The Need For Improved Metal Forming Simulation Material Cards

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GREAT DESIGNS IN STEEL™

About Me

The Johns Hopkins University (1984-1987) – BS, Materials Science and Engineering

Drexel University (1987-1991) - MS and PhD, Materials Engineering (Alloy Development of P/M HSS)

LTV Steel (1991-2001) - Manager of Automotive Market Development Group

Danny Schaeffler

Engineering Quality Solutions (2002-now) - consulting & training in sheet metal forming

Core competence: Product applications assistance to materials & manufacturing companies

Focus – Hands-On: Materials selection/ optimization, tooling buyoff, field formability analyses, stamping failure troubleshooting, manufacturing process improvement, and cost savings / cost avoidance projects. Sheet metals: mild, high strength, advanced high strength and stainless steels, aluminum, titanium, others

Focus – Education: Teaching the fundamentals and practical details of material properties, forming technologies, processes, and troubleshooting skills needed to reliably form high quality components

Market: Global, primarily North America, Europe, and Asia

Author of **MetalForming Magazine's Science of Forming / Metal Matters Columns** 2017 - 2023

Technical Editor for **Metallurgy and Forming, AHSS Application Guidelines**, AHSSinsights.org

Lead content creator and presenter on metallurgy and formability for WorldAutoSteel, Auto/Steel Partnership, and Precision Metalforming Association

Disclaimer

Generalized statements made in this presentation
may not be applicable to all simulation software packages
and even versions/releases of each software.

Consult your simulation software provider for specific
performance characteristics, capabilities, and input requirements
pertinent to your steel grades and forming processes.

Goal

GDIS

Art – to – Part

But for real this time …

First,
Achieve successful simulation
over the range of allowable properties
AND tolerances within processing conditions

Then,
Build tools to the simulation file
and run home-line production immediately with no tryout

What are Material Cards?

What it’s supposed to be:

A mathematical representation of how that grade will flow and fail

What it actual is:

Snapshot of one set of tests,

but …

does not capture all of the parameters that impact stamping success

does not capture the variation of properties expected over the life of the stamping

Where Do Cards Come From?

GDIS

Material library within given software

Provided by metal producer or OEM

Cards based on simple (and maybe incorrect or sub-optimized) assumptions

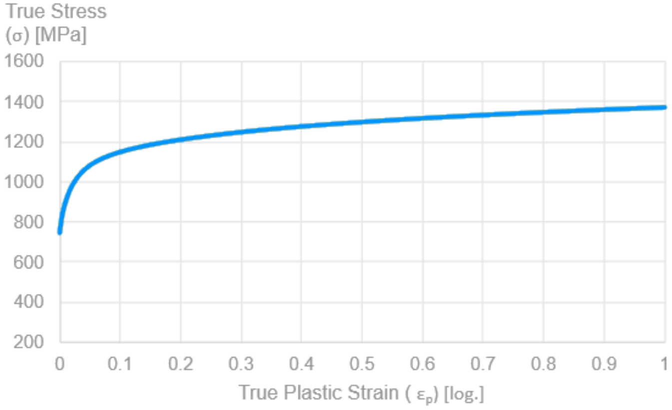
Experimental cards determined from samples taken from one coil

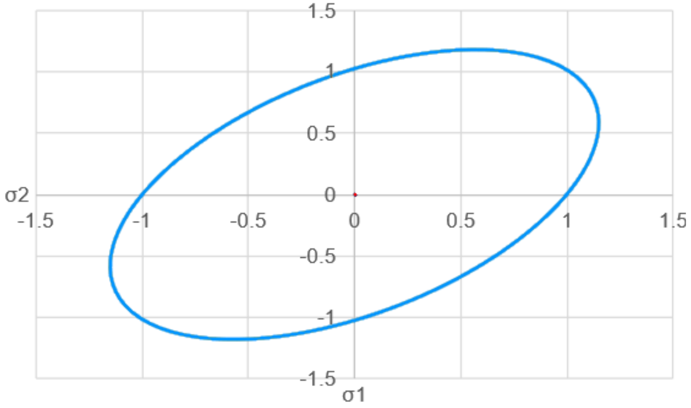
- From tensile test and models/correlations
- From a full spectrum of testing

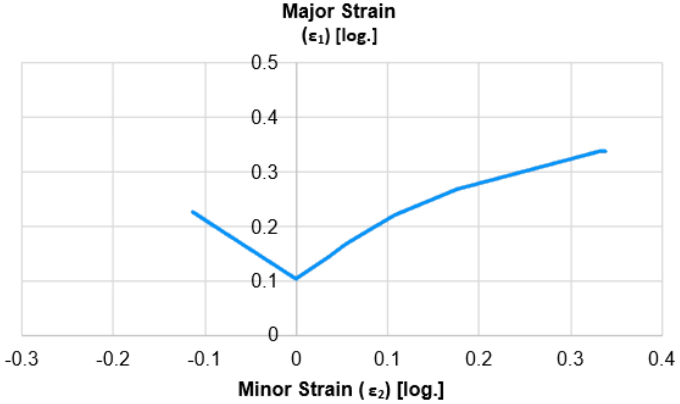
There is no standard or metric to measure the “quality” of a card

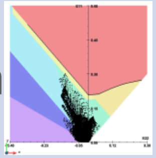
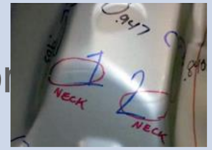
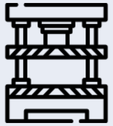
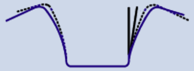
The material card name does not provide insight on the tests or assumptions baked into the card

