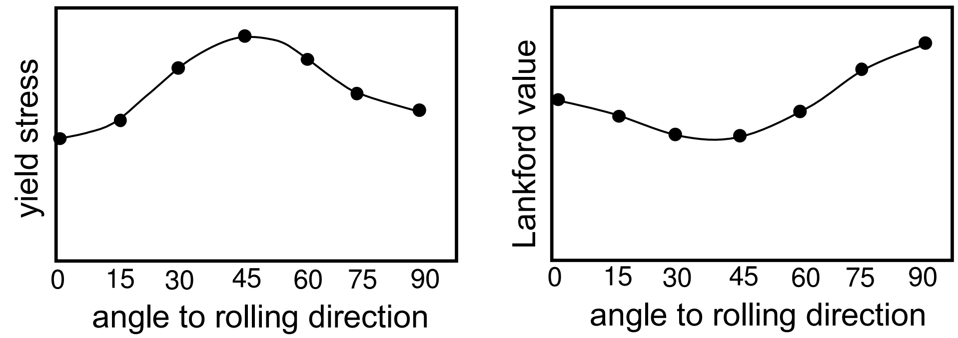
Point 3: $\sigma_1 = \sigma_2 = \sigma_b$

Point 4: $\sigma_1 = \sigma_2/2$ ($\varepsilon_2 = 0$)

Point 5: σ_{90}

Point 6: $\sigma_1 = -\sigma_2 = \tau$

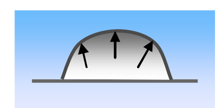
Tensile tests with different angle to rolling direction



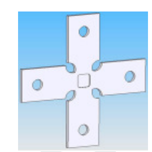
Tensile tests: r_0, r_{90}, r_{45}, (r_{15}, r_{30}, r_{60}, r_{75})

σ_0, σ_{90}, σ_{45}, (σ_{15}, σ_{30}, σ_{60}, σ_{75})

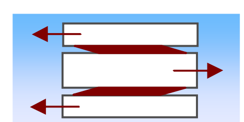
Hydraulic bulge test: σ_b



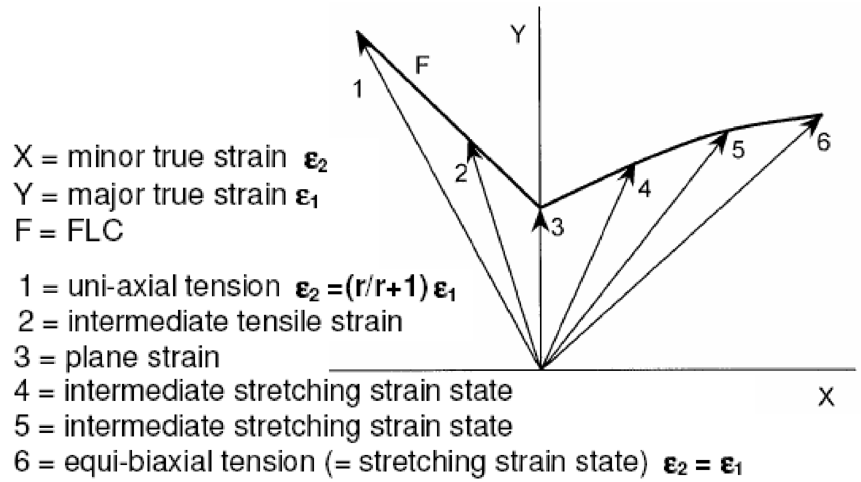
Biaxial tensile tests: σ_b, further biaxial stress combinations (σ_1 = x·σ_2)



