Karlsruhe Institute of Technology

Institute for Applied Materials

Plasticity

Lecture for "Mechanical Engineering" and "Materials Science and Engineering"

Dr.-Ing. Alexander Kauffmann (Bldg. 10.91, R. 375)
Dr.-Ing. Daniel Schliephake (Bldg. 10.91, R. 352)

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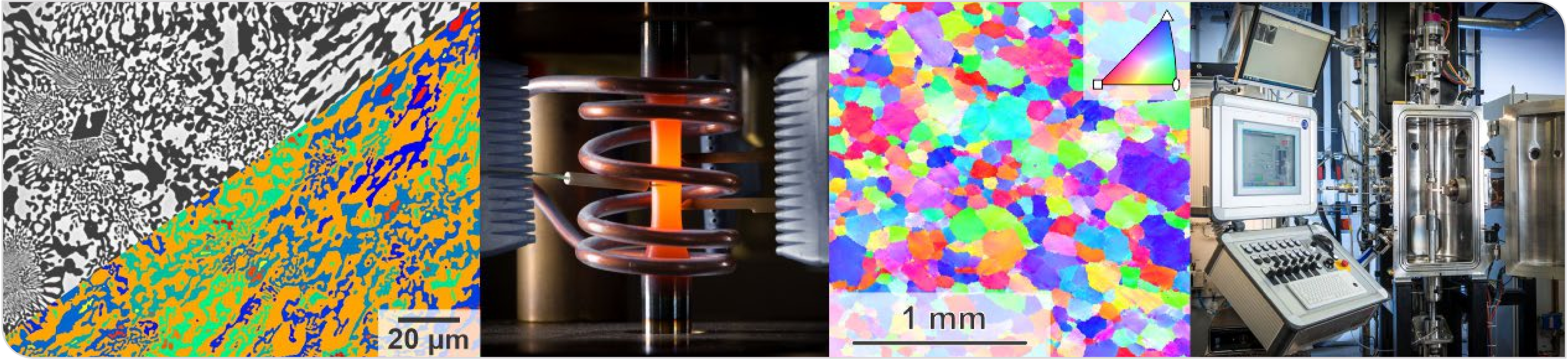


Topics

- Macroscopic Deformation: Stress Strain Curve in Tensile Tests
  - Sample Shapes
  - Tensile Test Setup
  - Quantities
  - Loading
  - Engineering Strain, Engineering Stress
  - Elastic Deformation: Stiffness/Compliance
  - Elastic-Plastic Deformation: Offset Strength
  - Localized Plastic Deformation I: Ultimate Tensile Strength, Uniform Strain
  - True strain, True stress, Work/Strain-Hardening
  - Considère Criterion
  - Localized Deformation II: Pronounced Yielding, Lüders Bands, Portevin-Le-Chatelier Effect

Revision from Other Lectures

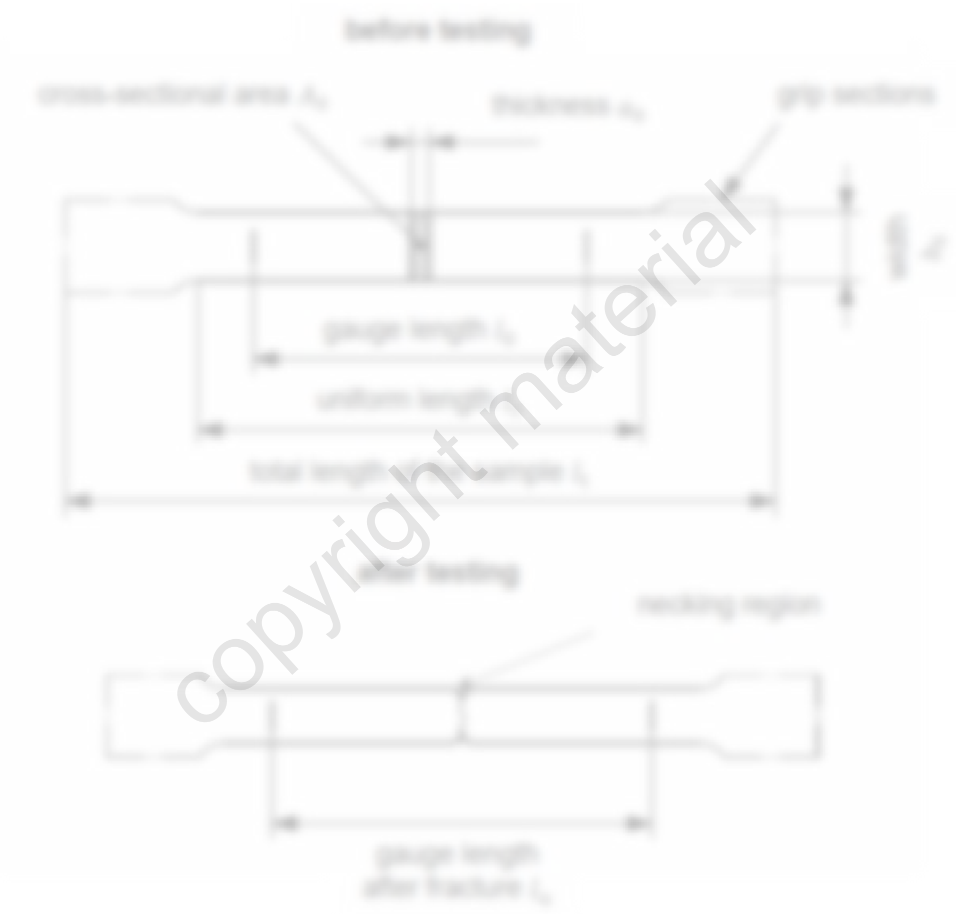
- As discussed in Ch. 1, multiple tests for the assessment of mechanical behavior exist. However, the most relevant test is still the tensile test. This chapter extensively discusses peculiarities of such tests on metallic materials. For complications in other test scenarios, we refer to other lectures.

- How is a tensile test done?
  - Which sample shapes are usually used in tensile tests?
  - Which quantities are typically controlled during the tests?
  - Which quantities are usually detected?