Minimum Inputs Into A Material Card



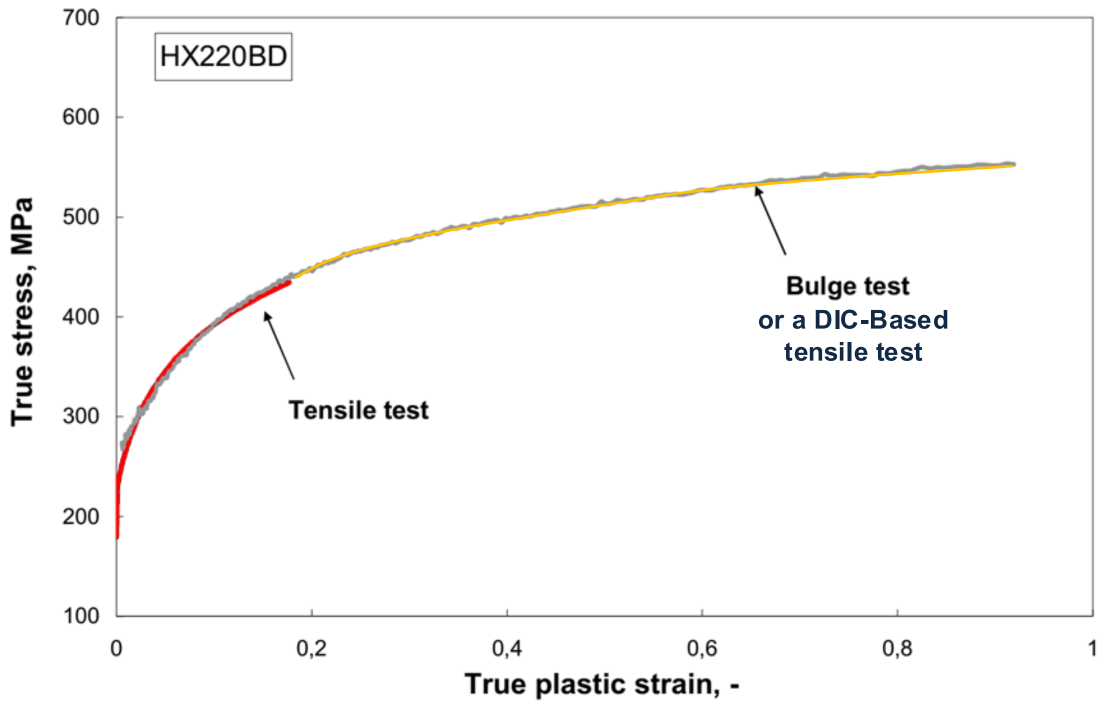


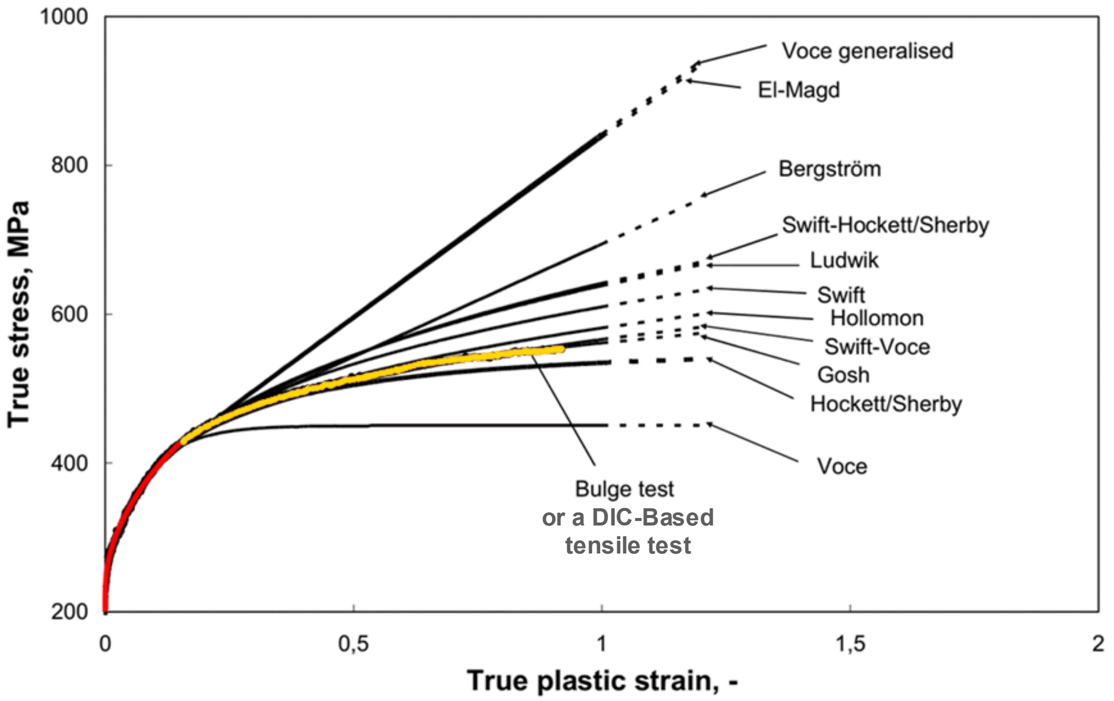


	Hardening Curve	Yield Surface	Forming Limit Curve (FLC)
Importance	Necking initiation 	Strain distribution 	Necking initiation 
	Press Tonnage 		
	Springback 		

Inputs Affect Quality

Hardening Curve: How a Metal Strengthens





Hardening curve needs to be extrapolated until true plastic strain = 1,

but traditional extensometer-based tensile test data is valid only through uniform elongation