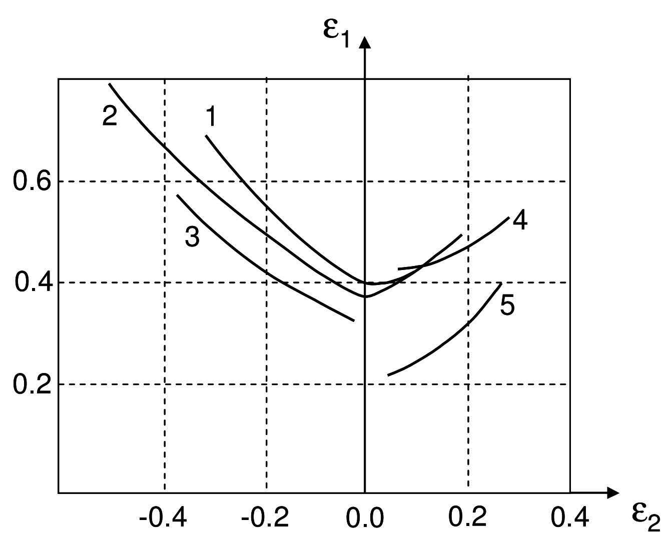
Shear test: τ



Determination of FLC



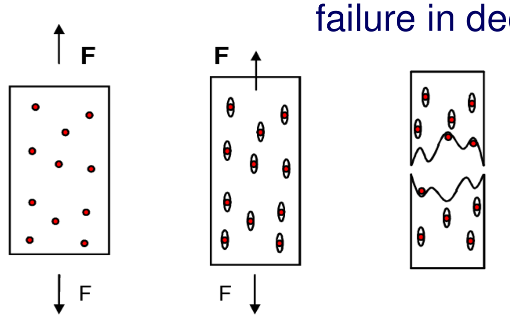
- **Uniaxial tensile test (3)**
- **Hydraulic bulge test (5)**
- **Punch stretching test**
- **Keeler test (4)**
- **Hecker test**
- **Marciniak test**
- **Nakajima test (2)**
- **Hasek test (1)**



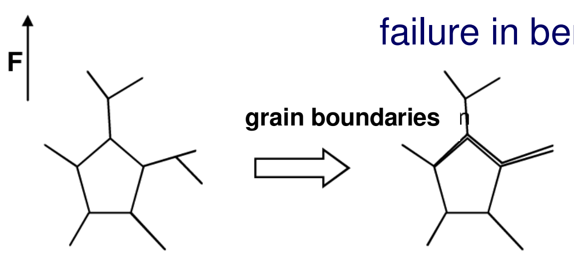
Forming seat tracks

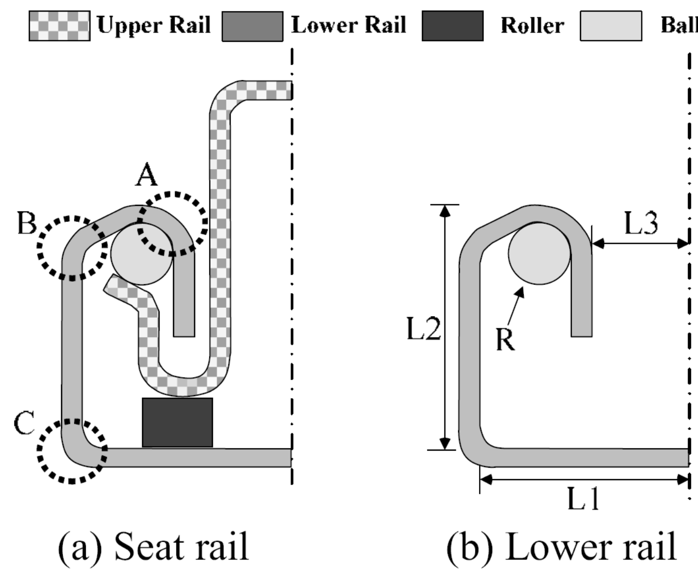
- Bending (bending limit curve, …)
- Spring back (Chaboche, Backhaus, Yoshida, …)
- Failure (Gurson, EWK, CrachFEM, …)

