Tensile Testing for Sheet Metal Formability

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splits

stress

failure

formability

YTE

N-value

TYE

cracking

strain

yield

tensile

dogbone

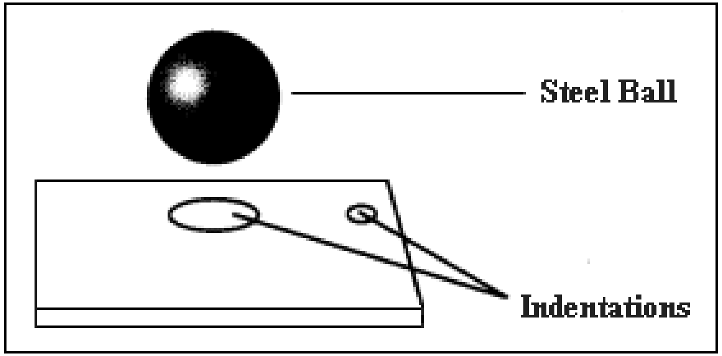
uniform elongation

necking

strain hardening

properties

Hardness



Resistance to Permanent Indentation

Quick and Easy

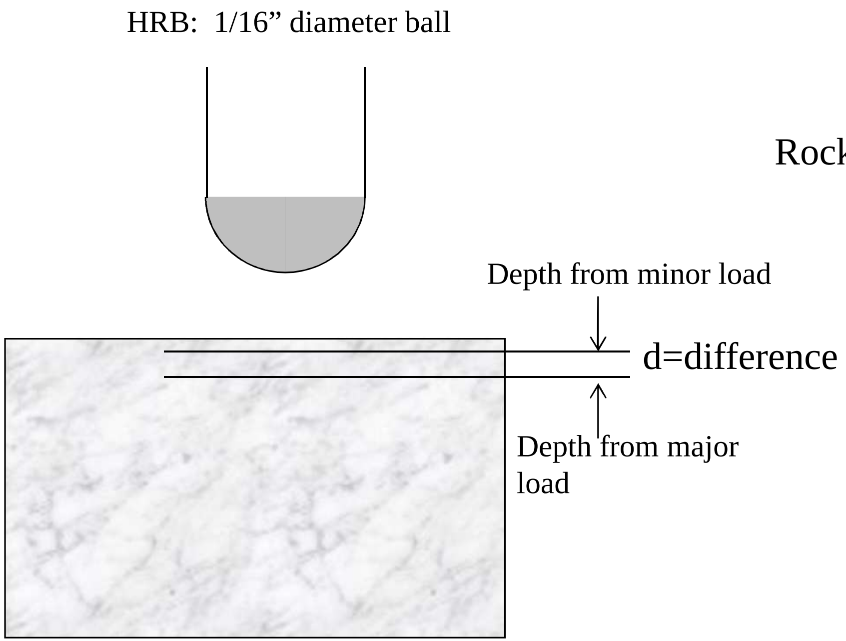
Test Procedure Dependent

Poor Indicator of Formability

Hardness

Mohs hardness	Mineral	Chemical formula	Absolute hardness
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	1
2	Gypsum	$CaSO_4 \cdot 2H_2O$	3
3	Calcite	$CaCO_3$	9
4	Fluorite	CaF_2	21
5	Apatite	$Ca_5(PO_4)_3(OH^-,Cl^-,F^-)$	48
6	Orthoclase Feldspar	$KAlSi_3O_8$	72
7	Quartz	SiO_2	100
8	Topaz	$Al_2SiO_4(OH^-,F^-)_2$	200
9	Corundum	Al_2O_3	400
10	Diamond	C	1600

Schematic of Rockwell Testing resistance to indentation



$$\text{Rockwell B Hardness} = 130 - \frac{d}{0.002\ \text{mm}}$$

HRB 80 = 0.10 mm

HRB 65 = 0.13 mm

HRB 50 = 0.16 mm

(human hair ≈ 0.10mm)

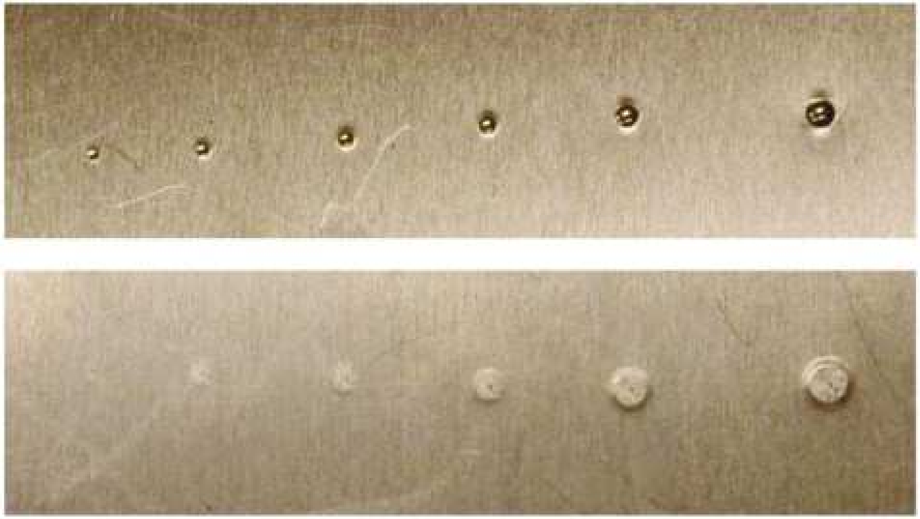
One Rockwell point =

2 microns = 0.00008 inch

Anvil Effect

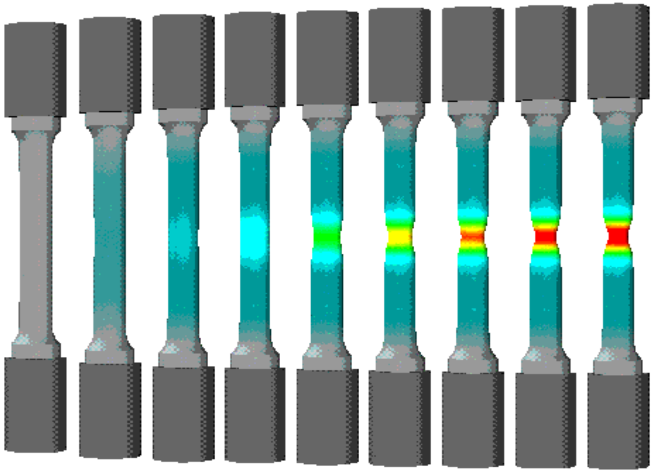
Indentation depth <10% of sample thickness

If not, then risk of shiny spot (burnish) on other surface



Zhang, Dhaigude, and Wang, *The Anvil Effect in the Spherical Indentation Testing on Sheet Metals,* Procedia Manufacturing Volume 1, 2015, Pages 828–839, doi: 10.1016/j.promfg.2015.09.072
https://www.researchgate.net/publication/283958501_The_Anvil_Effect_in_the_Spherical_Indentation_Testing_on_Sheet_Metals

Tensile Testing



Definitions

Strength (stress)