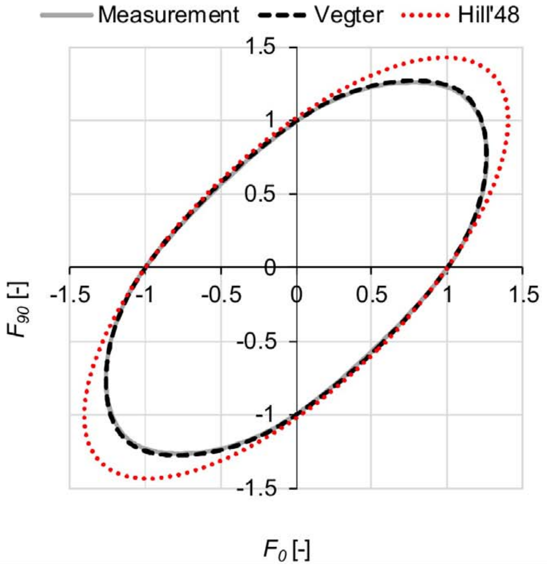
Either DIC-based tensile data or bulge testing extends the curve and reduces need to extrapolate

Which model should we select? Choice impacts prediction of necking initiation, press tonnage, & springback

Images: P. Larour, “Strain rate sensitivity of automotive sheet steels: influence of plastic strain, strain rate, temperature, microstructure, bake hardening and pre-strain,” Doctoral Dissertation, 2010, IEHK RWTH Aachen University, ISBN 978-3-8322-9149-5.

Yield Surface

Defines how the material deforms in multi-axial loading

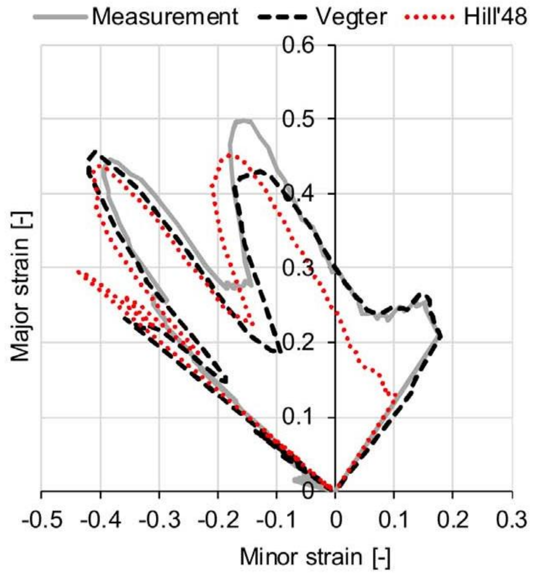


<u>Model selection and input data significantly affects:</u>

Major/Minor strain distribution (FLD & failure criterion)