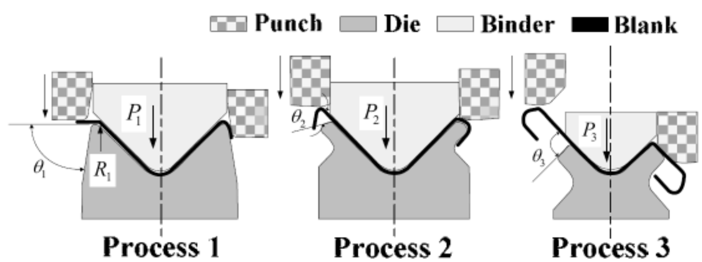
failure in deep drawing



failure in bending



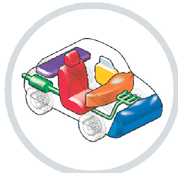




Cost assessment for advanced testing

- **Chemical composition**
- **Metallography**
- **Tensile tests on sheet specimens**
  - longitudinal, transversal, diagonal
  - statistically reliable (e.g. according to SEP 1240)
- **Flow curve up to high strains**
- **Plane strain and shear**
- **Forming limits**
- **Hole expansion and bending**

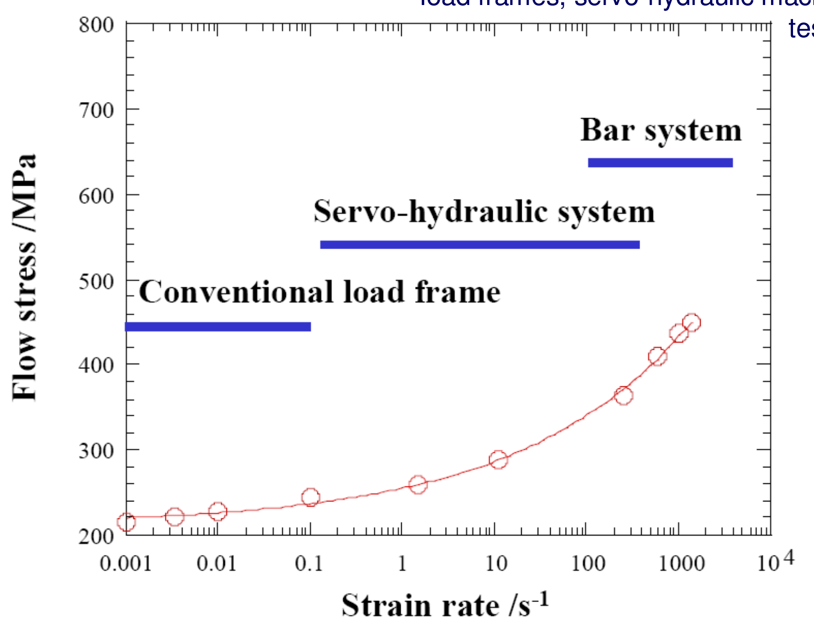
⇒ 5000 - 7000€ for one material



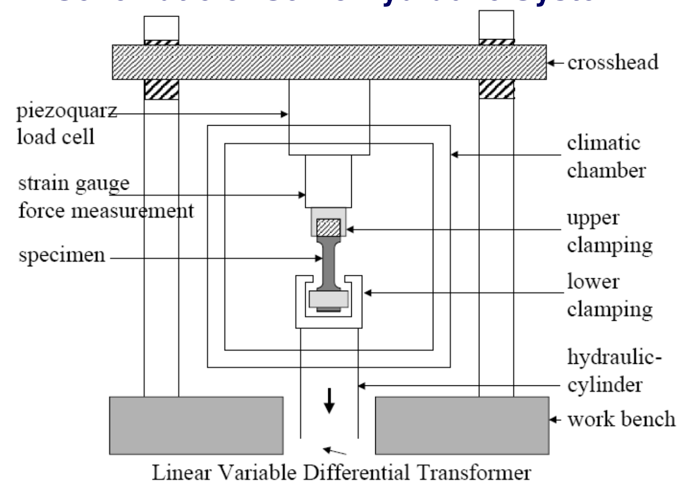
Dynamic tensile testing for crash

Specific requirements needed for load measurement, direct measurement of strain and specimen geometry