Sample Shapes

- In best case, the grip sections of typical tensile test specimen allow for proper **force transmission** into the sample.
- The stress state and distribution at least within the gauge length should be:
  - **uniaxial stress state**
  - **homogeneous stress state** across the cross section and along the length

Technical drawing of a tensile test specimen taken from flat semi-finished products, like tapes or flat bars:



DIN e.V.: DIN EN ISO 6892-1: Metallische Werkstoffe – Zugversuch - Teil 1, Berlin: Beuth Verlag GmbH (2009)

Sample Shapes

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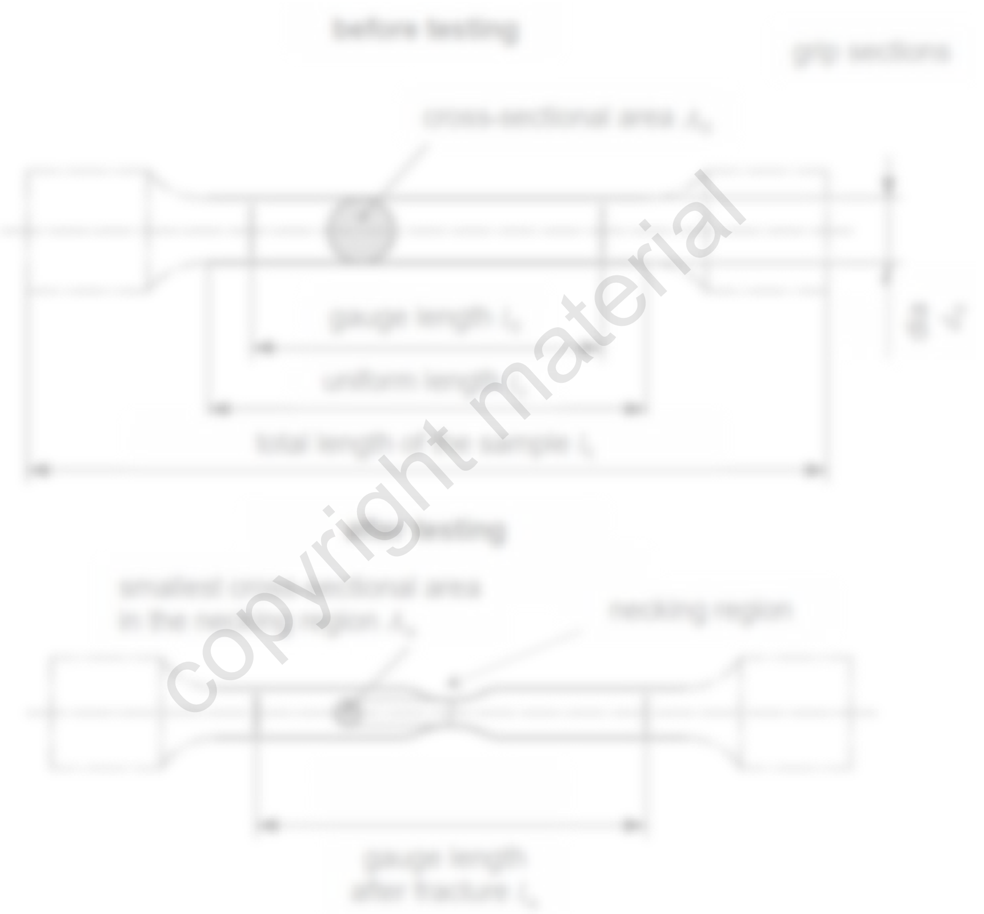
- The stress state and distribution at least within the gauge length should be:
  - **uniaxial stress state**
  - **homogeneous stress state** across the cross section and along the length

Technical drawing of a tensile test specimen taken from cylindrical semi-finished products, like rods or wires:



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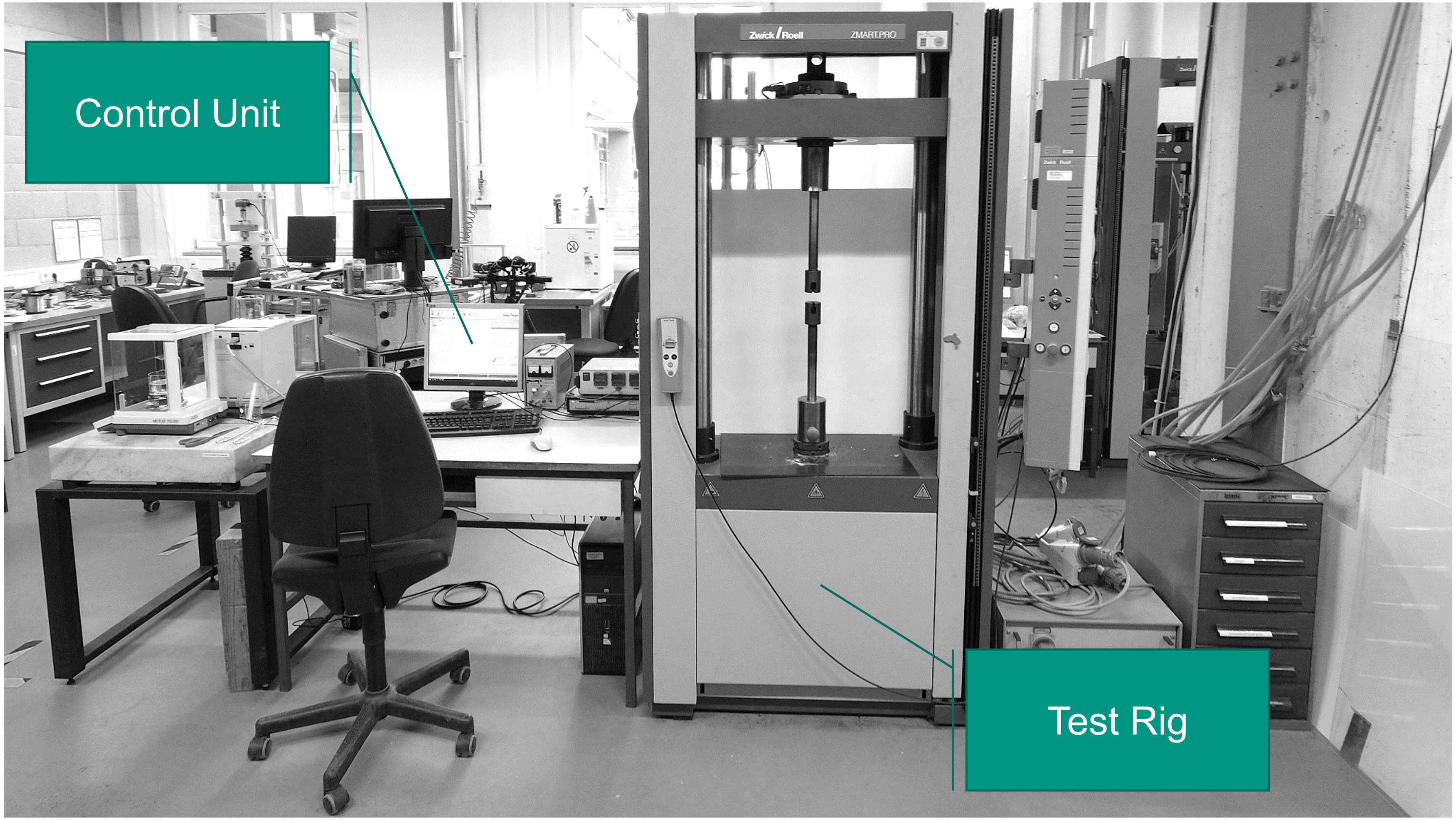
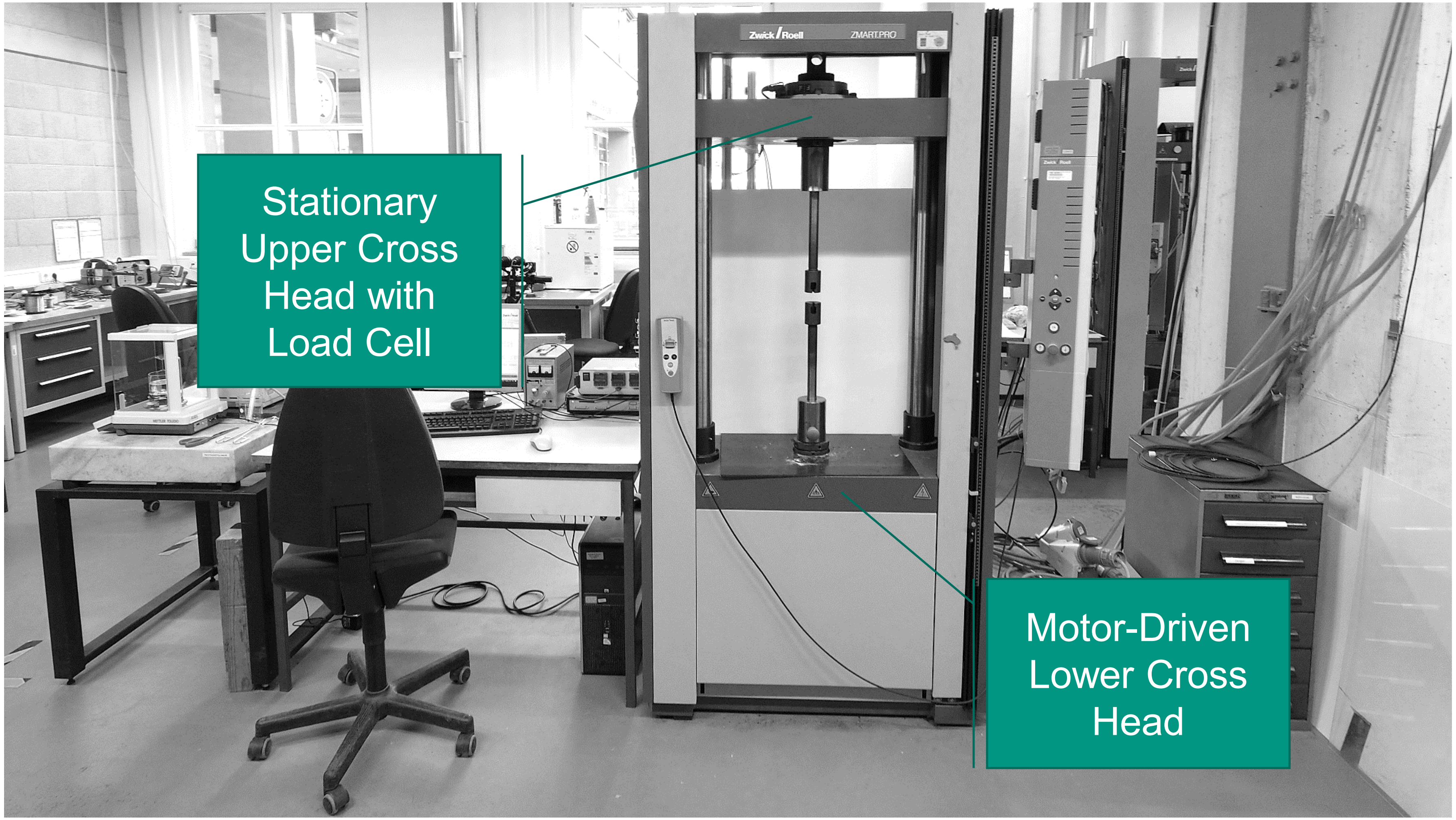
Setup