Draw-in

Thinning

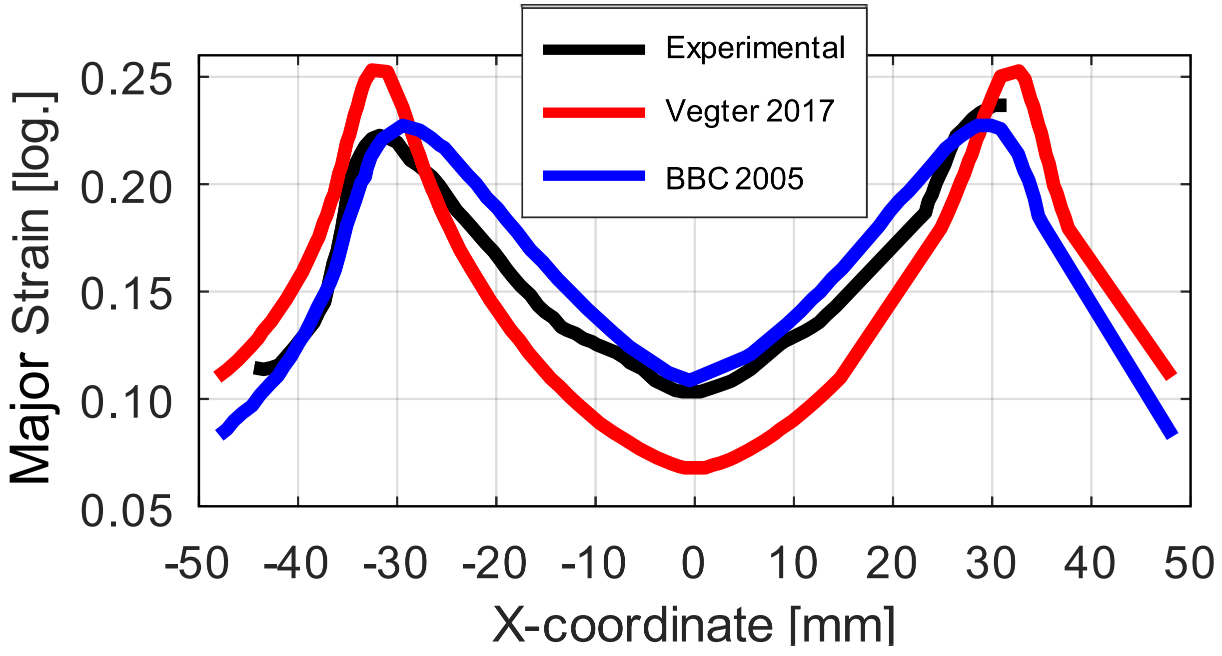


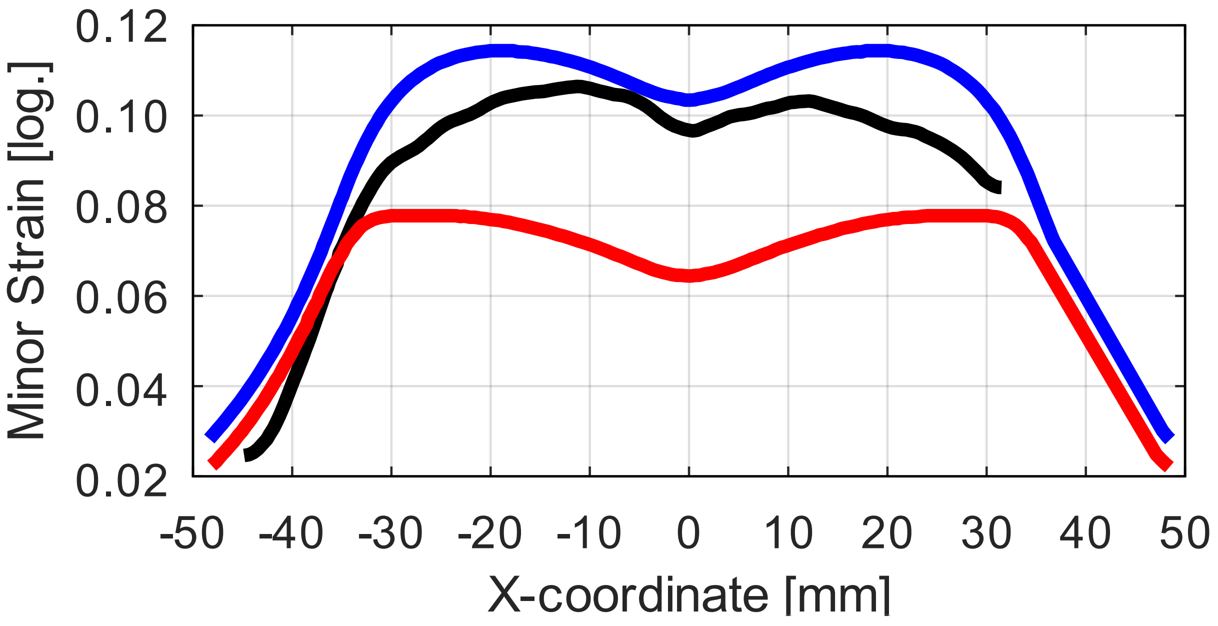
Images: M. Abspoel, M.E. Scholting, M. Lansbergen, Y. An, H. Vegter (2017) A new method for predicting advanced yield criteria input parameters from mechanical properties. Journal of Materials Processing Tech. 248, pp. 161–177, https://doi.org/10.1016/j.jmatprotec.2017.05.006

Yield Surface: Tests Required

Tests required (List by complexity)	Tensile Test			Bulge Test	Shear Test			Plane Strain Test		
	L (0°)	D (45°)	T (90°)		L (0°)	D (45°)	T (90°)	L (0°)	D (45°)	T (90°)
von Mises 1913										
Hill 1948										
Barlat 1989										
Vegter Lite 2011 (6p)										
Vegter 2017										
Vegter Lite 2011 (8p)										
BBC 2005 8p										
Vegter 2006 (Full)										

Why Do We Need Biaxial Data?





Black curve: Experiments

Red curve: Vegter 2017 → determined by LTD uniaxial tensile bars only

Blue curve: BBC 2005 (8p) → includes biaxial data along with LTD uniaxial tensile bars ✓

Plots recreated by E. Billur, Billur Metal Form, after H. Bentsrud, "Friction and material modelling in Sheet Metal Forming Simulations," Master of Science in Mechanical Engineering Thesis, May 2020, Blekinge Institute of Technology, Sweden; https://www.diva-portal.org/smash/get/diva2:1439839/FULLTEXT01.pdf

Obtaining Forming Limit Curves

Keeler – developed in 1961 for mild steels and most HSS, but should be avoided in most AHSS

- Correlation based on n-value and thickness only
- Independent of tensile specimen type
- Equations are publicly available

Arcelor V9 or Cayssials – developed in 2007 for HSS, AHSS and aluminum

- Independent of tensile specimen type
- Correlation based on transverse uniform elongation and tensile strength
- The equations are ***not*** publicly shared → They are confidential to Arcelor and AutoForm

Tata Steel or Abspoel-Scholting – developed in 2012, works for steel/aluminum/stainless

- Requires experimental tensile test data from ***ISO Type 2 (DIN 20 x 80) specimen***.
- Correlation based on total elongation in longitudinal, transverse, and diagonal orientations
- Developed with grades available in 2012, but still a correlation
- Equations are publicly available

Experiments – ASTM standard (E2218) and more common ISO experiments (12004-2)

- Can be applied to all materials (Steel, HSS, AHSS, Aluminum, Titanium, Superalloy, etc.)
- Multi-days testing, (much) more expensive than tensile testing

Going Beyond a Basic Material Card

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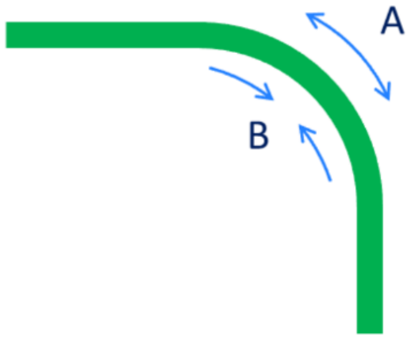
Costly

Time-consuming

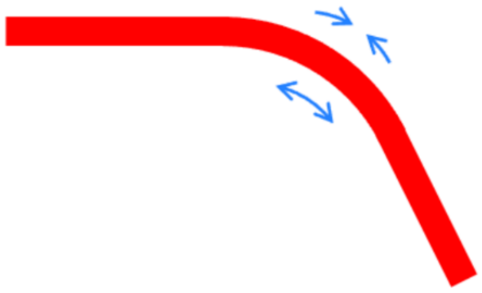
… and absolutely necessary to accurately model material flow
to go from Art – to – Part