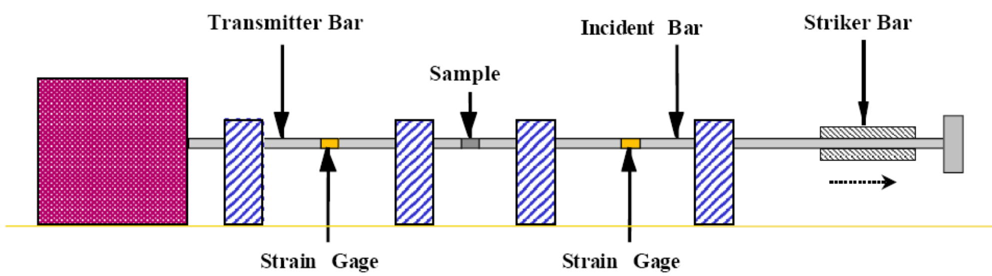
Typical ranges of strain rate covered by conventional load frames, servo-hydraulic machines and bar testing systems



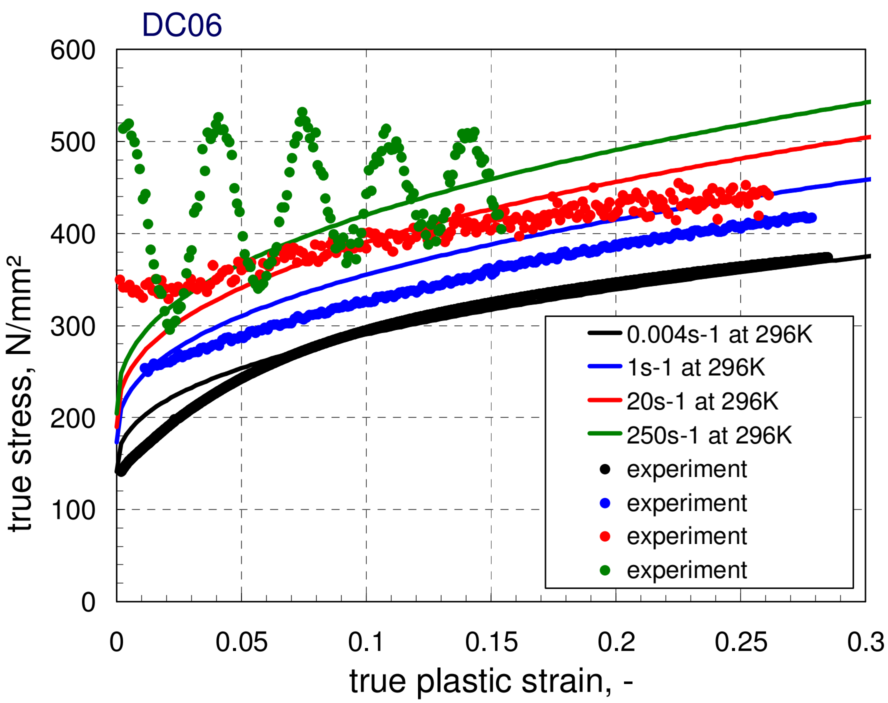
Schematic of Servo-hydraulic System

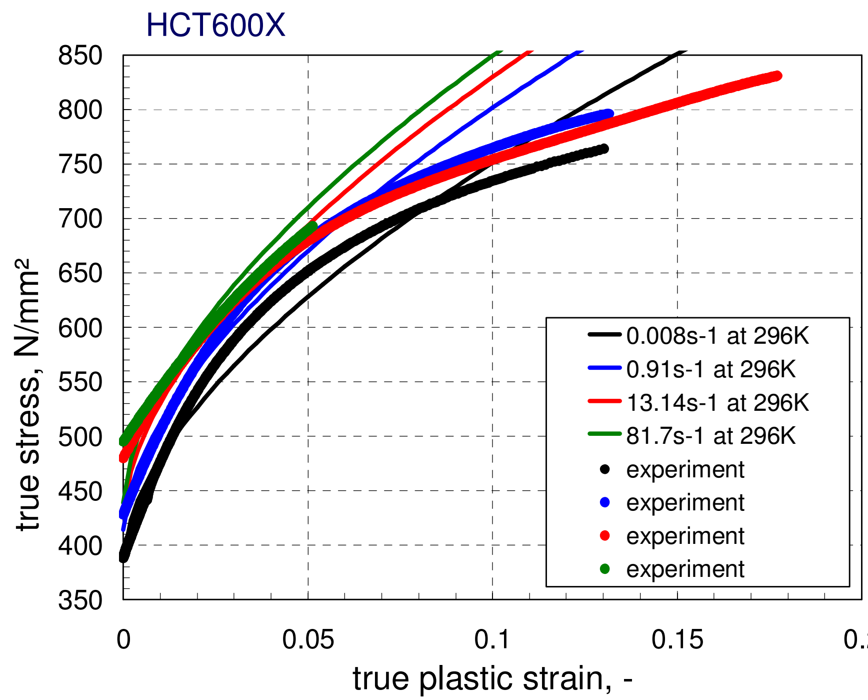


Schematic of tensile Split Hopkinson Bar System