= Resistance to Deformation

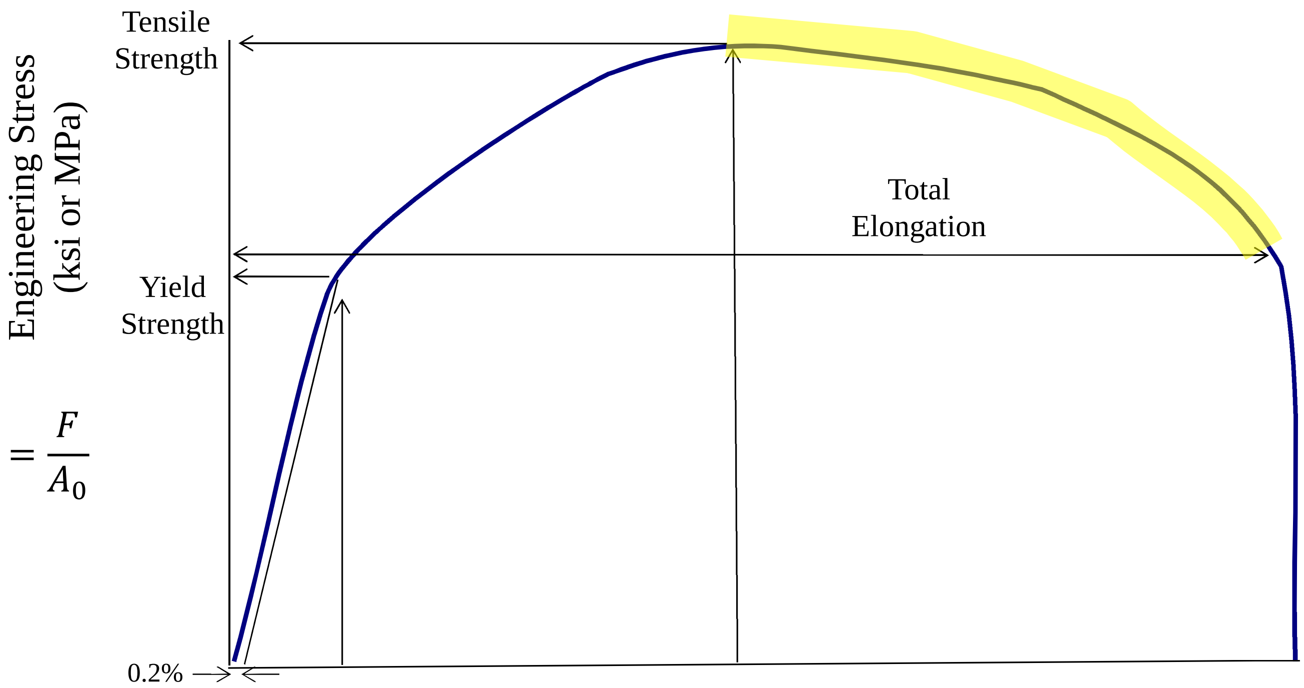
= Force / Area

Strain

= % Displacement

= Change in length / Original length

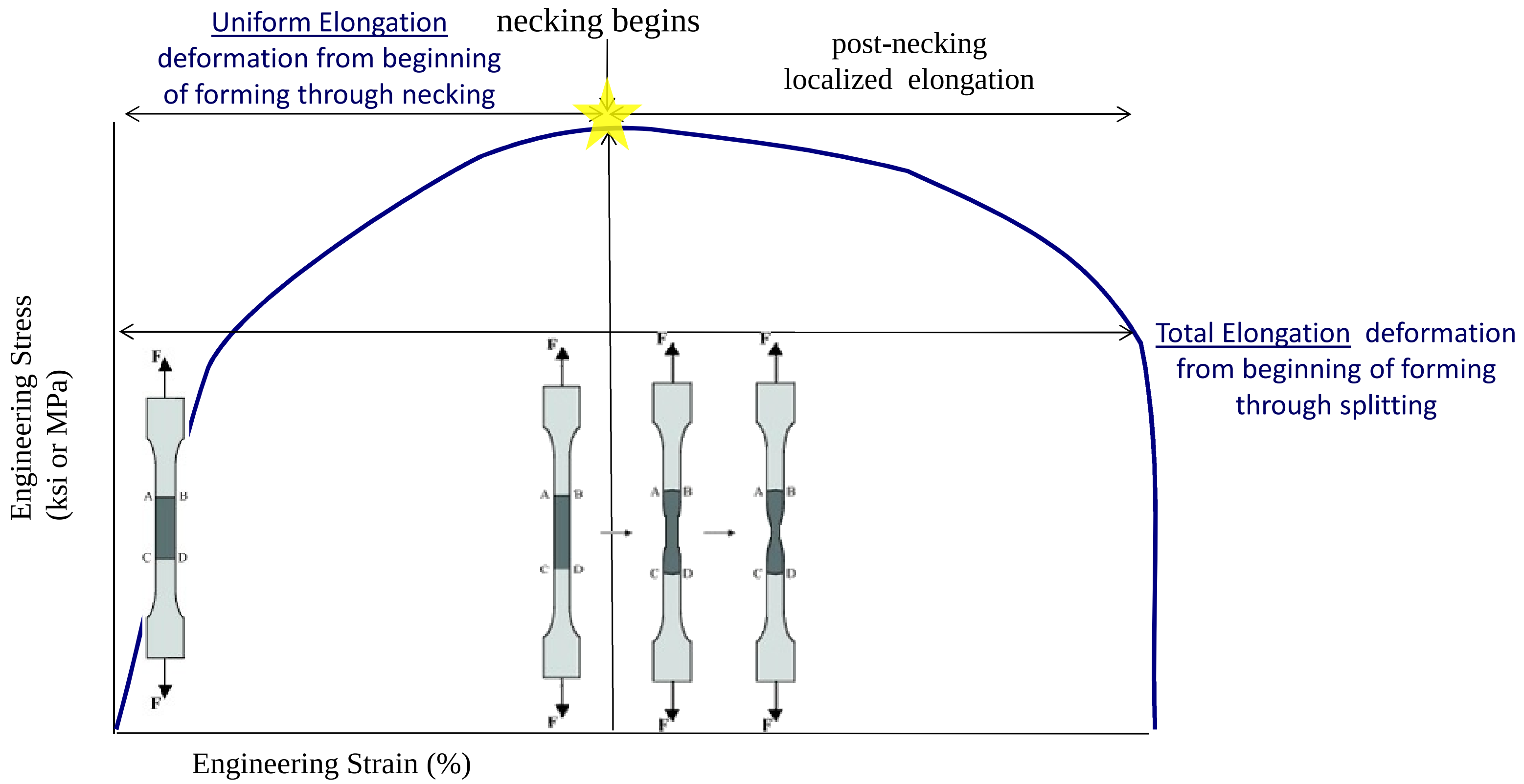
Tensile Testing



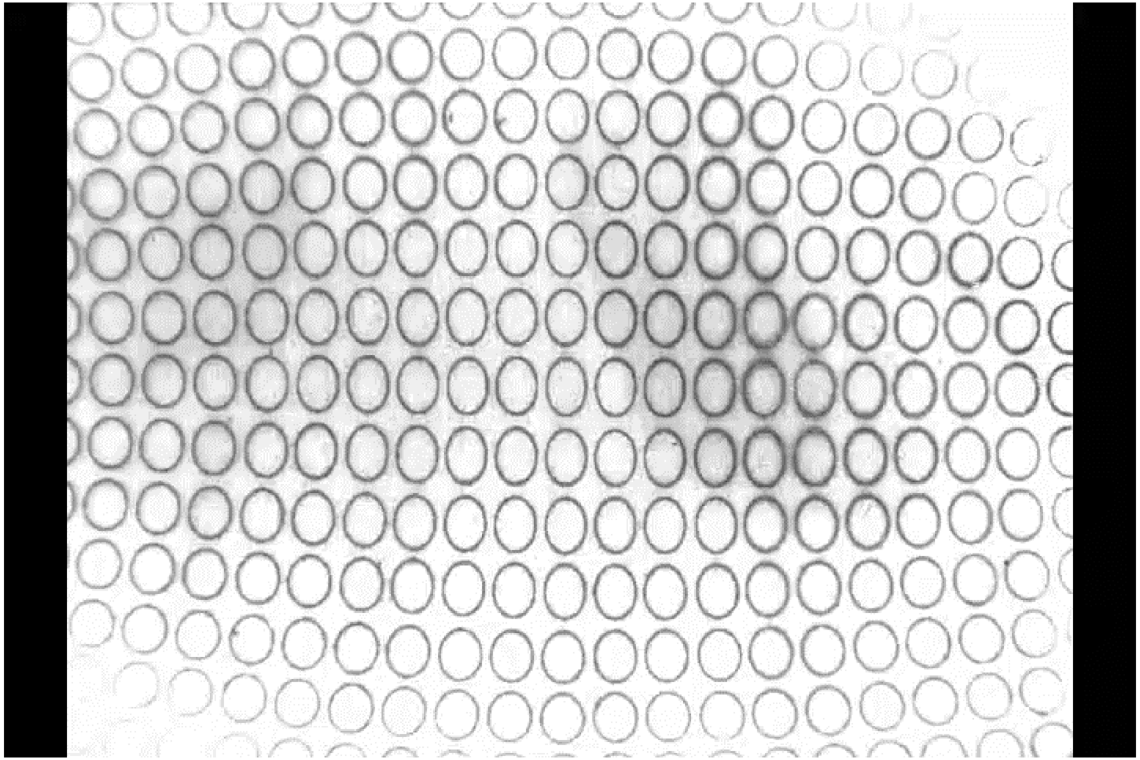
$$s = \frac{F}{A_0}$$

$$e = \frac{\Delta L}{L_0}$$

Elongation: Total vs Uniform



Necking and Fracture



Tensile Testing

Engineering Stress/Strain vs True Stress/Strain

$$Engineering\ Stress = s = \frac{F}{A_0} = \frac{Force}{Initial\ Cross\ Sectional\ Area}$$

$$True\ Stress = \sigma = \frac{F}{A_i} = \frac{Force}{Instantaneous\ Cross\ Sectional\ Area}$$

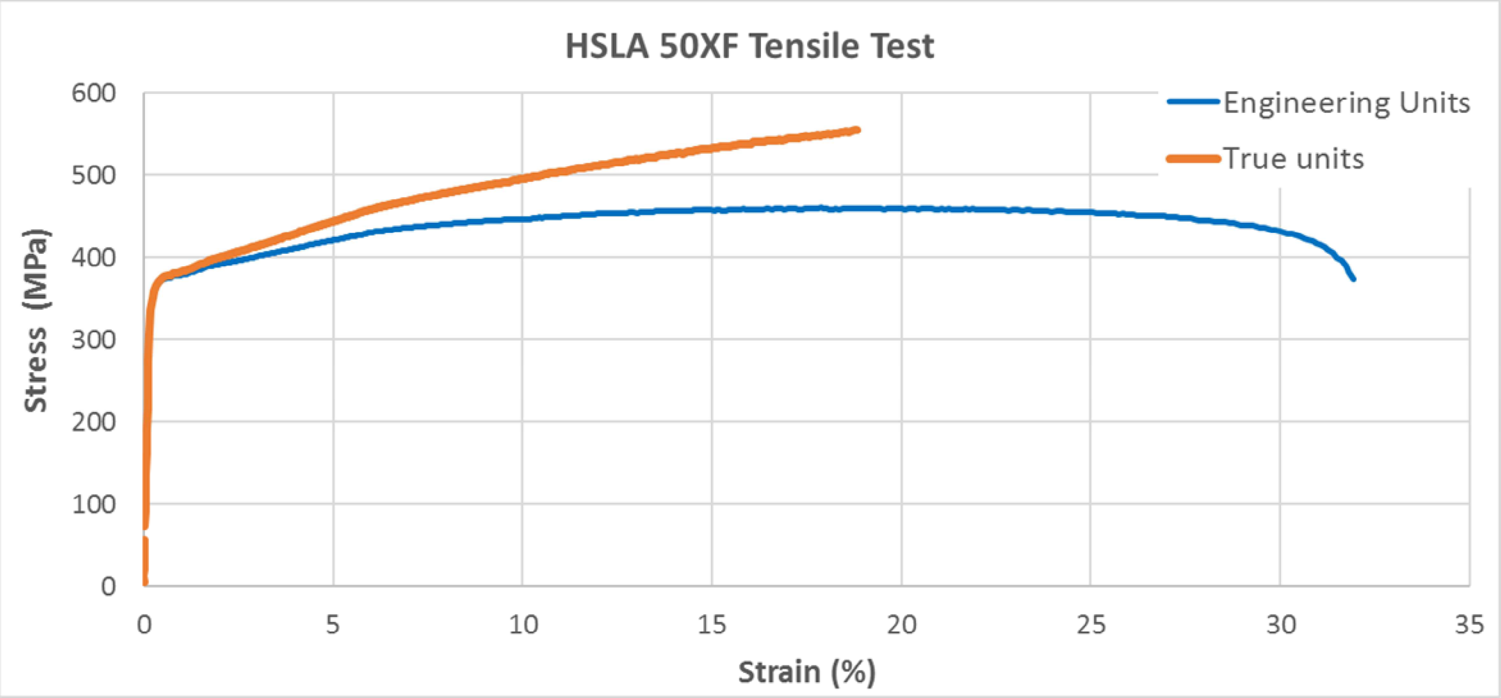
$$Engineering\ Strain = e = \frac{L_f\ - L_0}{L_0} = \frac{\Delta L}{L_0} = \frac{Change\ in\ Length}{Initial\ Gauge\ Length}$$

$$True\ Strain = \epsilon = \ln\left\{\frac{L_i}{L_0}\right\} = \frac{Instantaneous\ Change\ in\ Length}{Initial\ Gauge\ Length}$$

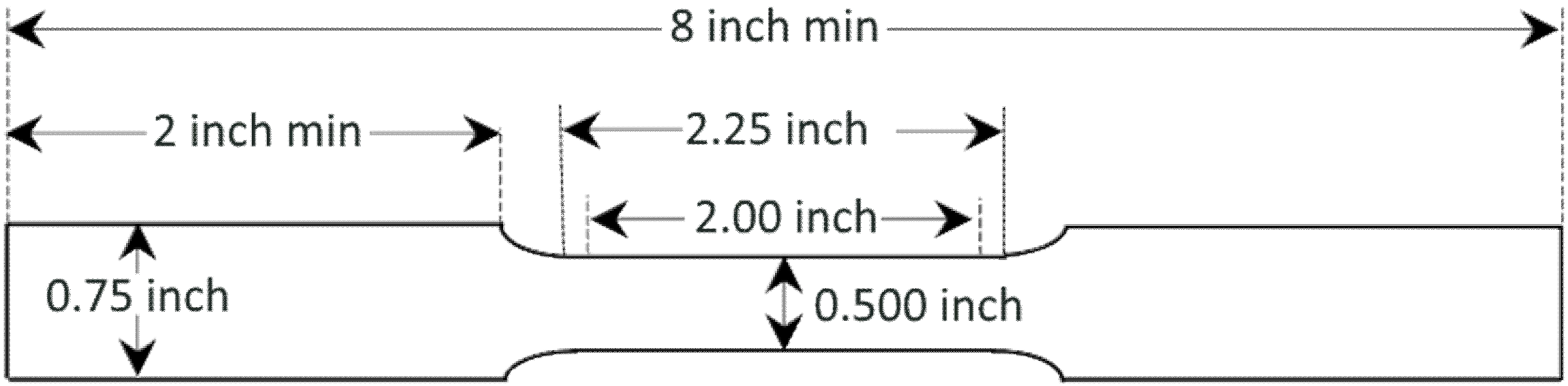
$\sigma = s\ (1+e)$ $\epsilon = \ln\ (1+e)$