Kinematic Hardening:
Incorporating Complexities of Real-World Behavior

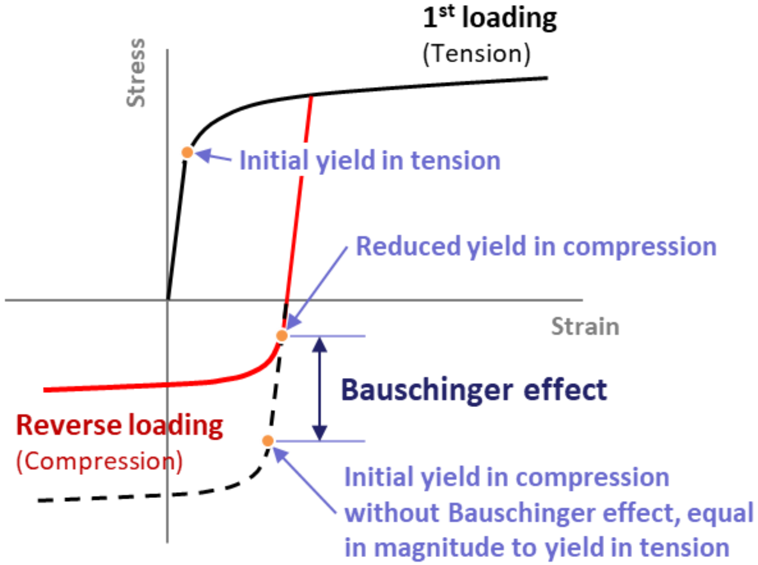
GDIS



Under Load:
Side A is in tension;
Side B is in compression



After springback



During bending-unbending over a drawbead or die radius, stress reversals through the sheet thickness results in yielding at lower stress levels.

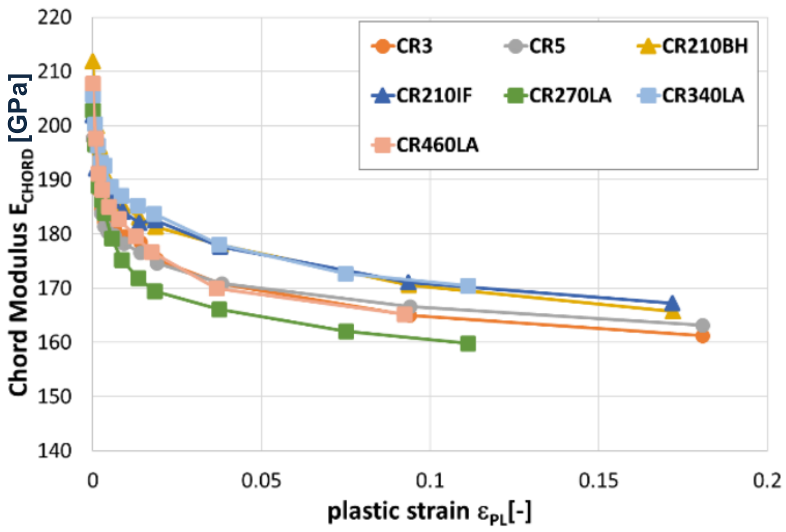
This is called the Bauschinger effect.

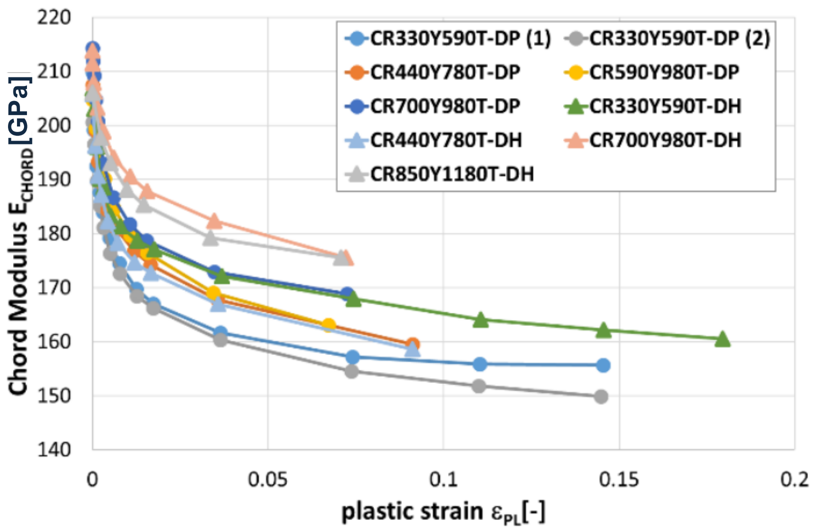
Kinematic Hardening:
Incorporating Complexities of Real-World Behavior

Young's Modulus is constant for each metal: 207 GPa for all steel grades

Nope - there is variation between grades (197 to 217 GPa in study below)

AND modulus also decreases as strain is applied to the part, primarily as the sheet bends and unbends as it goes over draw beads or moves over radii





Without KH and with constant modulus: springback angle = 36.9°

With KH and variable modulus: springback angle = 60.7°

Experiments: springback angle = 60.5° ± 1.2°

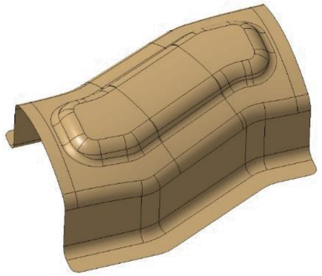
L. Wagner, M. Wallner, P. Larour, K. Steineder and R. Schneider, "Reduction of Young's Modulus For A Wide Range Of Steel Sheet Materials and Its Effect During Springback Simulation," IDDRG 2021, IOP Conf. Series: Materials Science and Engineering, 1157 (2021), 012031, doi.org/10.1088/1757-899X/1157/1/012031.

Why Bother with Kinematic Hardening?