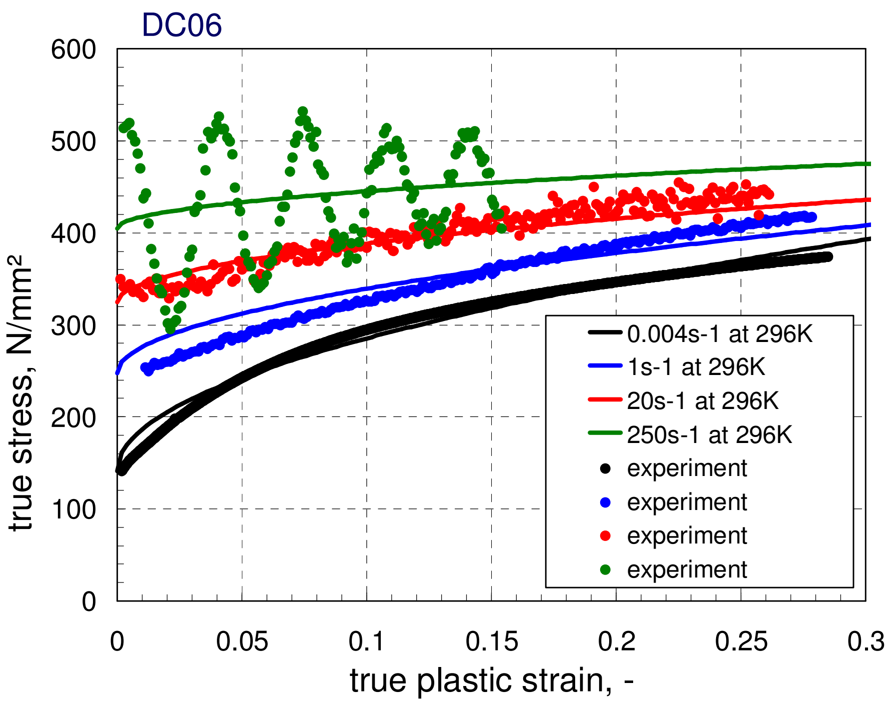
Johnson-Cook

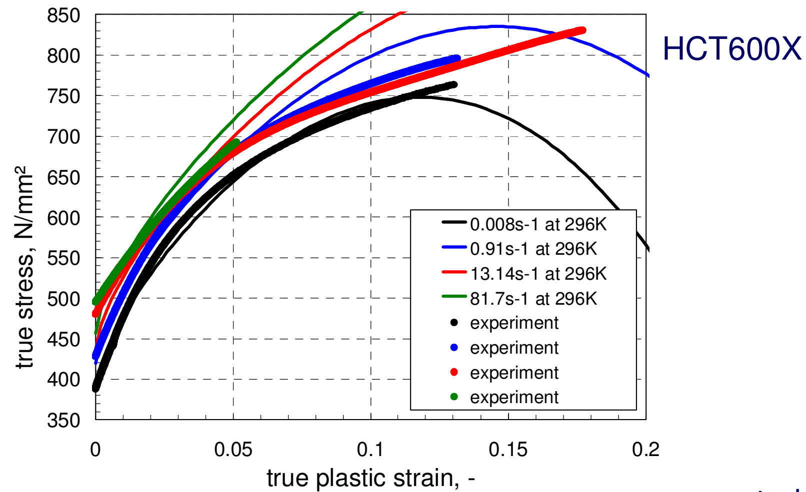


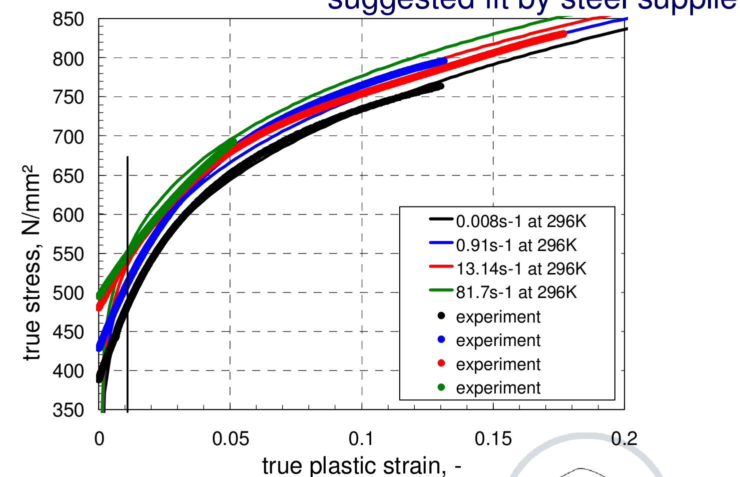


$$\sigma = \left(\sigma_0 + C_1 \varepsilon^n\right)\left(1 + C_2 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right) \quad (1983)$$