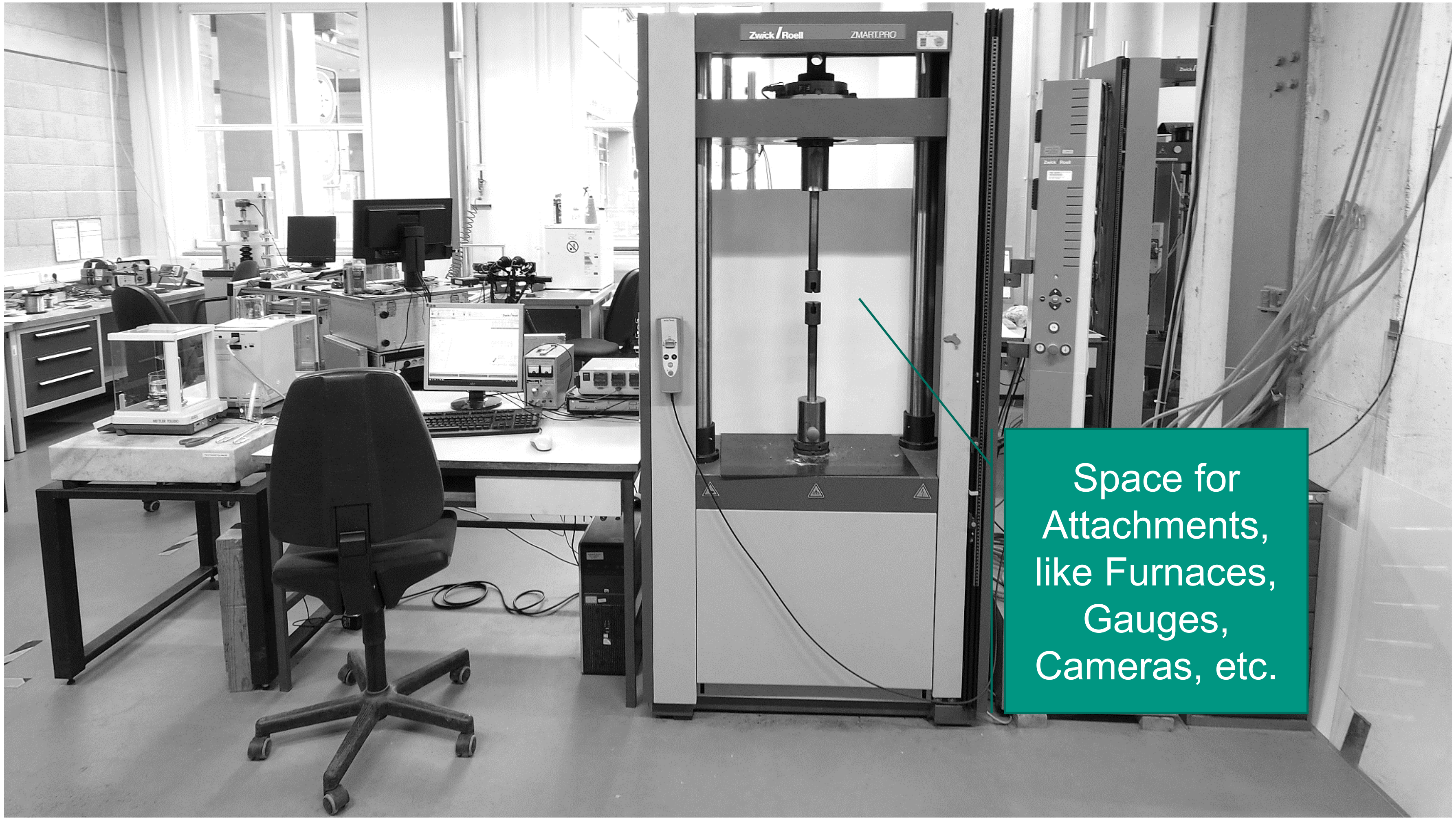


Setup


Stationary Upper Cross Head with Load Cell
Motor-Driven Lower Cross Head
Zwick/Roell
ZMART.PRO

Setup

Setup


Zwick/Roell
ZMART.PRO
Space for Attachments, like Furnaces, Gauges, Cameras, etc.