Capturing kinematic hardening improves the ability to predict formed part dimensions

Goal: sim within ± 1 mm of physical scanned panel

3rd Gen Steel with 980MPa Tensile:



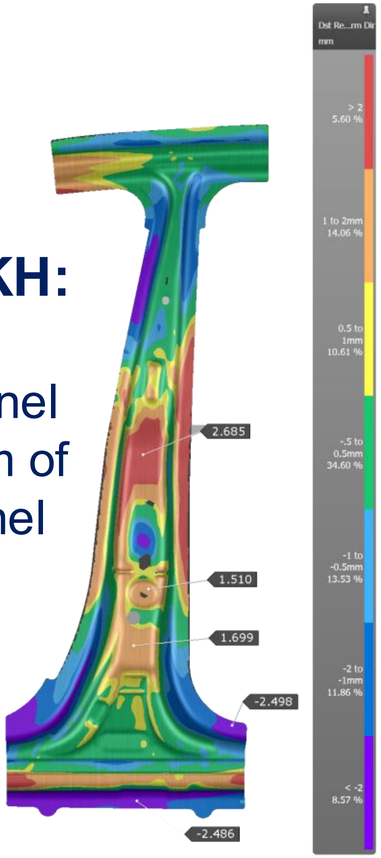
WITHOUT KH: 48% of simulated panel
within ± 1 mm
of physical scanned panel

WITH KH: 94% of simulated panel
within ± 1 mm
of physical scanned panel

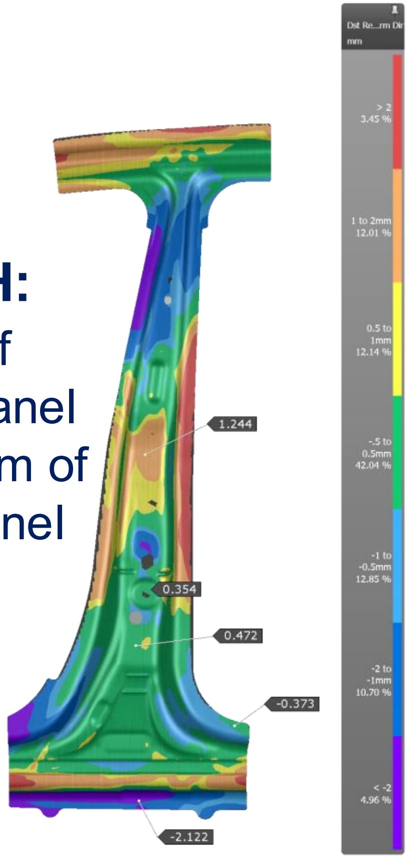
“Multi-Level Material Cards For Sheet Metal Forming Simulations,” presented by Billur and Karşı at the 2022 Great Designs in Steel Symposium sponsored by AISI.

3rd Gen Steel with 1180MPa Tensile

WITHOUT KH:
59.9% of
simulated panel
within ± 1 mm of
scanned panel



WITH KH:
68.9% of
simulated panel
within ± 1 mm of
scanned panel



“Characterization of 3rd Gen AHSS Towards Reliable Forming And Springback,” presented by K. Kannan at the 2022 Great Designs in Steel Symposium sponsored by AISI

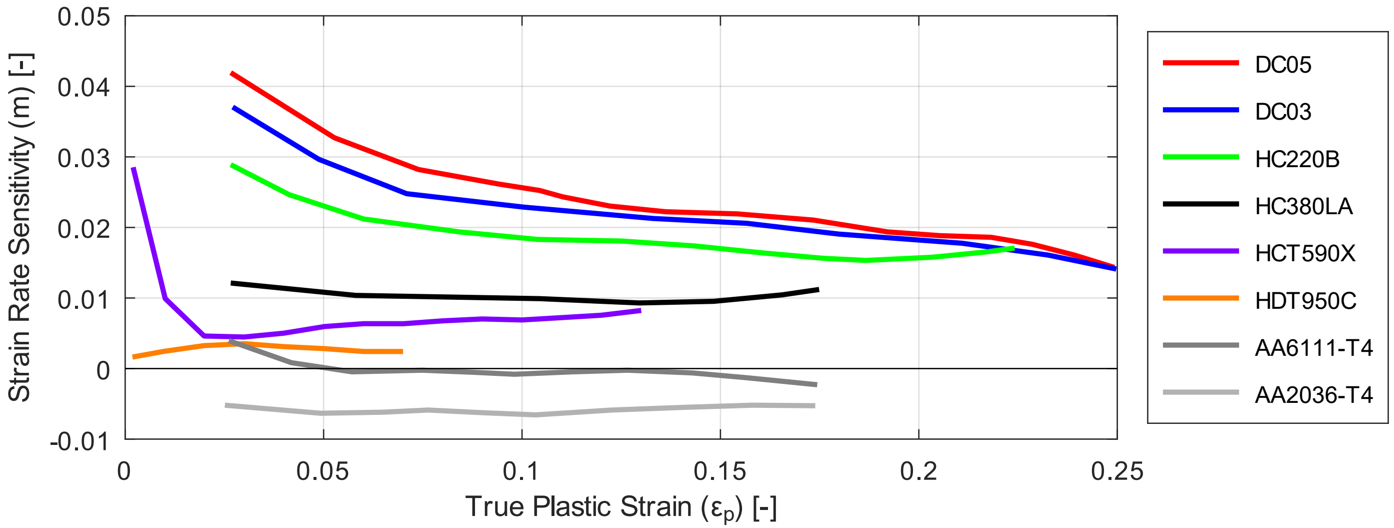
Strain Rate Sensitivity (m-value)

Many materials show strain rate sensitivity:
some strengthen when deformed faster (m>0); others strengthen when deformed slower (m<0)

Strain rate in stamping is ≈1000x the strain rate during tensile testing

Typically entered into simulation software as a single number, aka constant "m-value"

Even though m-value may be negative, most software cannot accept negative m-value



Friction

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Friction is a function of
contact pressures, sliding velocities, orientation, and test temperature

Friction Models	Software 1	Software 2	Software 3	Software 4
Constant number				
Function of pressure				
Function of velocity				
Function of p and v				
Function of direction				
Function of d and v				
Function of d and p				
Function of d, p and v				