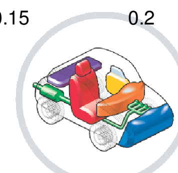
Tanimura



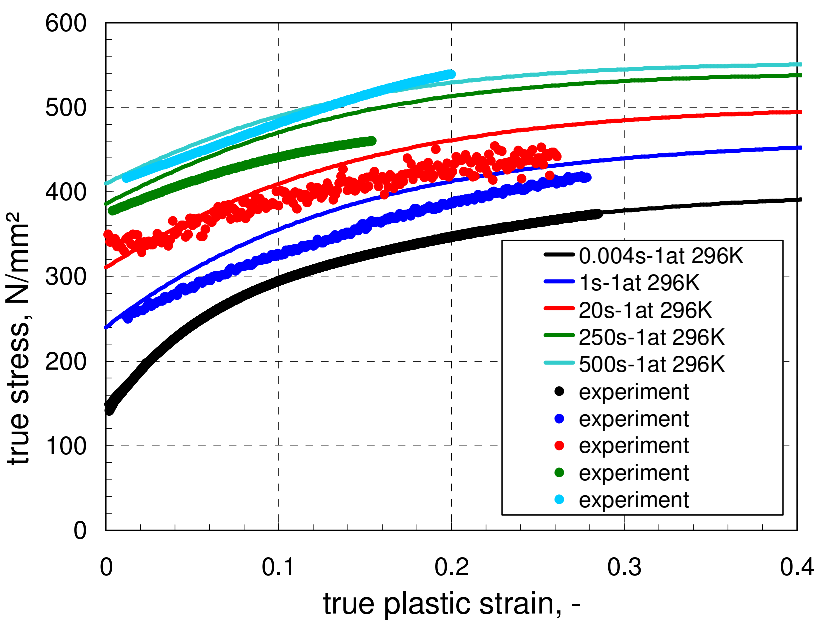


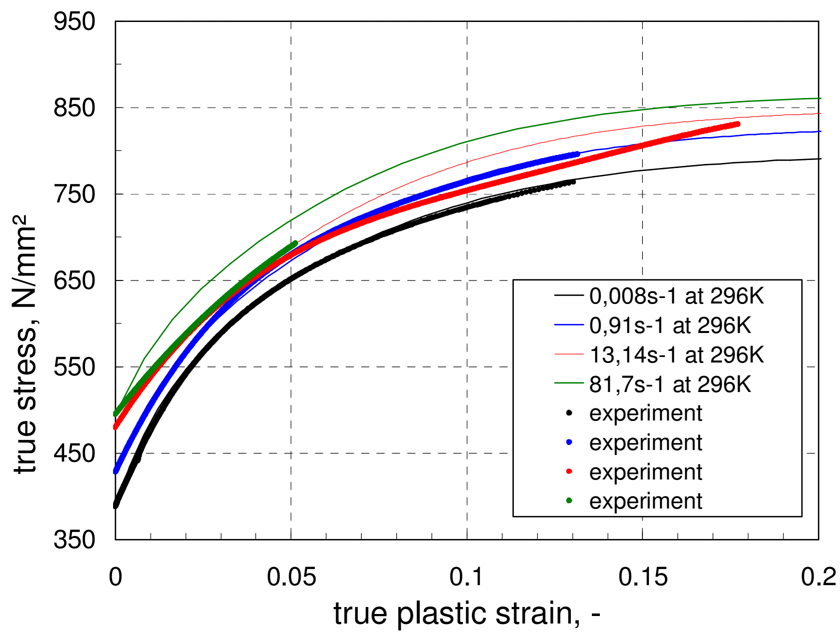


$$\sigma = \left(A + B \cdot \varepsilon^{n}\right) + \left(C - D\varepsilon^{m}\right)\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) + \left(E\dot{\varepsilon}^{k}\right) \text{ (1992)}$$