Quantities

- During the test, following quantities are typically recorded:
  - **Force**
  - **Cross Head Position**
  - **Strain**
- Force is measured by load cells of different technology. They differ in precision, linearity, sensitivity and force range (e.g. tension and compression).
- Strain is measured in different ways, e.g. tactile by attachment gauges, DMS gauges, optical by digital image correlation.

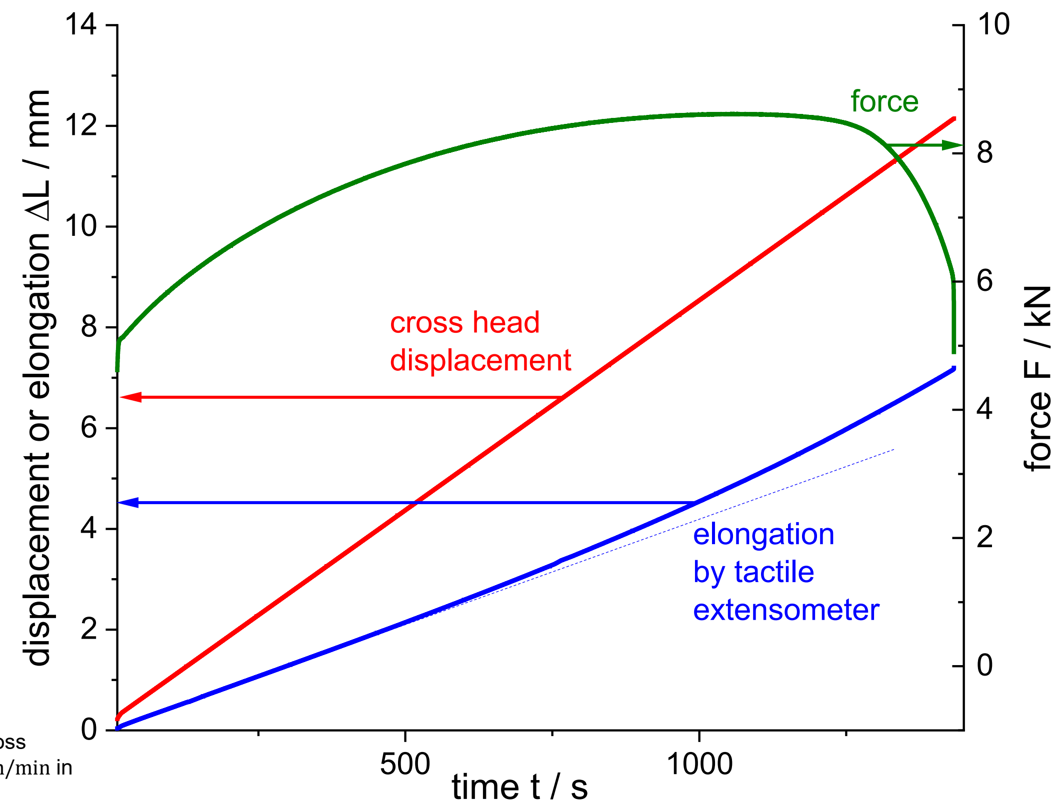
Different types of load cells and strain measurement systems:

https://www.zwickroell.com/fileadmin/content/Files/SharePoint/user_upload/Brochures_DE/Industry_Brochures/99_253_Pruefmaschinen_und_Pruefsysteme_fuer_Metall_D_DE.pdf
https://www.instron.com/de-de/products/testing-accessories/extensometers/high-temperature/950-deg-c/2632-056
https://www.zwickroell.com/fileadmin/content/Files/SharePoint/user_upload/PI_EN/08_684_videoXtens_biax_2_150_HP_PI_EN.pdf
https://www.nextgentest.com/blog/the-importance-of-an-extensometer-in-materials-testing/

Loading

- In most cases, loading occurs at **constant, slow cross head velocity** in order to achieve a **quasistatic** test at *initial* strain rates of typically 10^{-5} to $10^{-3}\ s^{-1}$.
- Only in special cases, a strain-controlled or force-controlled test is performed with a closed-loop control (strain/force is recorded and cross head speed is adjusted to meet constant strain/force rate)

Comparison of signals obtained during tensile tests:

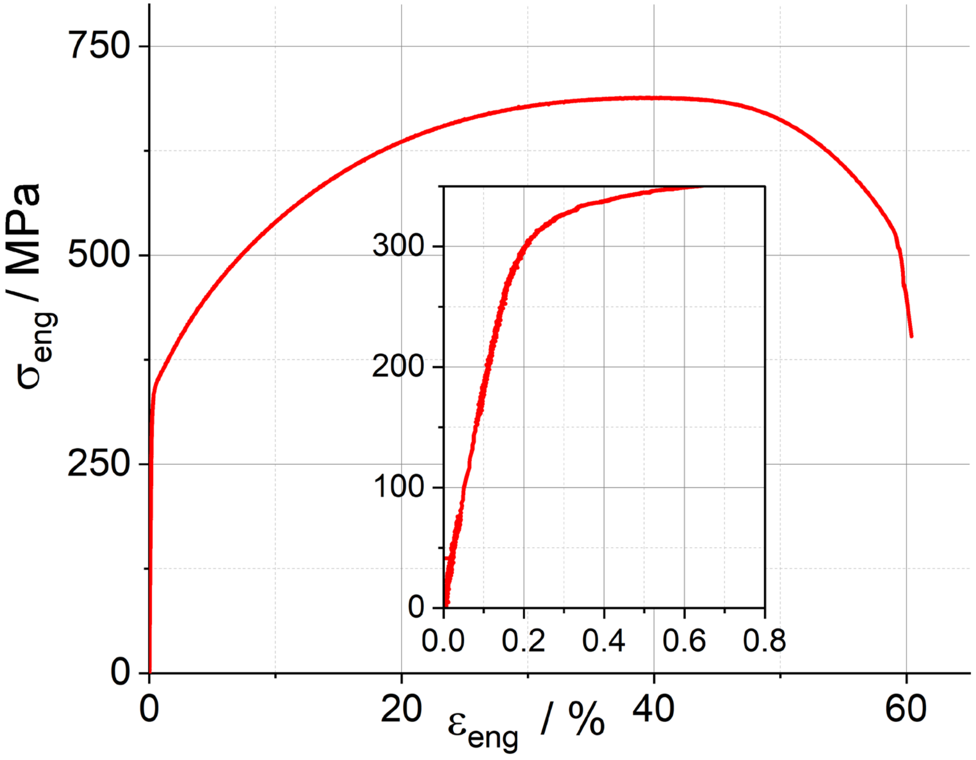


Note the linear rate of the cross head displacement at $0.5\ \mathrm{mm/min}$ in comparison to the non-linear response of strain/sample elongation due to non-linearity of the gauge and machine stiffness contribution.