Temperature adds complexities to the testing

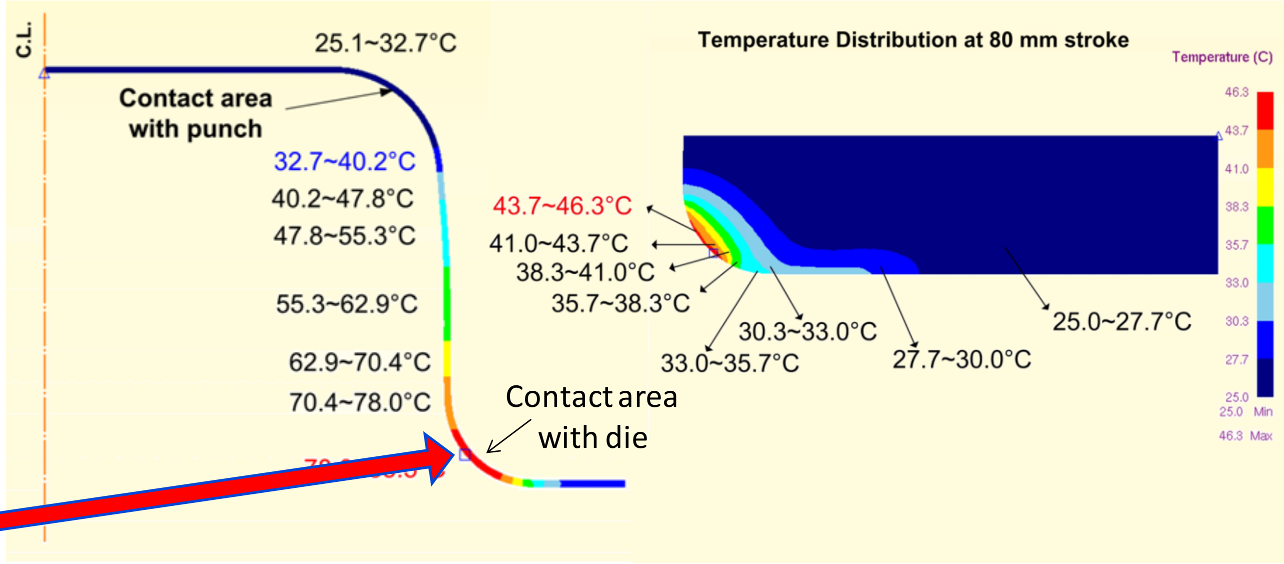
Temperature:
Heat from Plastic Deformation and Contact Friction

GDIS

Heat from plastic deformation only

(friction not considered)

Material	Max Temperature	
Mild Steel	50 °C	120 °F
DP600	80 °C	175 °F
DP980	100 °C	210 °F
DP1180	150 °C	300 °F
Aluminum 5182-O	80 °C	175 °F



Courtesy of A. Fallahiarezoodar and T. Altan, Center for Precision Forming, Ohio State University

Failure Does Not Necessarily Mean Fracture

FLC predicts necking failure only

- Good enough on traditional grades since necking occurs before fracture
- New grades might fracture before necking → FLC cannot be used for fracture!

Fracture models are designed to predict cracking fracture

- Surface Cracks
- Shear Cracks
- Edge Cracks

Each software package has a different approach

	Software 1	Software 2	Software 3
Bending ratio (Surface Crack)			
Max. Shear Strain (Shear Crack)			
Max. Edge Strain (Edge Crack)			
Element Deletion (Surface & Shear Crack)			
Triaxial Failure Curve (Surface & Shear Crack)			

No standard test procedure for surface, shear, and edge cracks;
No guidance on what threshold to use within software

What Is Not Captured?

GDIS

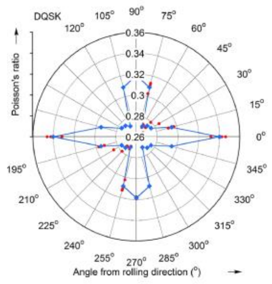
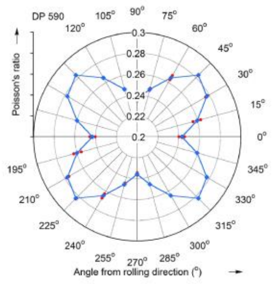
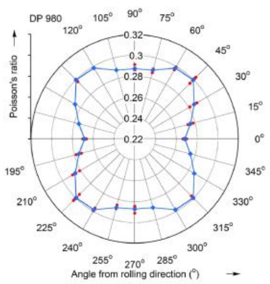
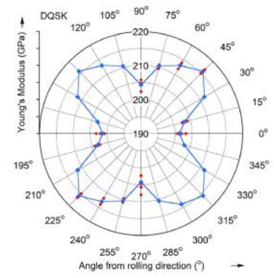
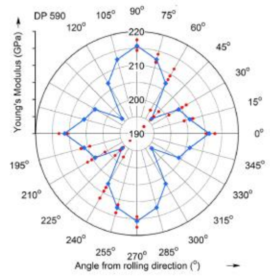
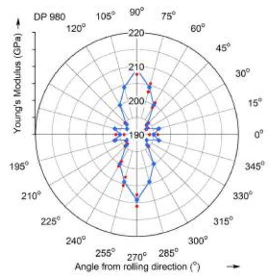
Negative strain rate sensitivity is incapable of being captured in any of the common software

Effect of temperature can be captured, but requires more experiments and much more CPU time

All hardening curve related data (including hardening curve, elastic and unloading moduli, Bauschinger effect, m-value) **are defined only in rolling direction**

Effect of variability
coil-to-coil, mill-to-mill (even within same company)

Properties Changes with Grade and Orientation

	Drawing Steel	DP 590	DP 980
Poisson's Ratio			
Elastic Modulus (sheet)			

Although not part of the Material Card, **press motion curves and speed (SPM)** are frequently ignored

N. Deng and Y.P. Korkolis, "Elastic anisotropy of dual-phase steels with varying martensite content," International Journal of Solids and Structures, Volumes 141–142, 1 June 2018, Pages 264-278, doi.org/10.1016/j.ijsolstr.2018.02.028.