Engineering vs True

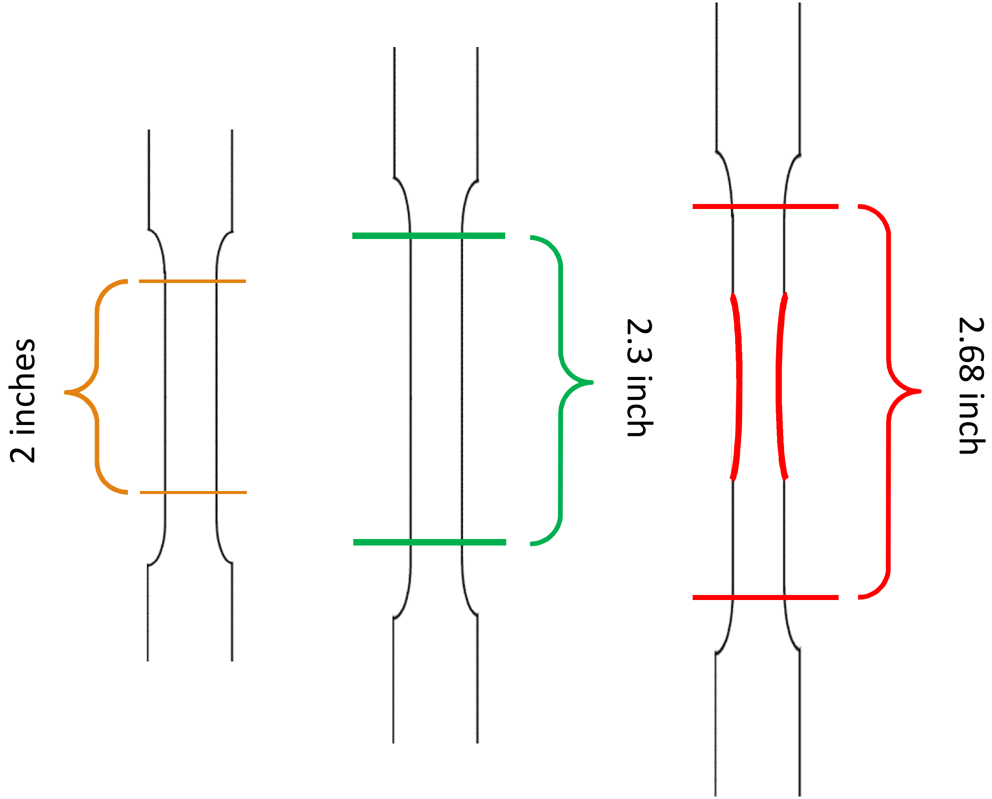
$$\sigma = s\,(1+e) \qquad \epsilon = \ln\,(1+e)$$



ASTM Tensile Bar



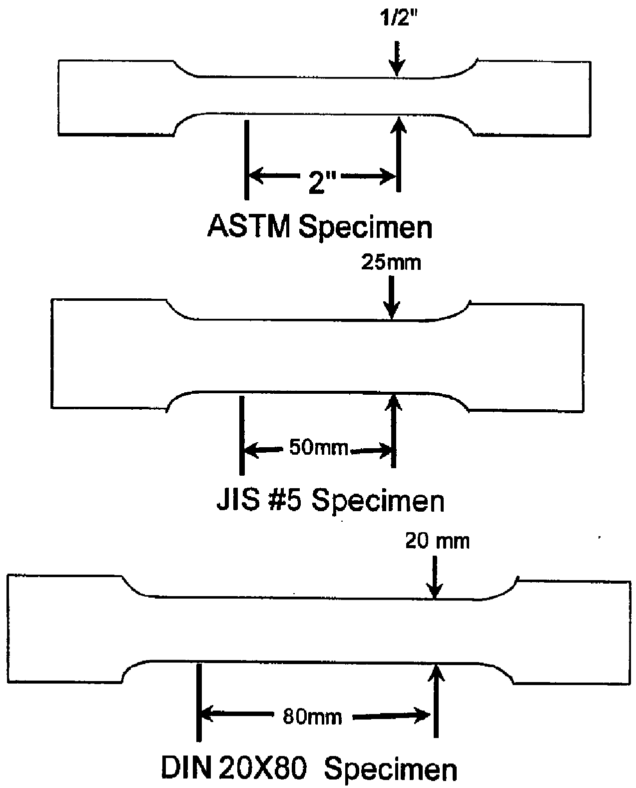
Calculating Elongation



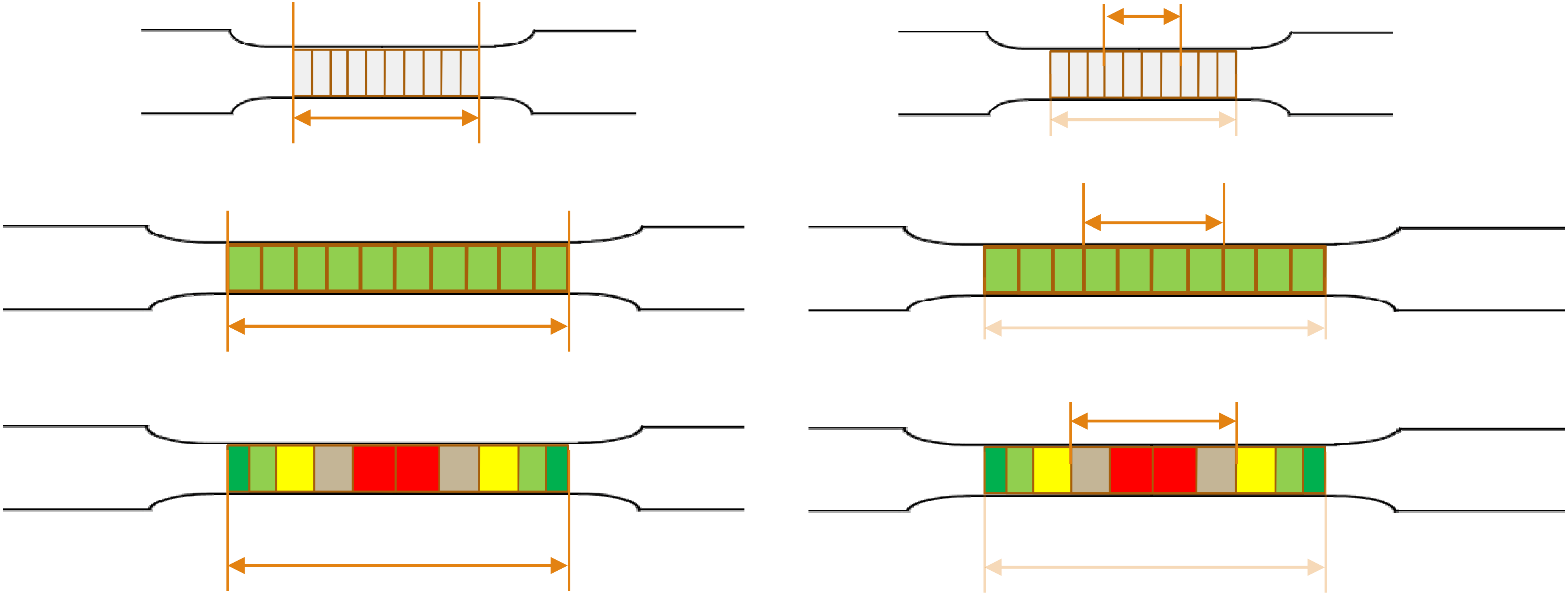
$$\frac{\Delta L}{L} = \frac{2.3 - 2}{2} = \frac{0.3}{2} = 0.15 = 15\%$$