Plasticity in Metals, Alloys and Intermetallics

- **Metallic materials are very ductile even though being crystalline!**
- The chapter will deal with the macroscopic interpretation of simple mechanical tests.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C/vacuum/1 h/water-quenched, 4 mm diameter) at room temperature

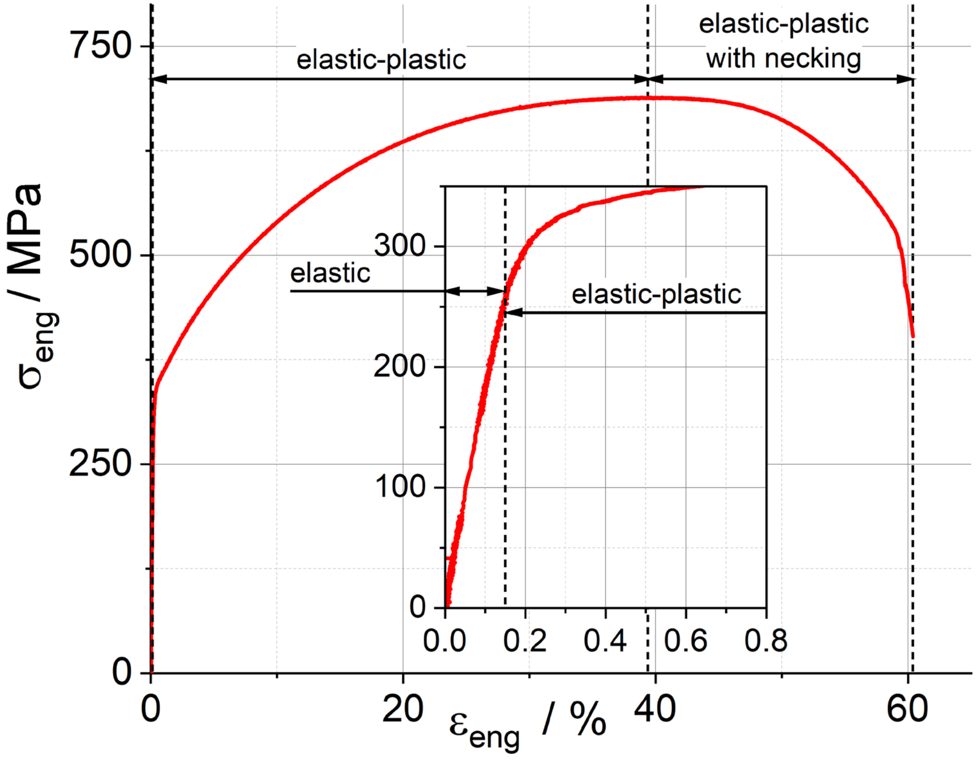


A. S. Tirunilai: "Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures", Journal of Materials Research 33 (2018) 3287-3300

Stages of Tensile Tests

- Stages of the deformation during the tensile test:
  - **Linear-elastic deformation**
    (reversible (almost) without internal friction)
  - **Elastic-plastic deformation**
    (partially reversible, partially irreversible)
  - **Elastic-plastic deformation with necking**
    (localization of plastic deformation)
- Mostly presented using engineering quantities:
  - **Engineering strain** $\varepsilon_{\mathrm{eng}} = \frac{\Delta l}{l_0}$
    (sometimes “total strain”)
  - **Engineering stress** $\sigma_{\mathrm{eng}} = \frac{F}{A_0}$
    (sometimes “nominal stress”)

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*



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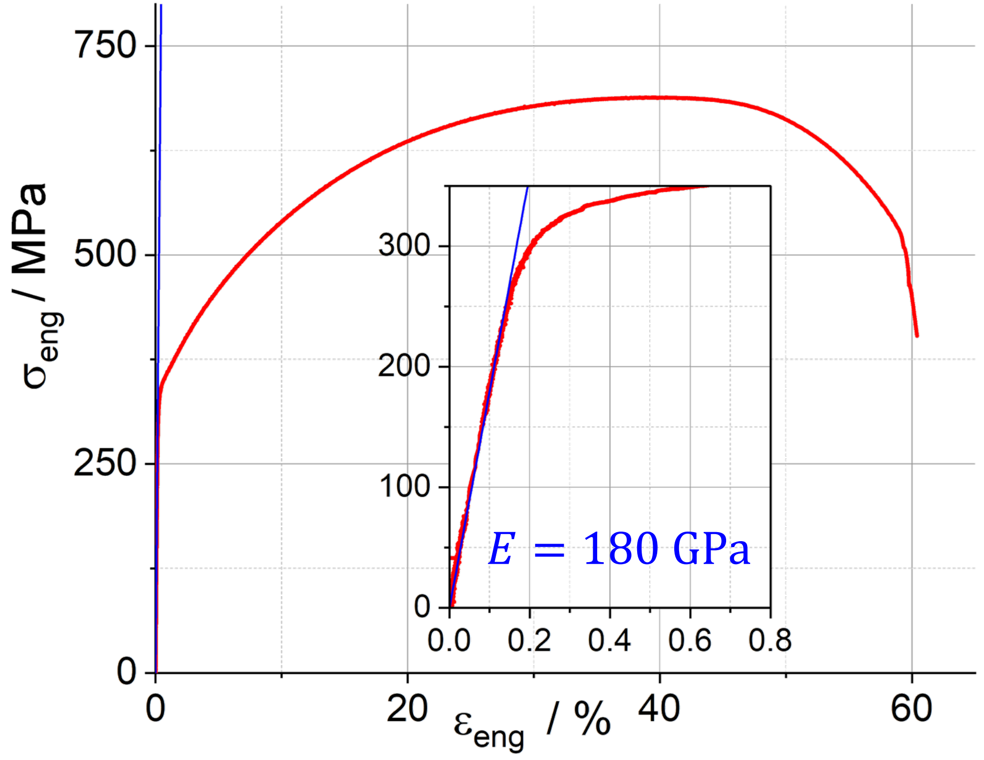
Linear-Elastic Deformation