Use Caution When Pulling a Card Out of The Library!

Named as Level 0, by Billur and Karşı 2022

[E. Billur & A. Karşı, “Multi-Level Material Cards for Sheet Metal Forming Simulations,” Great Designs in Steel 2022, Sponsored by American Iron and Steel Institute; steel.org/wp-content/uploads/2022/06/Track-1-Session-10-Billur-Billur-Metal-Forming.pdf]

Information received from third party

No details are given

May use simple equations and simple assumptions (for example: $r_0 = r_{45} = r_{90} = 1$),

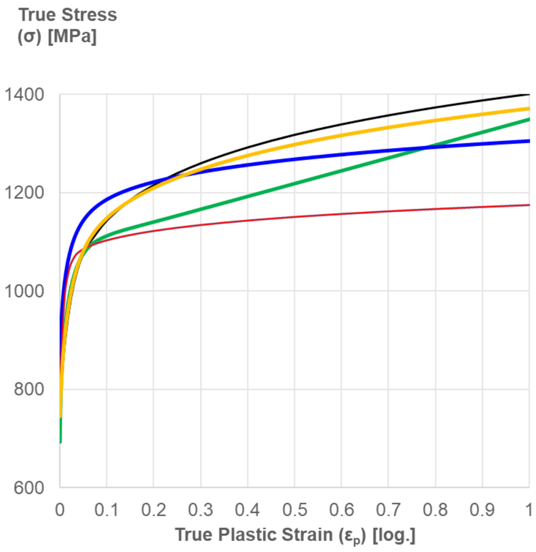
May use older material models and correlations, not necessarily appropriate for the grade (examples: Hill ’48 should not be used with r<1; Keeler FLC proven not to work for most AHSS)

```
########################################################
## NOTE:                                              ##
## The information shown in this card is presented   ##
## only as an example and should NOT be               ##
## viewed as representative of any real material.    ##
########################################################

#GeneralCommentStart
#GeneralCommentEnd

YoungsModulus 210000
PoissonsRatio 0.3
SpecificWeight 7.8e-005
SpecificHeatCapacity 3.642
ThermalConductivity 0
HardeningCurve
Ludwik 1137.01 0.11 605
# Sigma = 1137.01*(Eps)^0.11; Sigma_0 = 605

R-Values 1 1 1

FailureCurve
Keeler
```

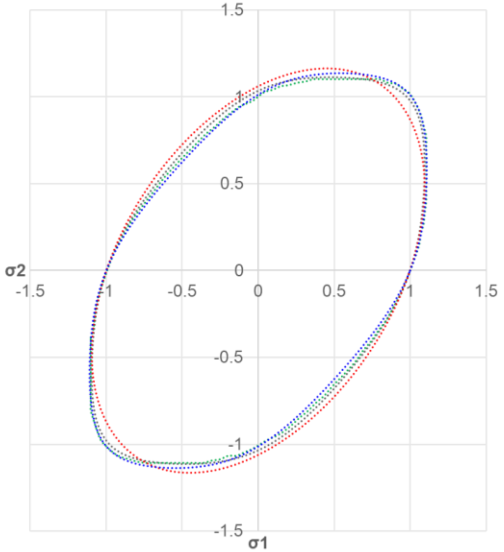
Use Caution When Pulling a Card Out of The Library!

GDIS

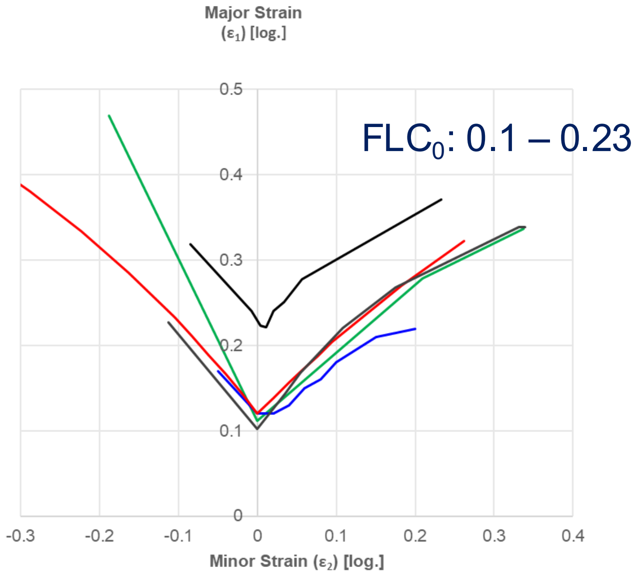
CR700Y/980T-DP



22% difference in YS
True stress level at 0.2 plastic strain:
1122-1215 MPa



2 cards were written with Hill 1990,
2 were written with BBC 2005,
1 with Vegter Full



2 generated from Nakajima experiments,
1 from Abspoel-Scholting correlation;
2 are either from equations or
Marciniak experiments

Among 4-5 suppliers of 700/980-DP, 590/980-DP; 780/980-CP; 440/780DP; 330/590DP; and 340LA …
YS varies between 12% and 24%
True stress at 0.20 true plastic strain varies between 5% and 17%

Stamping tonnage, metal flow, and springback approximation will be affected based on the chosen material card

Influence of Algorithms

Elastic Modulus accuracy is CRITICAL for improved springback prediction

2025/2026 study: Same dataset analyzed by 20 labs (NOT from multiple tests)

Participants: OEMs, Tier 1s, Steel & Aluminum producers, Universities, Simulation companies, Independent Test labs, and industry experts

Range → 183.0 GPa to 218.4 GPa

Similar spread in YS, TS, El, n … one csv file, not different tests

ASTM E8 created more than 100 years ago

No standardized calculation algorithms exist yet → maybe we need that?

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