$$\frac{\Delta L}{L} = \frac{2.68 - 2}{2} = \frac{0.68}{2} = 0.34 = 34\%$$

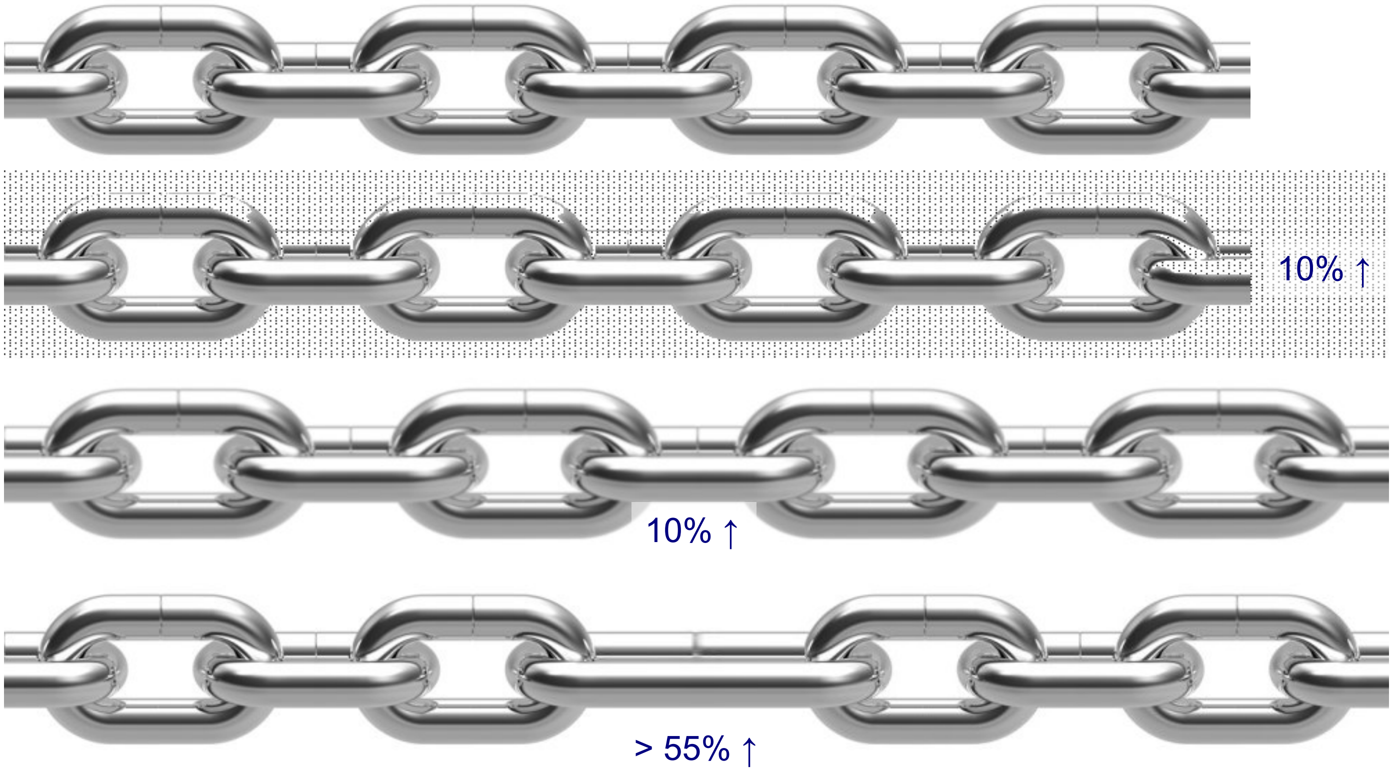
Tensile Bar Specification



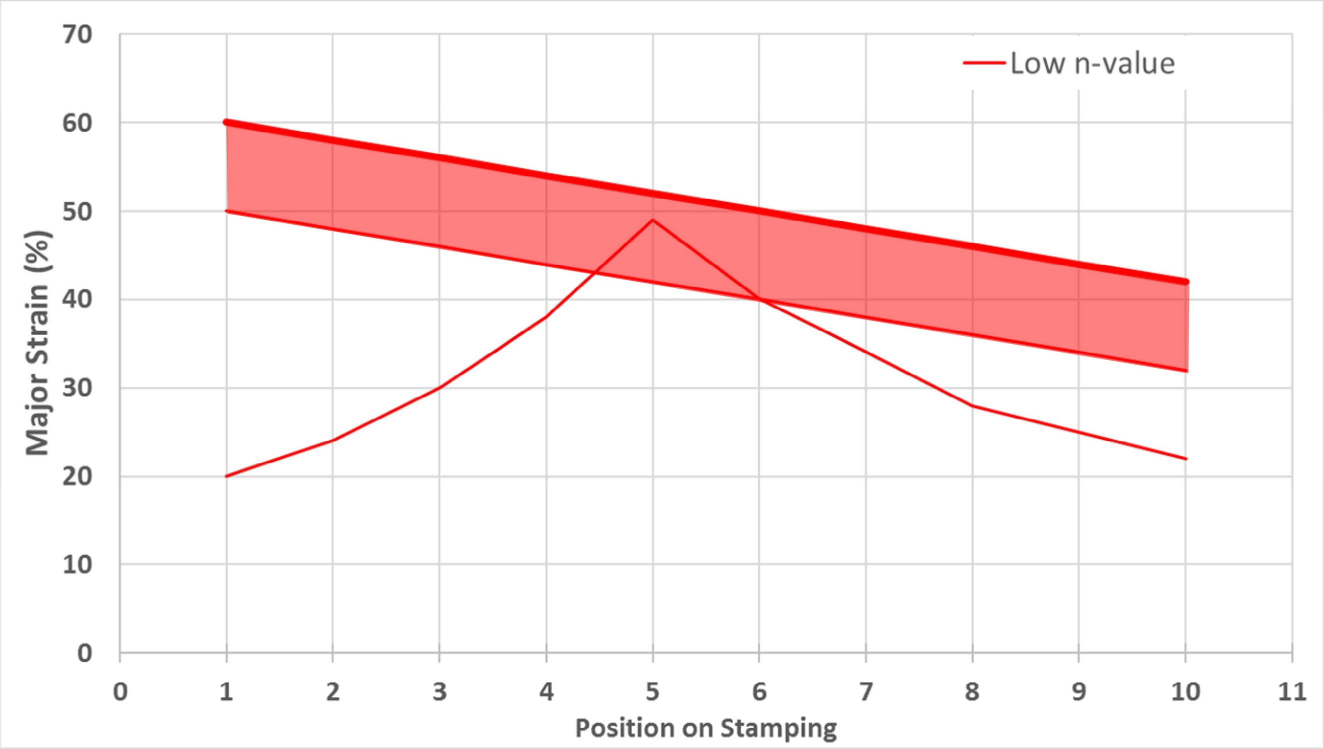
Effect of Gauge Length



↑n-value means Better Ability to Distribute Strains

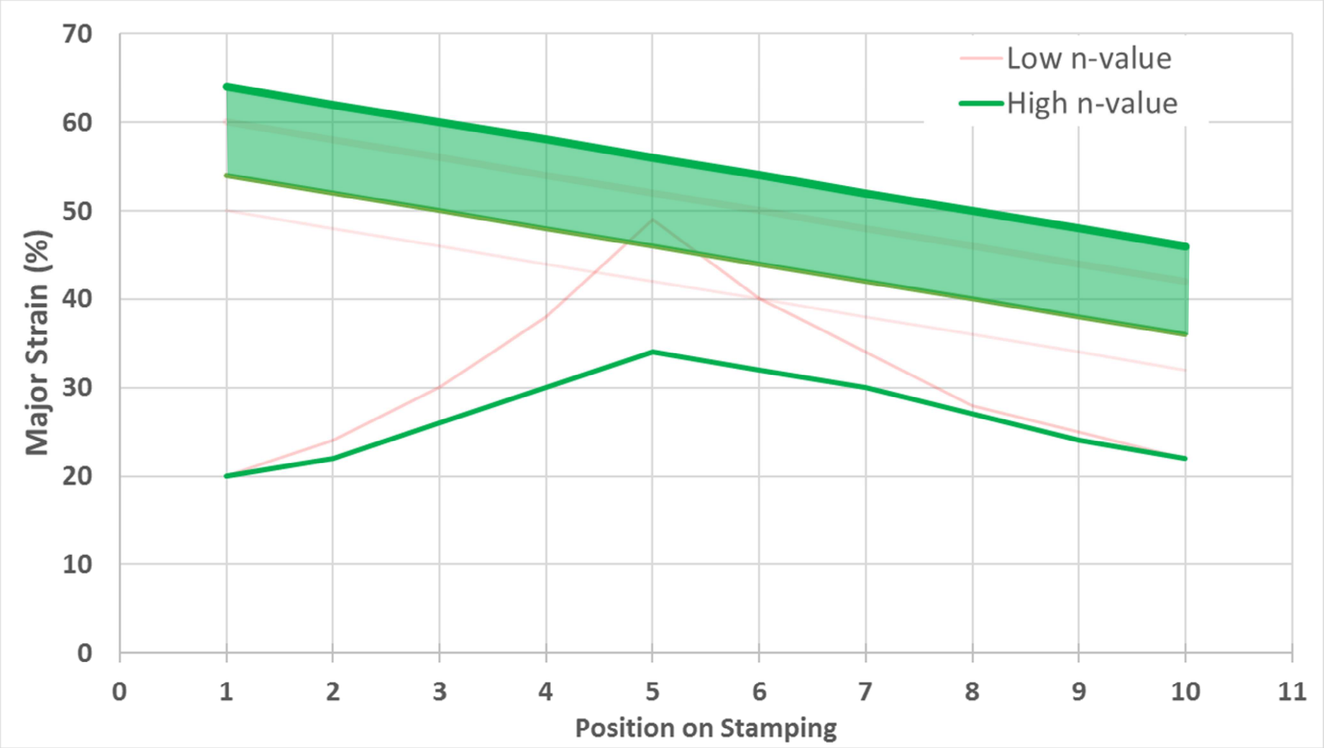


N-Value



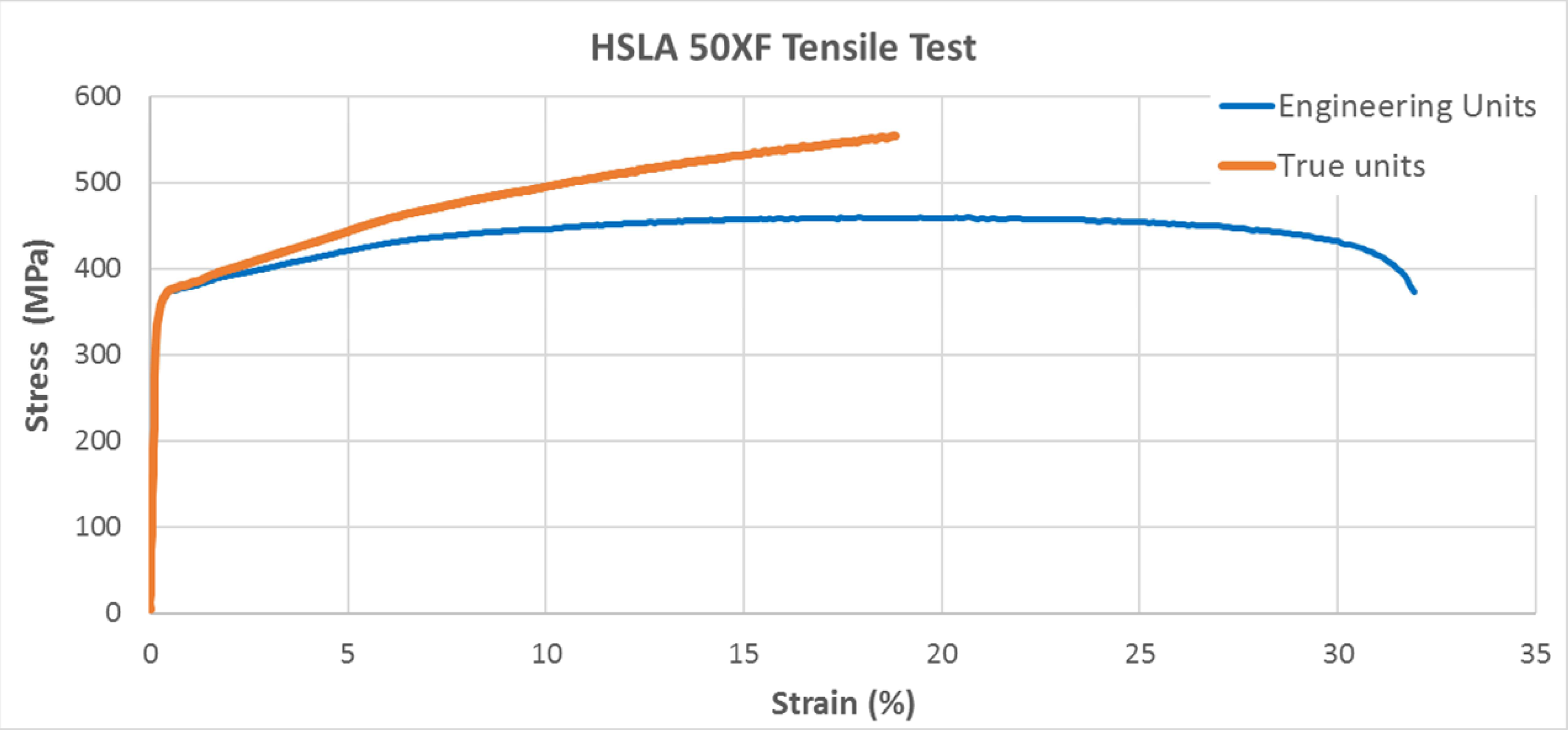
Low n-value
Major Strain (%)
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
Position on Stamping

N-Value



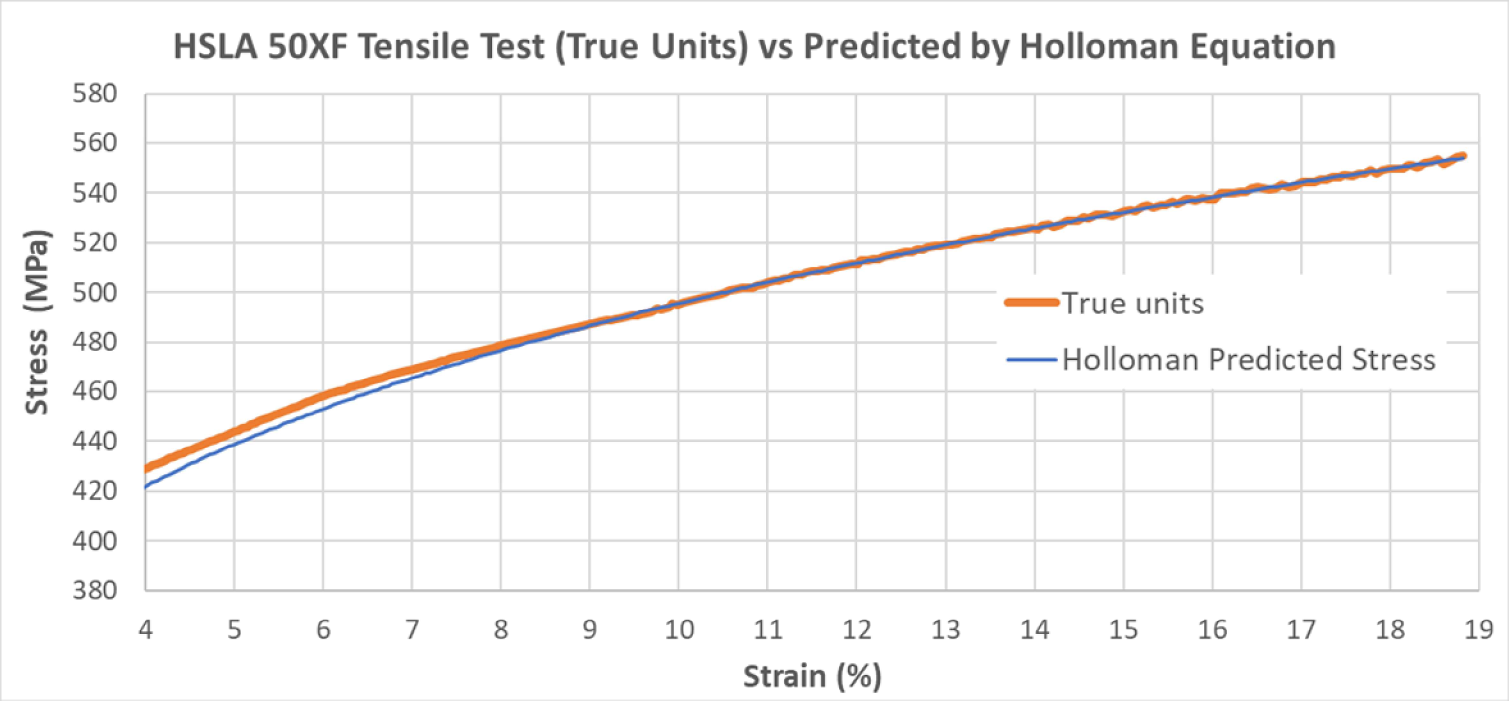
70
60
50
40
30
20
10
0
Major Strain (%)
0 1 2 3 4 5 6 7 8 9 10 11
Position on Stamping
Low n-value
High n-value