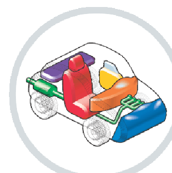
One Internal Variable Models (OIVM)



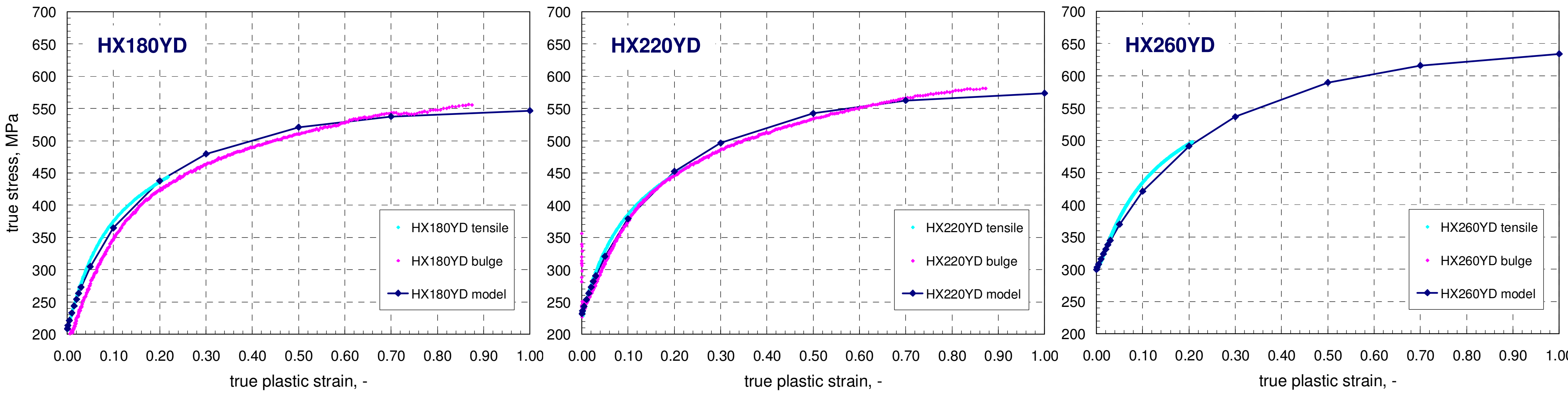


Estrin-Mecking
extended by heat effects

Hybrid model extended by dislocation self organisation, two-phase description and heat effects



Identifying family parameters for OIVM



HX180YD, HX220YD and HX260YD by Estrin-Mecking:

Model constants:

Taylor factor *M*:	3
Numerical constant α:	0.5
Shear modulus *G*:	80769 MPa
Burgers vector *b*:	2.5 $\times 10^{-10}$m
Normalising strain rate ε_0:	1000s^{-1}

Material parameters to adjust:

Grain size *d*

Recovery factor k_{20}

Exponent *n*

Exponent *m*

Family parameters determined:

a and b for *d*

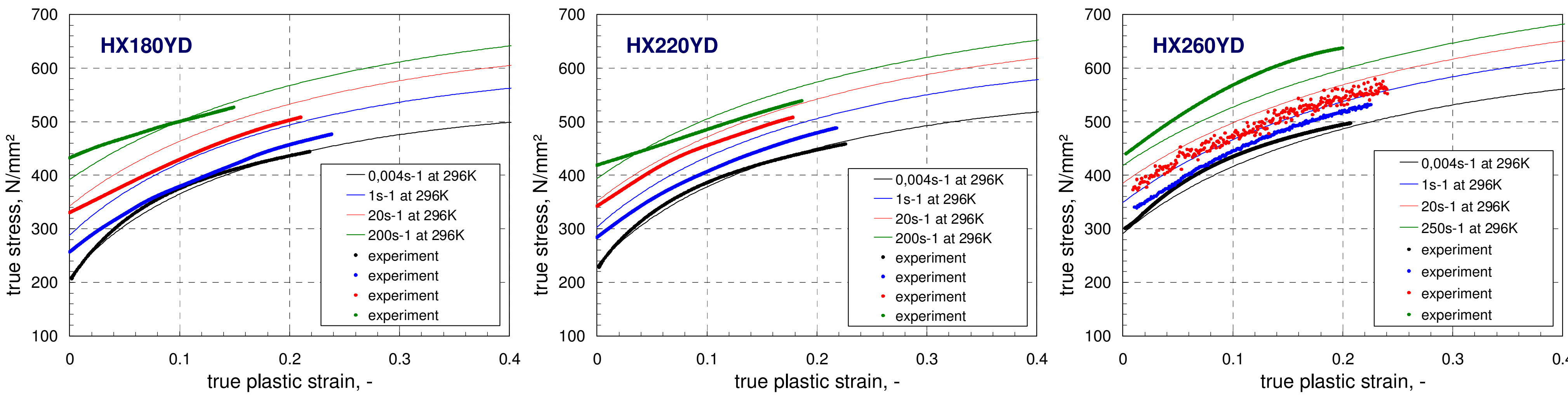
c and d for k_{20}

e and f for *n*

g and h for *m*

and use of yield strength for each alloy

Application of family parameters



Family parameters determined:

a and b for *d*

c and for k_{20}

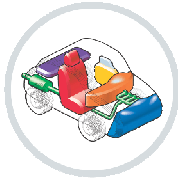
e and f for *n*

g and h for *m*

and use of yield strengths for each alloy

Heat conduction parameters:

Heat transfer parameter β:	0.018s^{-1}
Specific heat capacity c_{spec}:	477 Nmkg^{-1}K^{-1}
Material density d_{dens}:	7800 kgm^{-3}
Heat dissipation factor χ:	1



Other models for strain rate dependence

- Extended Hollomon
- Cowper-Symonds
- 10 Parameter model
- Bergström
- Zerilli-Armstrong
- Mechanical Threshold (MTS)
- …

Cost assessment complete process chain

- **Formability testing: 5000 – 7000€**
- **Strain rate dependence of material**

⇒ 10.000 – 15.000€ for one material

(plus joinability testing and evt. fatigue testing)

General questions

- **How to come from the material testing to the models of choice?**
- **How to ensure reliable FEM input data worldwide?**
- **How to deal with the customer diversification?**

Potential criteria for model choice

- Accuracy of model prediction proved by simulating standard material tests by FEM
- Number of model parameters
- Financial efforts for the material tests to determine the model parameters
- Number of materials the model chosen is applicable to
- Modular character of model
- Level of commercialisation
- …