- The linear-elastic region can be described by Hooke's law:
  $\sigma_{\text{eng}} = E \cdot \varepsilon_{\text{eng}}$.
- E is the **resistance against elastic deformation** and called **Young's modulus**.
- In case of polycrystals, E corresponds to an averaging of the compliance/stiffness values weight by the orientations distribution function (see Ch. 3). It mostly determined by the base element of an alloy, its crystal structure and bond type.
- E is one particular stiffness property. Depending on the loading conditions, there are also other stiffness properties, like for example G with $\tau = G \cdot \gamma$ or K with $p = -K \cdot \frac{\Delta V}{V}$.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ ^\circ\text{C}$*/vacuum/*$1\ \text{h}$*/water-quenched,* $4\ \text{mm}$ *diameter) at room temperature*



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Isotropic, Linear-Elastic Deformation

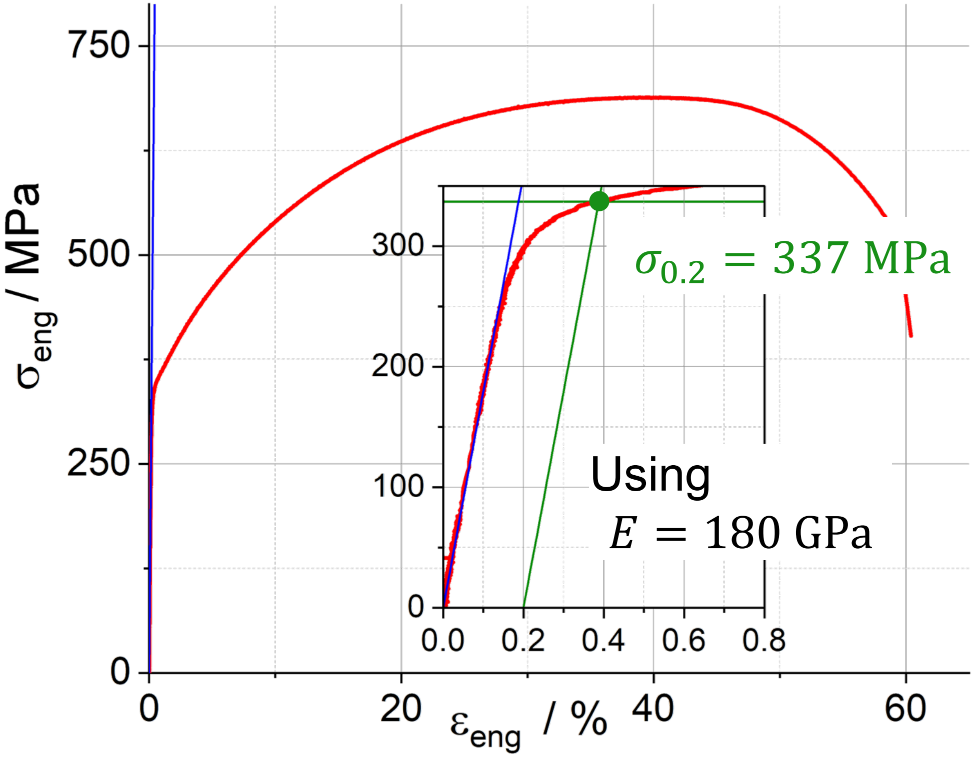
Material	Prototype	Strukturbericht	G / GPa	ν / 1	E / GPa
Cu	Cu	A1	48	0.34	130
Al			26	0.34	70
Au			28	0.42	79
Ni			76	0.31	201
α-Fe	W	A2	82	0.29	212
W			160	0.28	411
Mg	Mg	A3	17	0.29	45
Zn			42	0.25	104
α-Ti			44	0.32	117
Si	diamond	A4	80	0.22	145
NaCl	NaCl	B1	20	0.34	53

G. W. C. Kaye & T. H. Laby: “Tables of Physical and Chemical Constants”, Essex, England; New York: Longman (1995)
M. Matsui: “Simultaneous sound velocity and density measurements of NaCl at high temperatures and pressures: Application as a primary pressure standard”, American Mineralogist 97 (2012) 1670-1675

Elastic-Plastic Deformation

- In the elastic-plastic region, some portion of the deformation is irreversible.
- The onset of plastic deformation is called **yield strength σ_y** and determines the **resistance against plastic deformation**.
- In the case of rather continuous stress-strain curves **without pronounced yielding**, **offset strength** is used to describe onset of plastic deformation. For example $\sigma_{0.2}$ is the **resistance against 0.2% plastic strain**.
- Anyhow, **both quantities indicate macroscopic strength**. **Microscopic plasticity is taking place also at stresses below σ_y**.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ °C$/vacuum/$1\ h$/water-quenched, $4\ mm$ diameter) at room temperature



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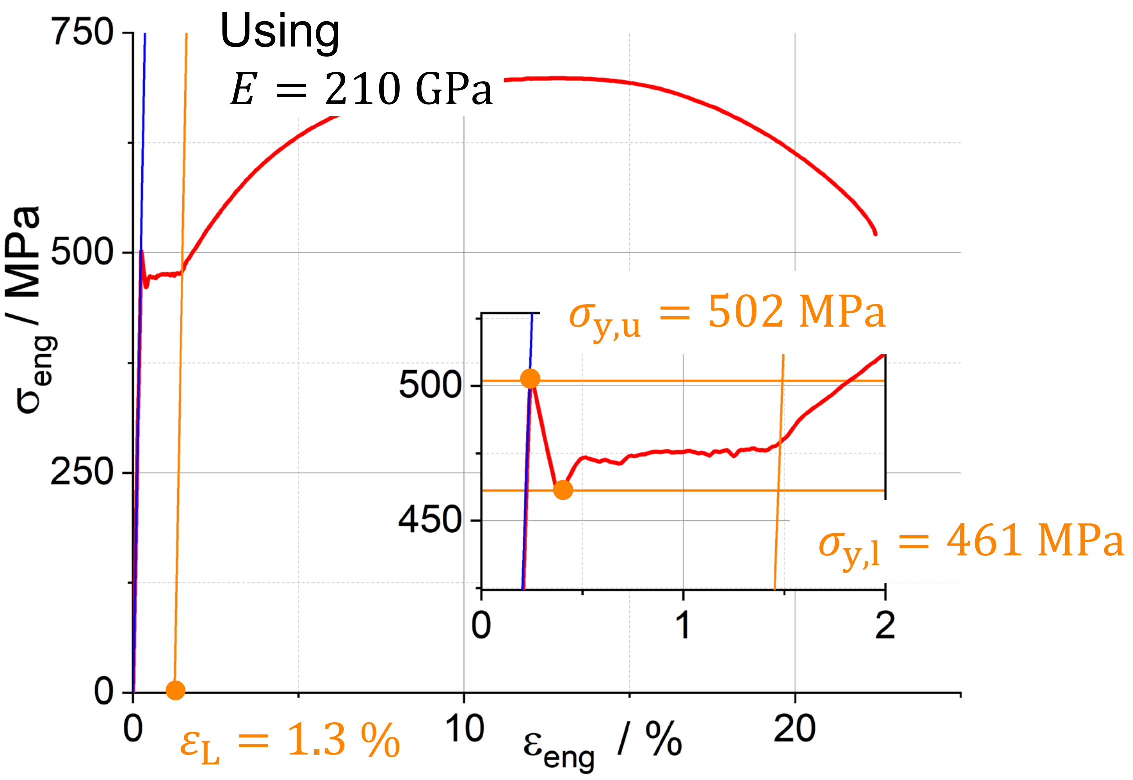
Elastic-Plastic Deformation

- In some cases, a pronounced yield point phenomenon occurs.
- It is a result of localized plastic deformation as discussed in the later part of Ch. 2.
- Apart from σ_{y}, an **upper** $\sigma_{\mathrm{y,u}}$ and **lower yield strength** $\sigma_{\mathrm{y,l}}$ are differentiated if a **drop in stress** occurs after initiation of plastic deformation.
- In case of a pronounced yield point, a **yield point elongation (better yield point strain)** or **Lüders strain** ε_{L} can be determined.