Data Points from Tensile Testing



Holloman Power Law: true stress-strain

$$\sigma = K\varepsilon^n$$



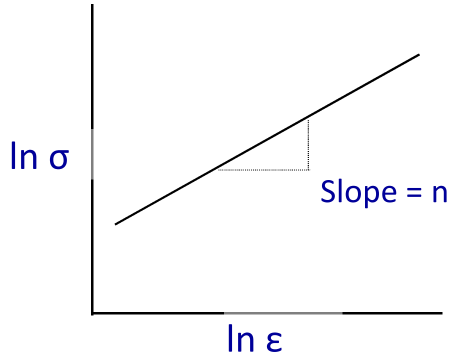
Strain Hardening Exponent = N-Value

Holloman Power Law:

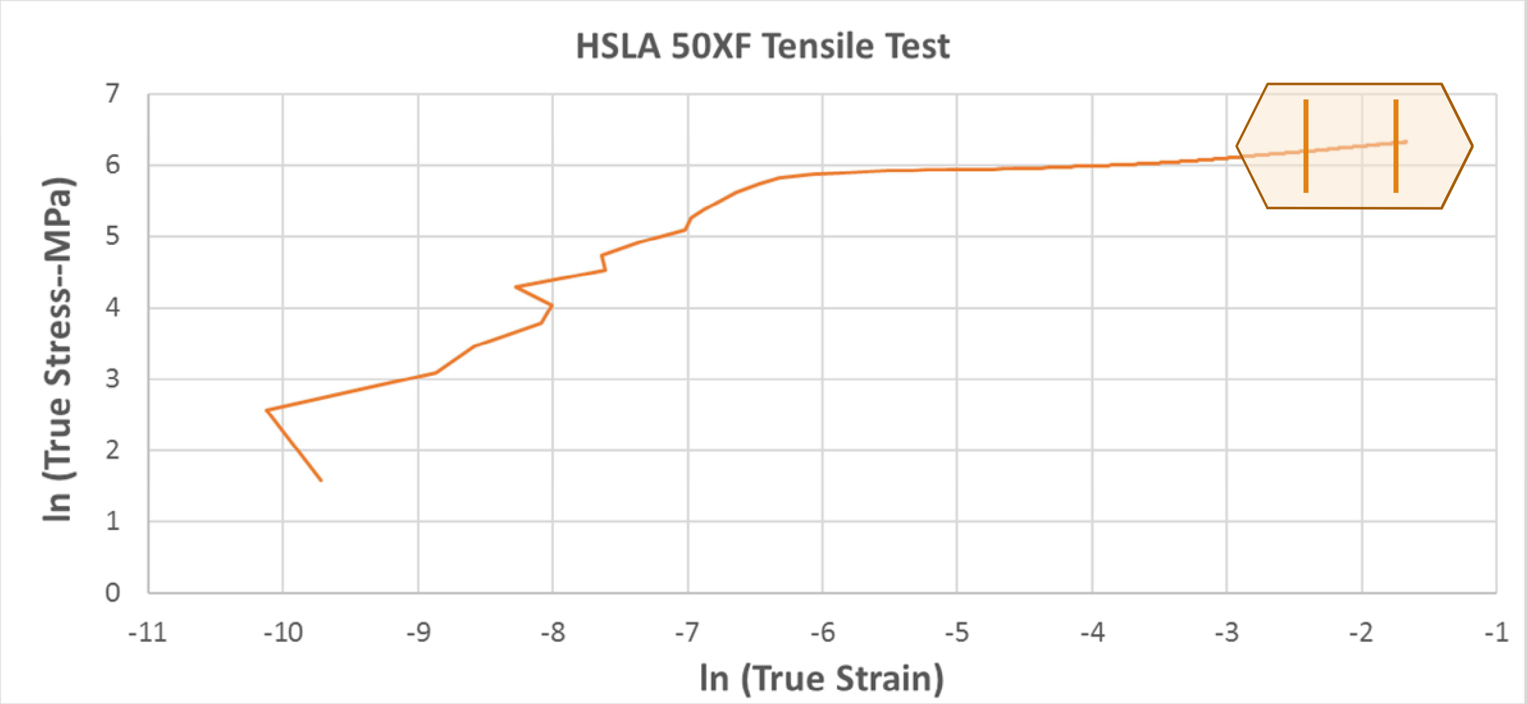
$$\sigma = K\varepsilon^n$$

$$\ln\sigma = \ln K + n(\ln \varepsilon)$$

n the slope of the ln σ - ln ε plot

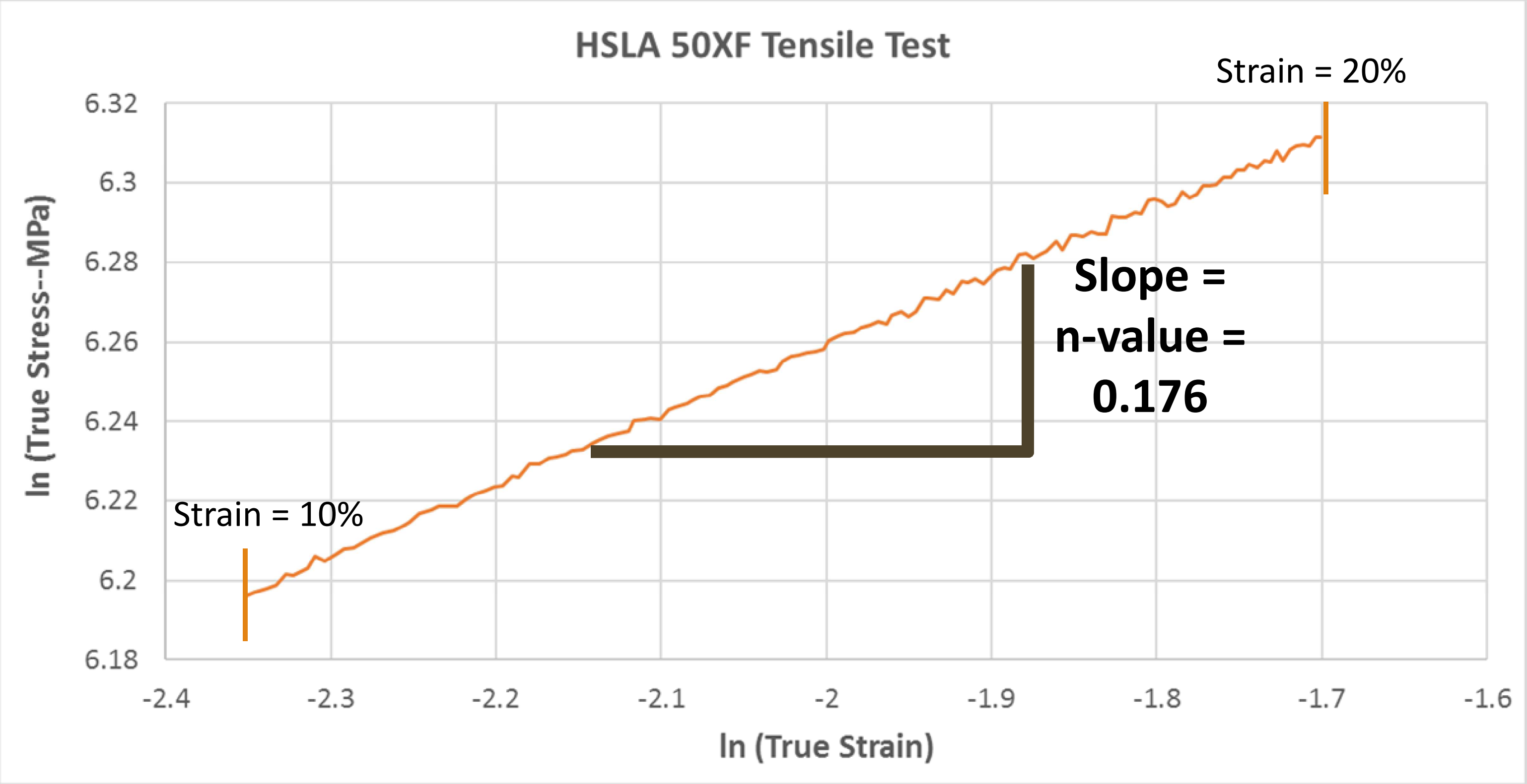


$$\sigma = K\varepsilon^n \qquad \ln\sigma = \ln K + n(\ln \varepsilon)$$



$\sigma = K\varepsilon^n$ $\ln\sigma = \ln K + n(\ln \varepsilon)$

K=743MPa, n=0.176

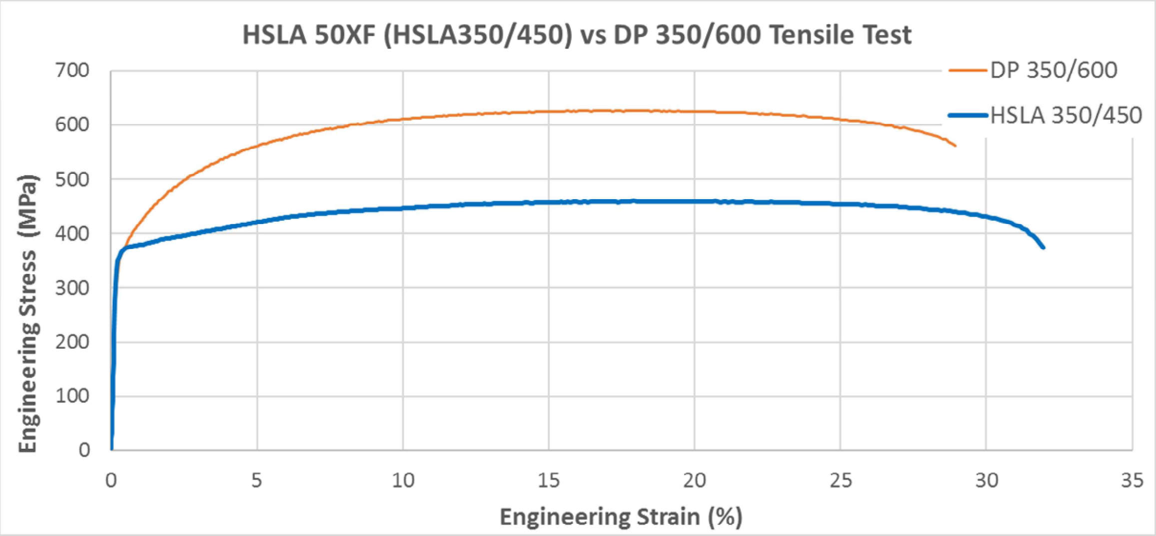