Example: tensile test conducted on normalized C45 plain carbon steel (880 °C/air/30 min/air-cooled, 4 mm diameter) at room temperature

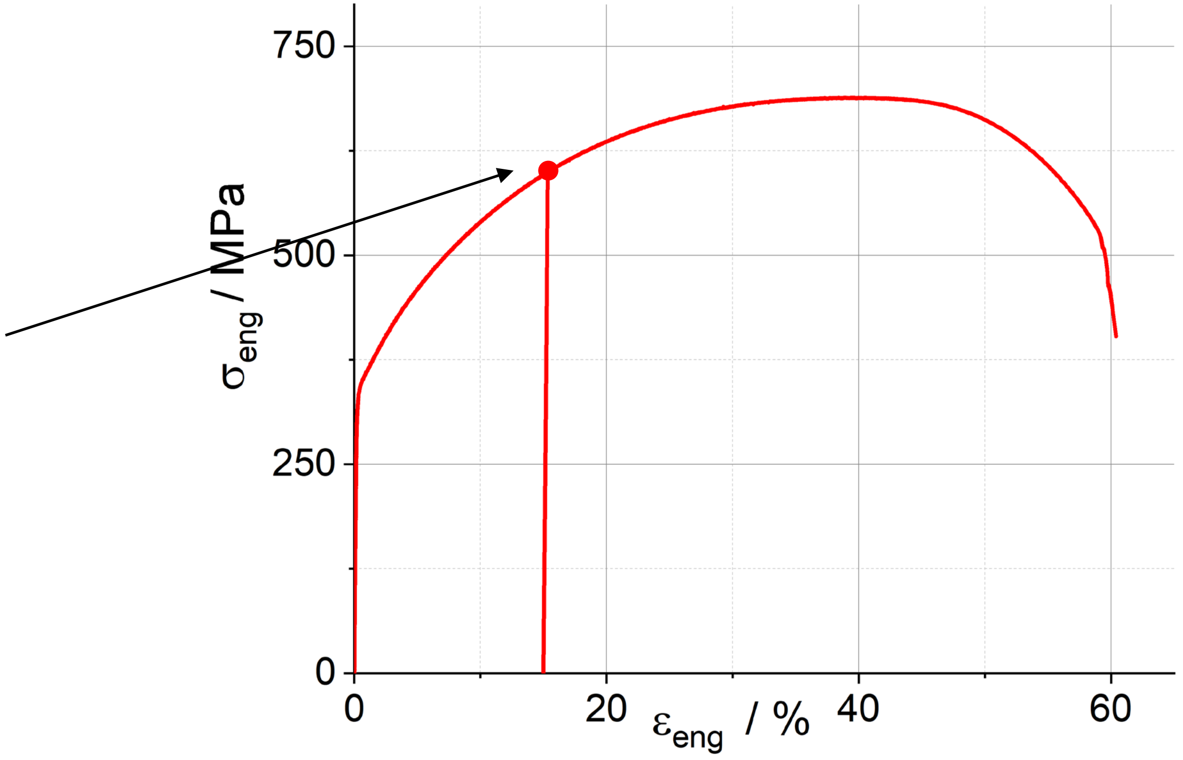


Elastic-Plastic Deformation

- During unloading, **the elastic deformation *almost** resets**.
- **Onset of plasticity during re-loading is observed at a higher stress in comparison to the initially undeformed material.** This is called strain- or **work-hardening**.

* Bauschinger effect

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*



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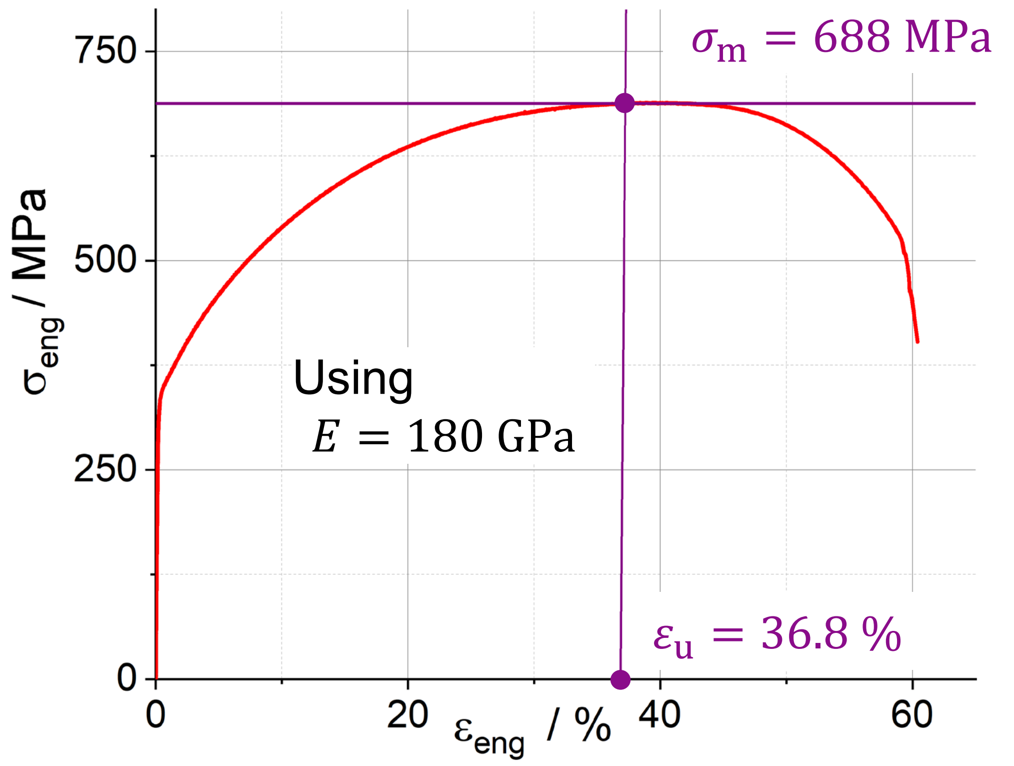
Necking