Physical Meaning of N-value

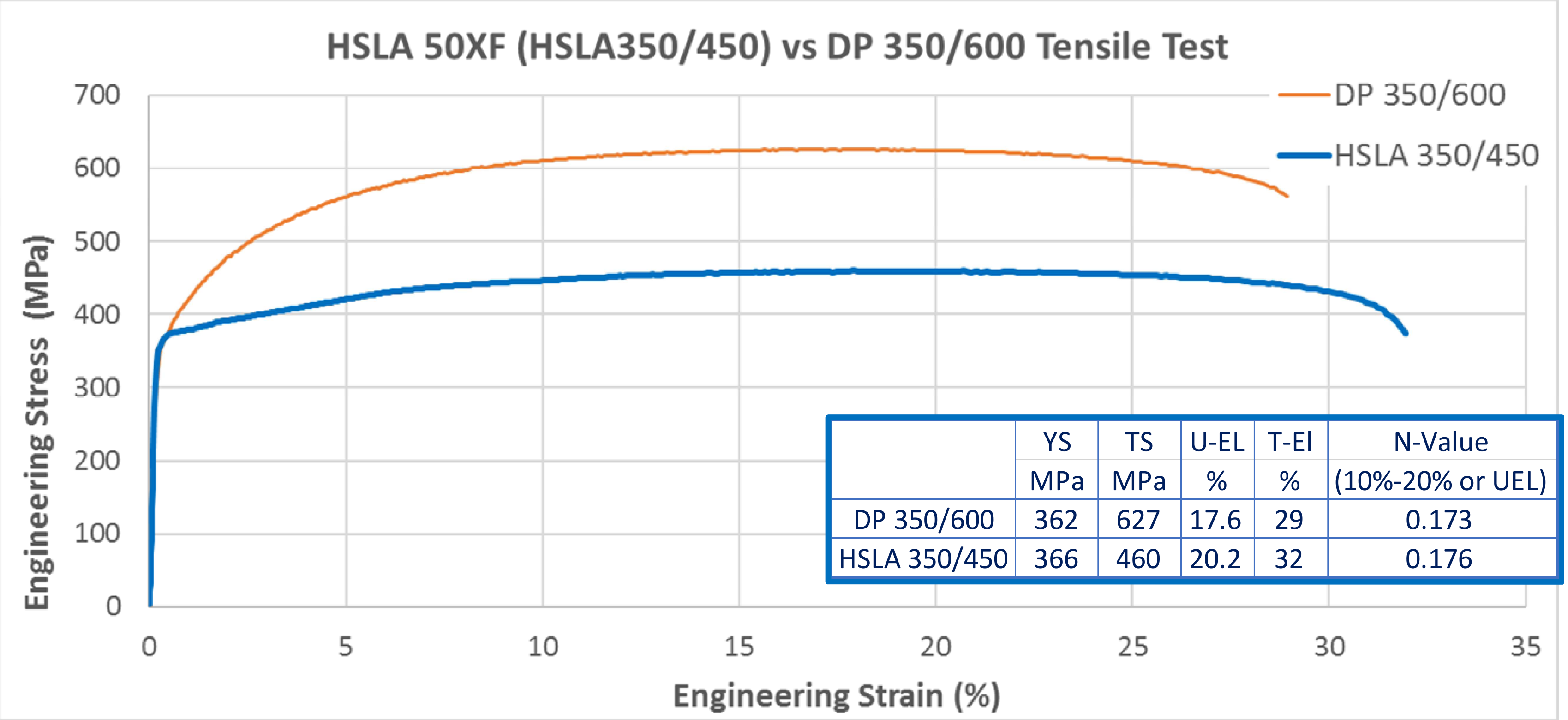
Calculated as slope of the ln σ - ln ε plot

Higher slope = higher n-value

The larger the YS and TS gap, the better the formability.



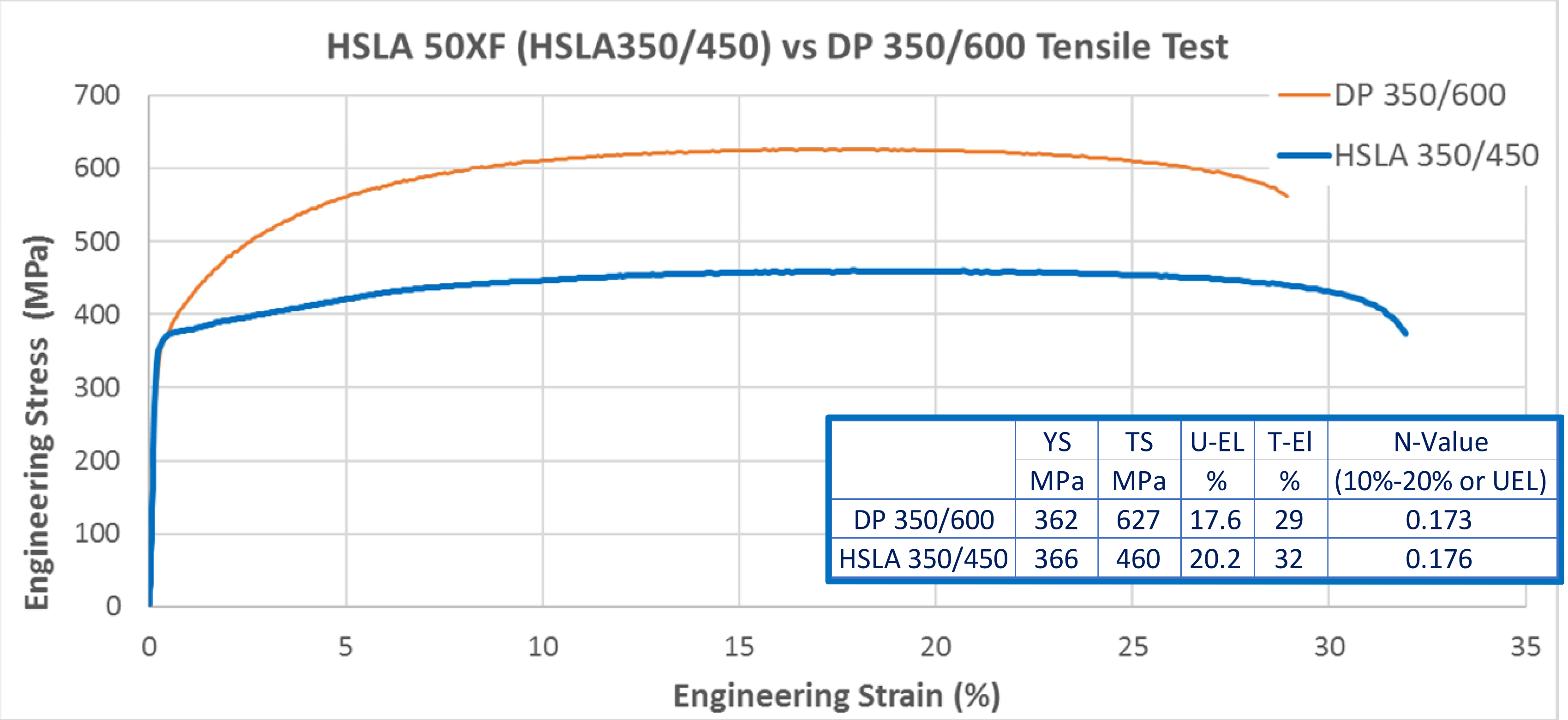
Typical Stress-Strain Curves



	YS MPa	TS MPa	U-EL %	T-El %	N-Value (10%-20% or UEL)
DP 350/600	362	627	17.6	29	0.173
HSLA 350/450	366	460	20.2	32	0.176

With both having similar YS, EL, and n-value…

Why does DP form better than HSLA?



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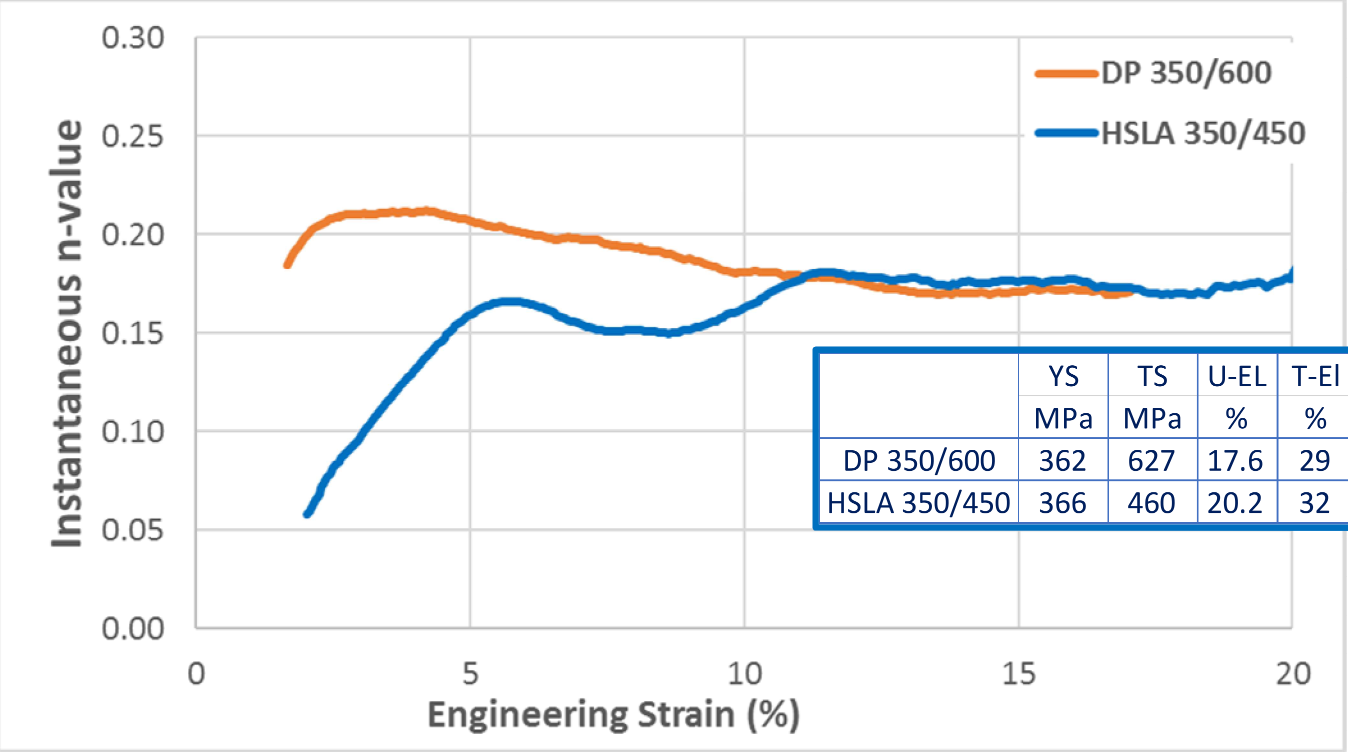

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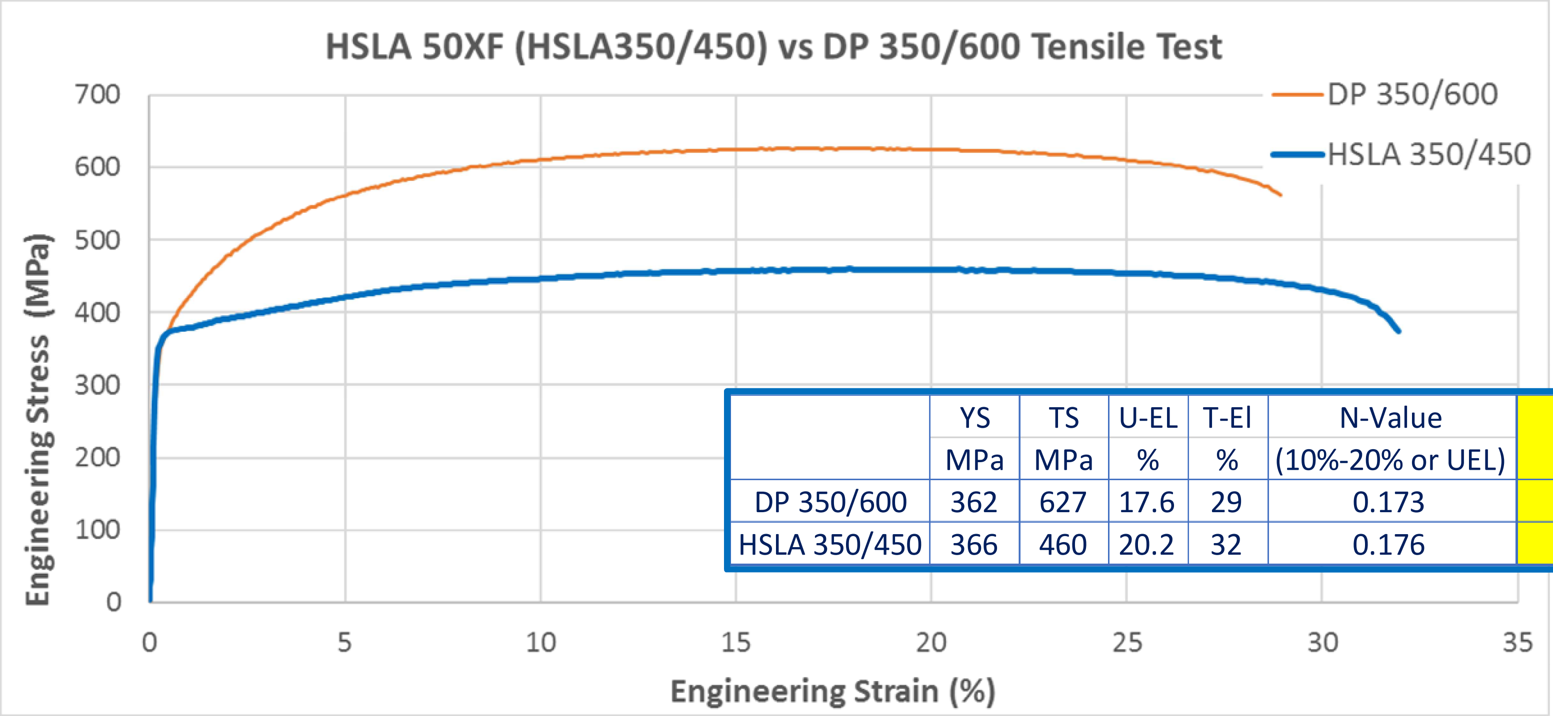
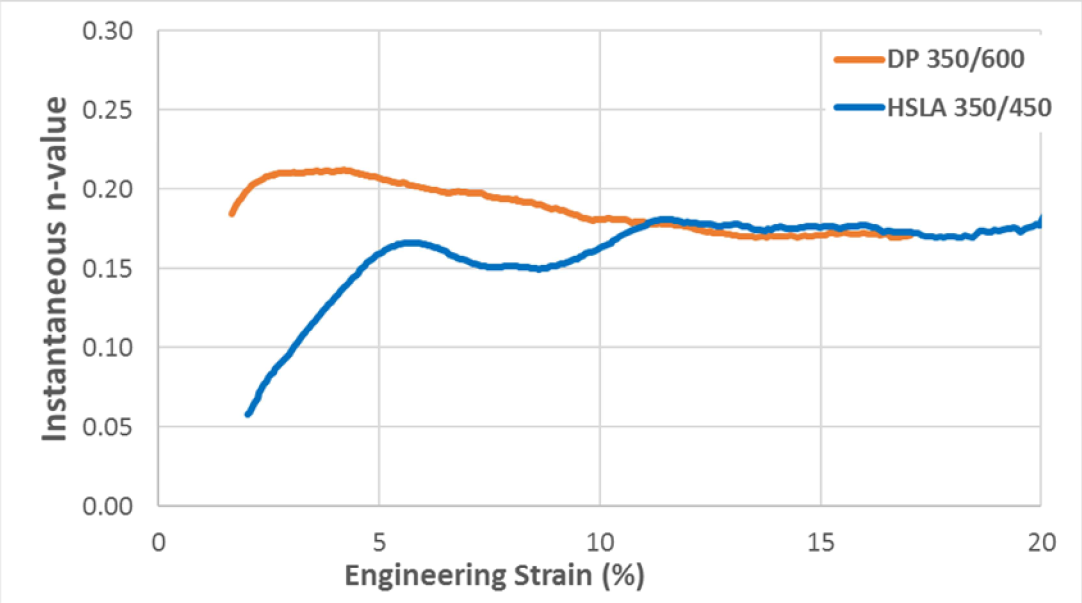


	YS MPa	TS MPa	U-EL %	T-El %	N-Value (10%-20% or UEL)	N-Value (4%-6%)
DP 350/600	362	627	17.6	29	0.173	0.205
HSLA 350/450	366	460	20.2	32	0.176	0.161

High initial n-value reduces opportunities for strain localization and strain gradient formation

Simulation Input?



Which n-value to use??

4% to 6%

6% to 12%

10% to 20%

10% to Uniform Elongation?

Plastic Strain Ratio
Lankford Coefficient
Plastic Anisotropy

r-value

Ratio of true width strain to true thickness strain

in uniform elongation region

Higher r-value indicates better resistance to thinning

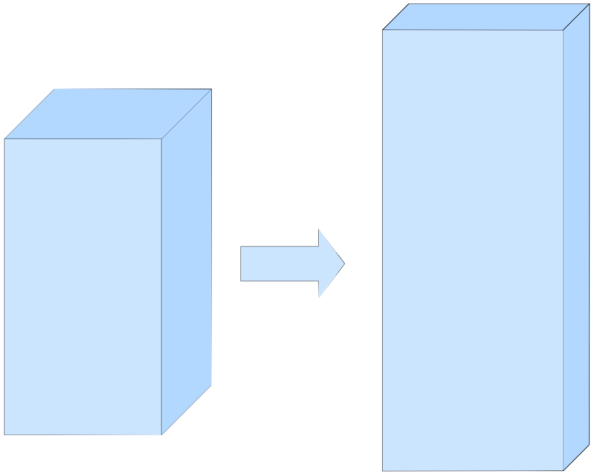
$$r = \frac{\epsilon_w}{\epsilon_t} = \left\{ \frac{\ln \frac{w}{w_0}}{\ln \frac{t}{t_0}} \right\}$$

r-value

Ratio of true width strain to true thickness strain

in uniform elongation region

Low r-value → width strain is small compared with thickness strain



Material with low r-value:
longer and thinner
after straining without much
width change

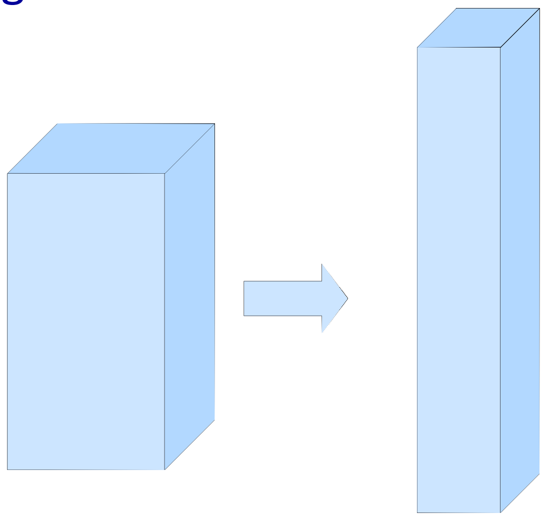
Plastic Strain Ratio
Lankford Coefficient
Plastic Anisotropy

r-value

Ratio of true width strain to true thickness strain

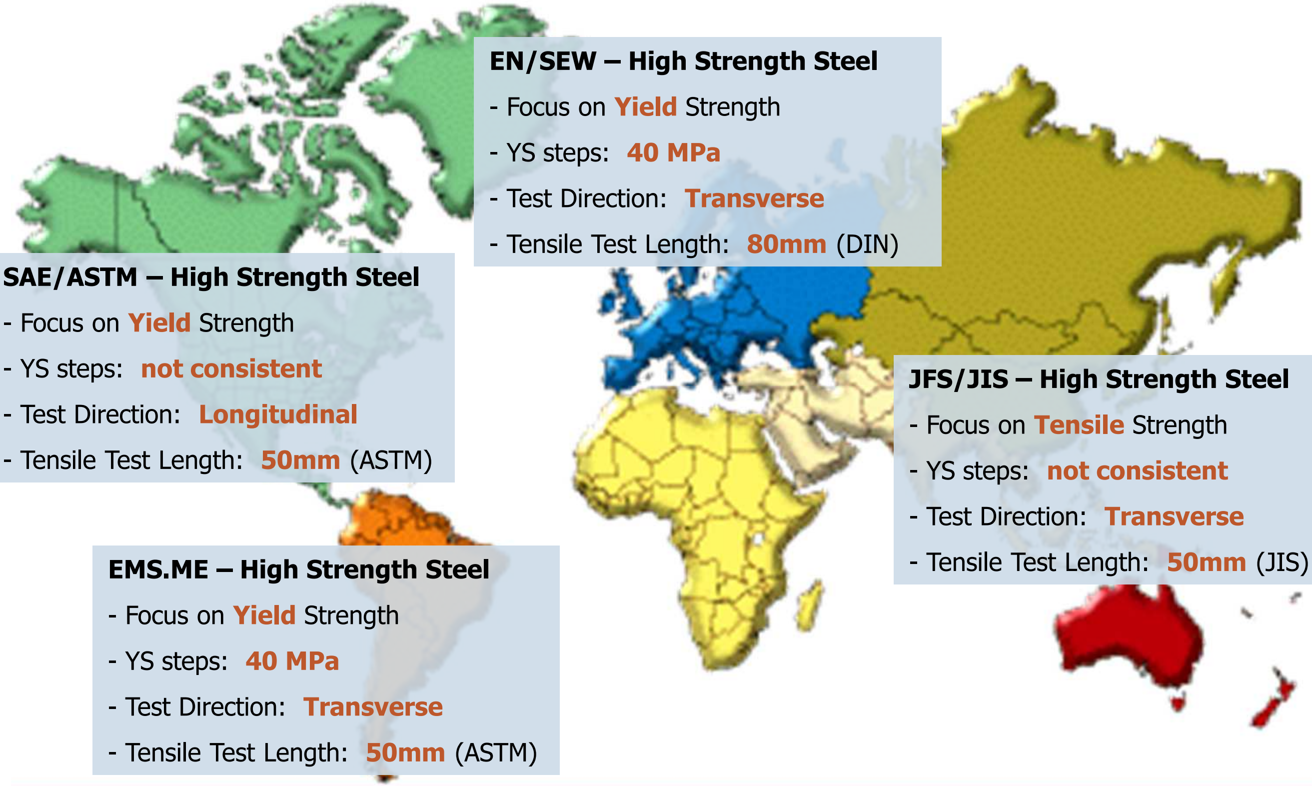
in uniform elongation region

High r-value → width strain is large compared with thickness strain



Material with high r-value:
longer and more narrow
after straining without much
thickness change

Worldwide Specifications



SAE/ASTM – High Strength Steel

- Focus on **Yield** Strength
- YS steps: **not consistent**
- Test Direction: **Longitudinal**
- Tensile Test Length: **50mm** (ASTM)

EN/SEW – High Strength Steel

- Focus on **Yield** Strength
- YS steps: **40 MPa**
- Test Direction: **Transverse**
- Tensile Test Length: **80mm** (DIN)

EMS.ME – High Strength Steel

- Focus on **Yield** Strength
- YS steps: **40 MPa**
- Test Direction: **Transverse**
- Tensile Test Length: **50mm** (ASTM)

JFS/JIS – High Strength Steel

- Focus on **Tensile** Strength
- YS steps: **not consistent**
- Test Direction: **Transverse**
- Tensile Test Length: **50mm** (JIS)

Strength Conversion

psi = pounds per square inch

ksi = kilo (thousand) pounds per square inch

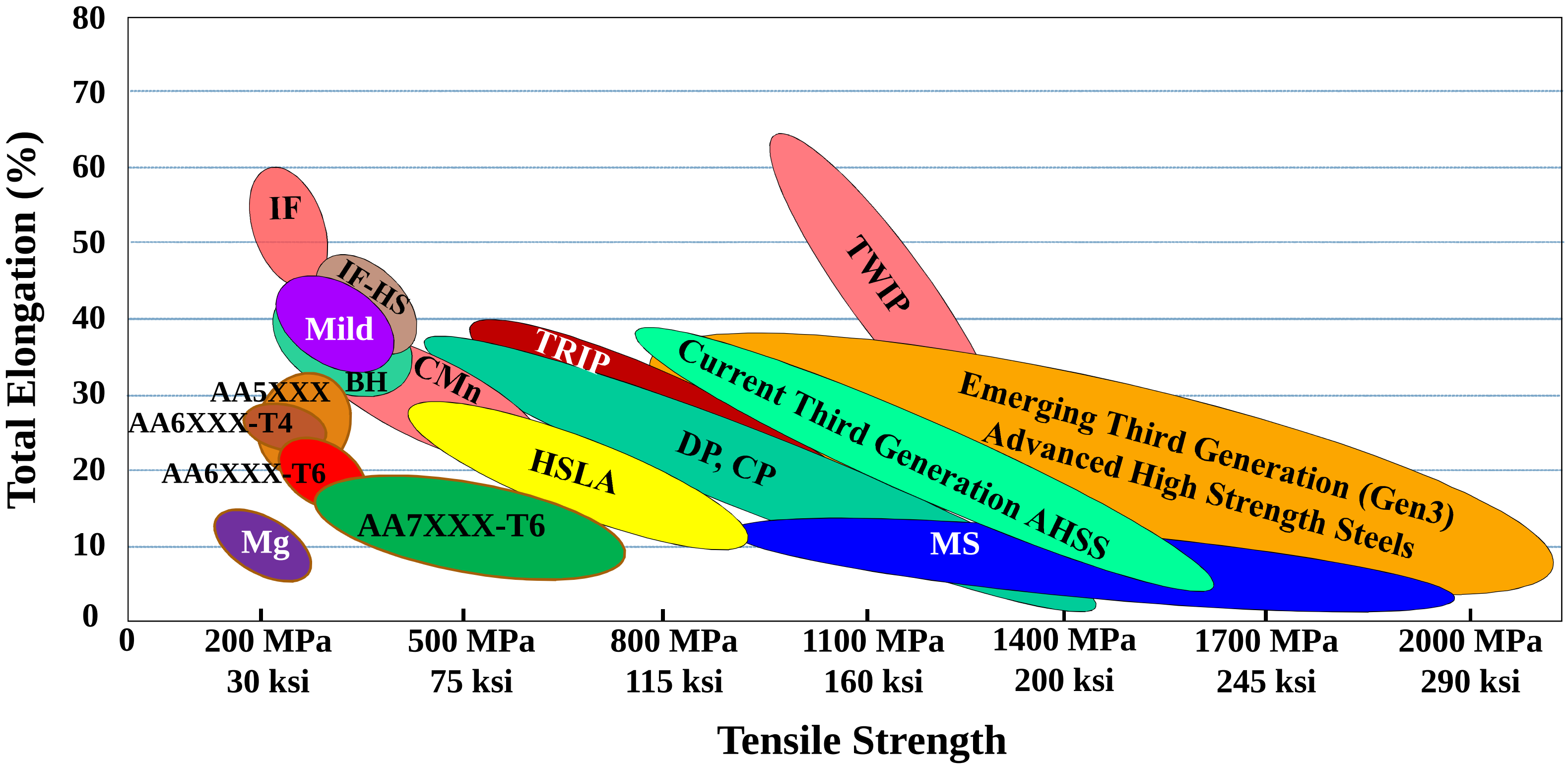
MPa = mega Pascal = 1,000,000 Pascal

GPa = giga Pascal =1,000 MPa

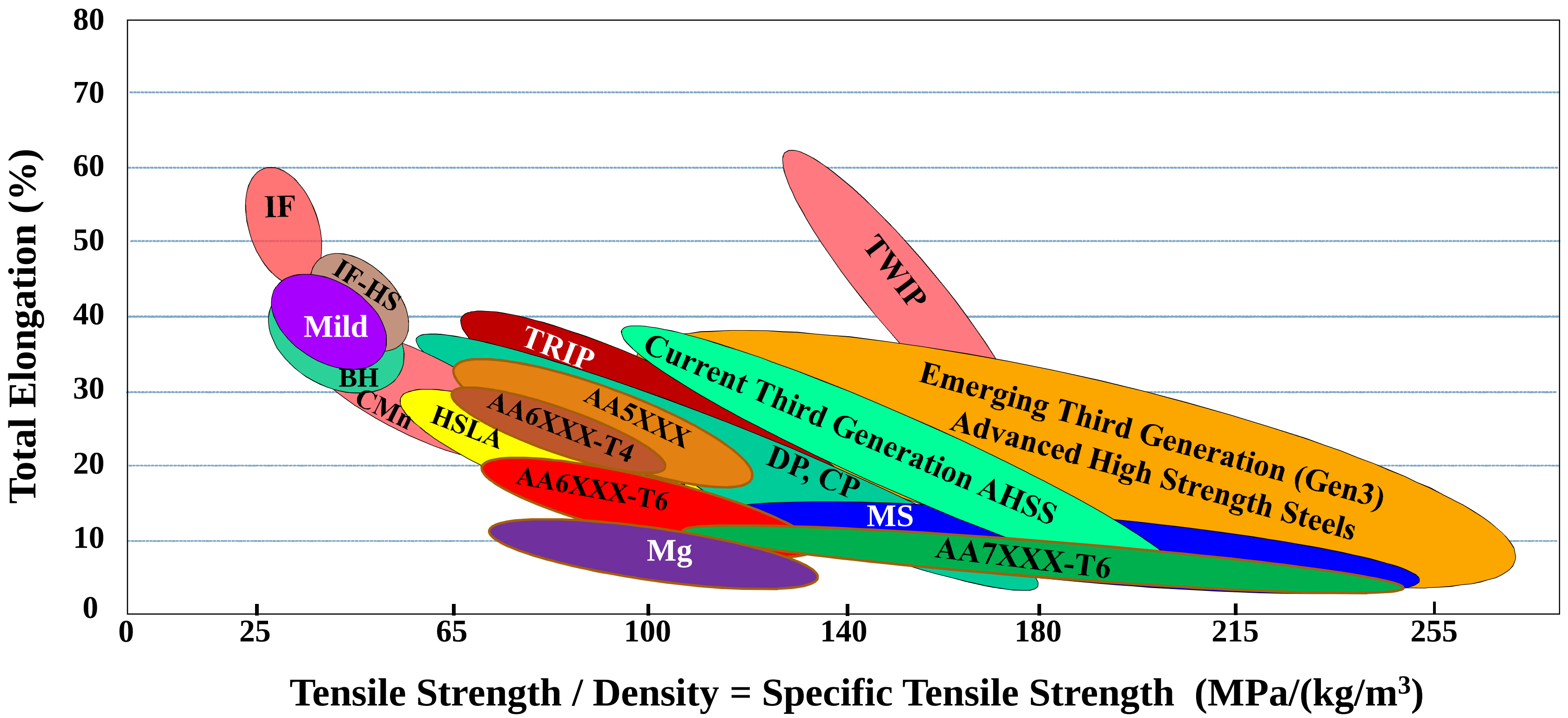
1 ksi = 6.895 MPa 1 ksi ≈ 7 MPa

HSLA 50XF = HSLA 350/450

Tensile Strength vs Elongation

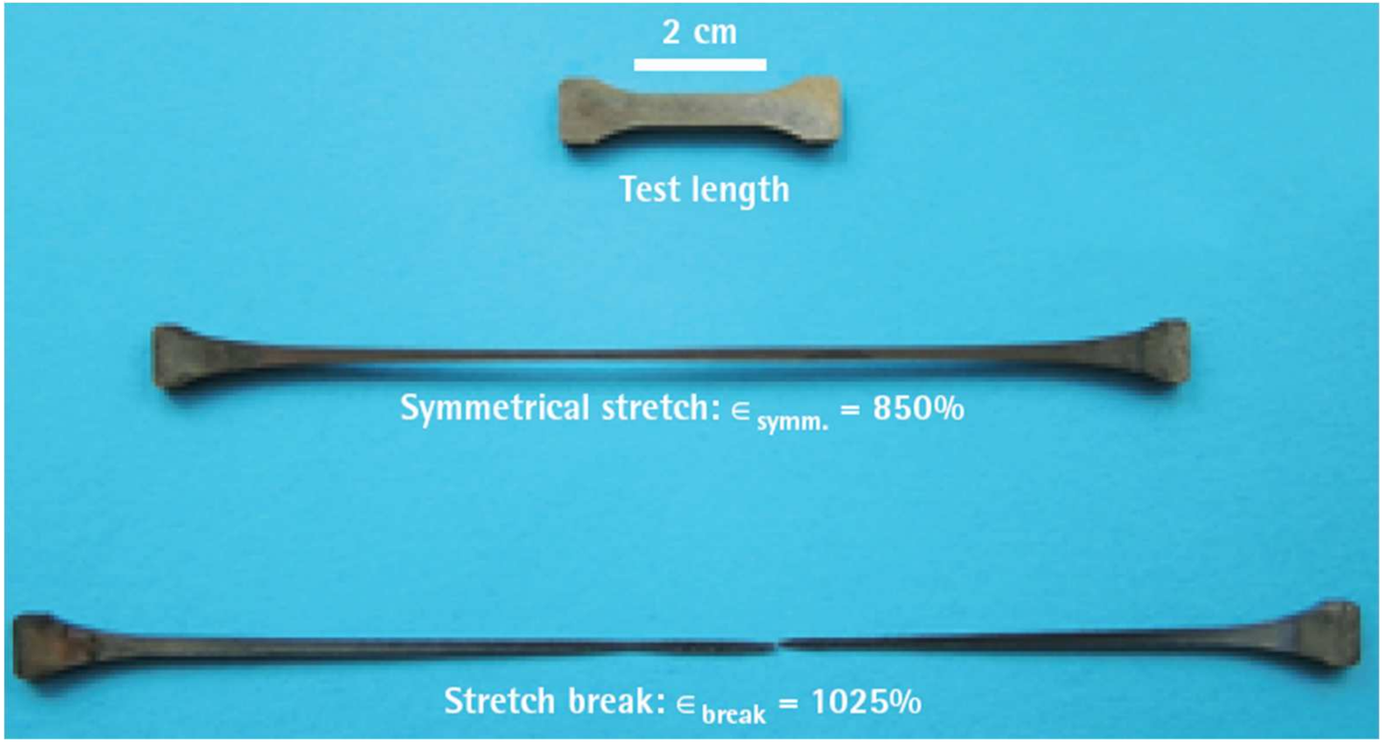


Specific Strength vs Elongation
Effect of Density



TWIP: Twinning Induced Plasticity

X-IP™: Xtremely formable + Xtremely high strength steels with Induced Plasticity
http://www.mpg.de/english/illustrationsDocumentation/multimedia/mpResearch/2004/heft04/4_04MPR_36_41.pdf



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