- **Ultimate tensile strength** σ_m determines the **maximum engineering stress** that the sample can resist. Beyond σ_m, the sample exhibits **necking** and the **plastic deformation becomes localized** to a small portion of the gauge length.
- Plastic strain which achieved up to σ_m is called **uniform elongation** ε_u **(common but imprecise; better to use uniform strain)**.
- Necking occurs due to the **mechanical-geometrical instability** of the tensile test.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ °C$*/vacuum/*$1\ h$*/water-quenched,* $4\ mm$ *diameter) at room temperature*



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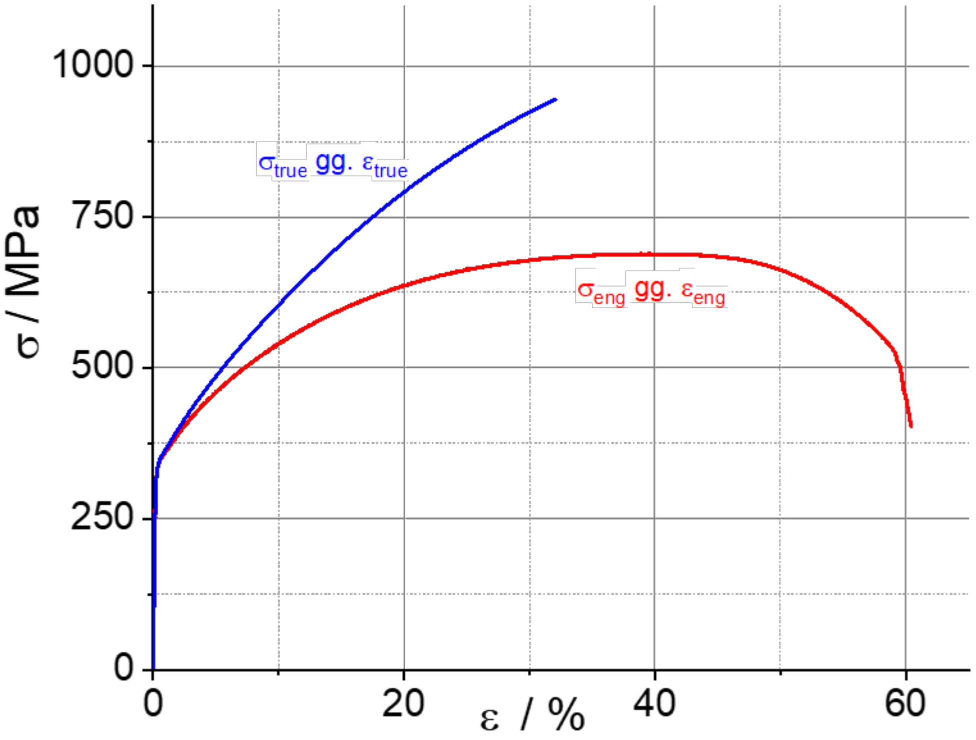
True Stress, True Strain

- For further analysis, the introduction of instantaneous stresses and strains is useful, true strain and true stress:
  - $\mathrm{d}\varepsilon_{\mathrm{true}} = \frac{\mathrm{d}l}{l}$, hence, $\varepsilon_{\mathrm{true}} = \ln\frac{l}{l_0}$
  - $\sigma_{\mathrm{true}} = \frac{F}{A}$
- Assuming uniform elongation (prismatic sample shape) and volume conservation:
  - $V = A_0\, l_0 = A\, l = \mathrm{const.}$
  - hence, $A = \frac{A_0}{1+\varepsilon_{\mathrm{eng}}}$

  gives
  - $\sigma_{\mathrm{true}} = \sigma_{\mathrm{eng}}\left(1+\varepsilon_{\mathrm{eng}}\right)$
  - $\varepsilon_{\mathrm{true}} = \ln\left(1+\varepsilon_{\mathrm{eng}}\right)$

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*



Note that true strains can be added while engineering strains cannot.

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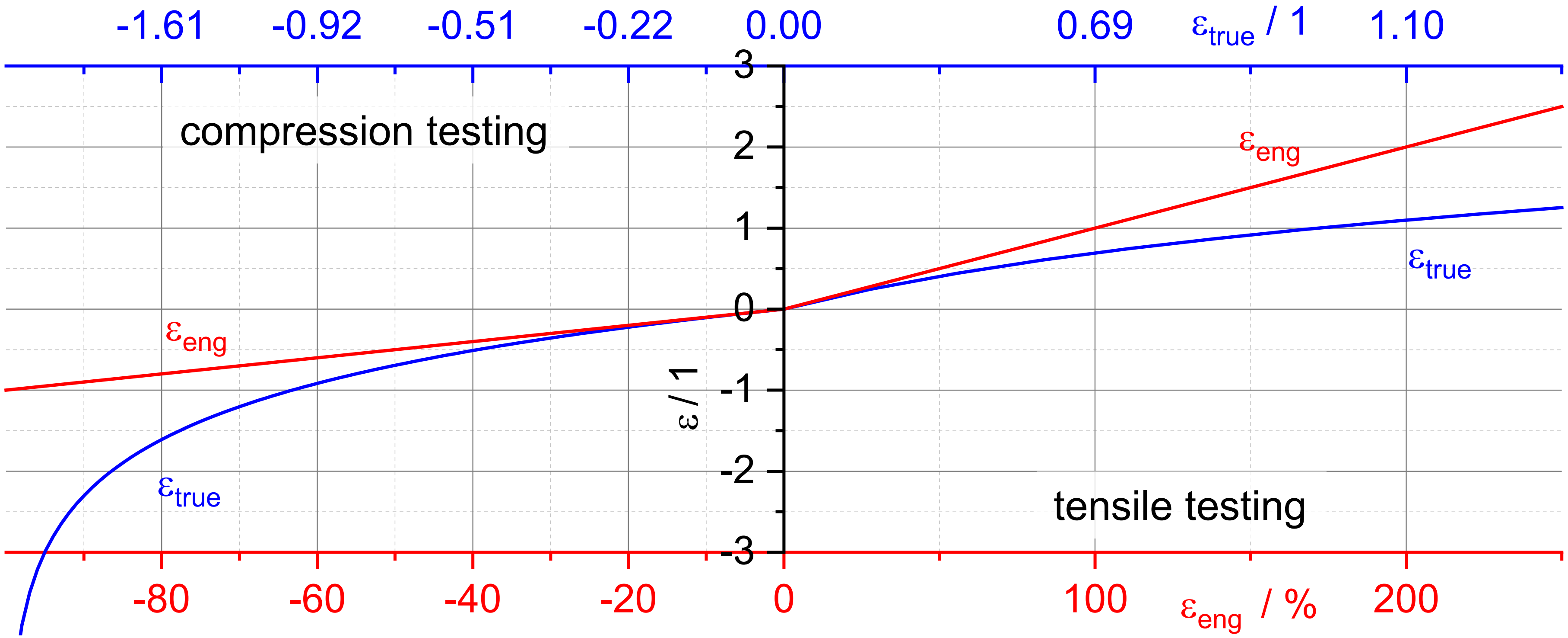
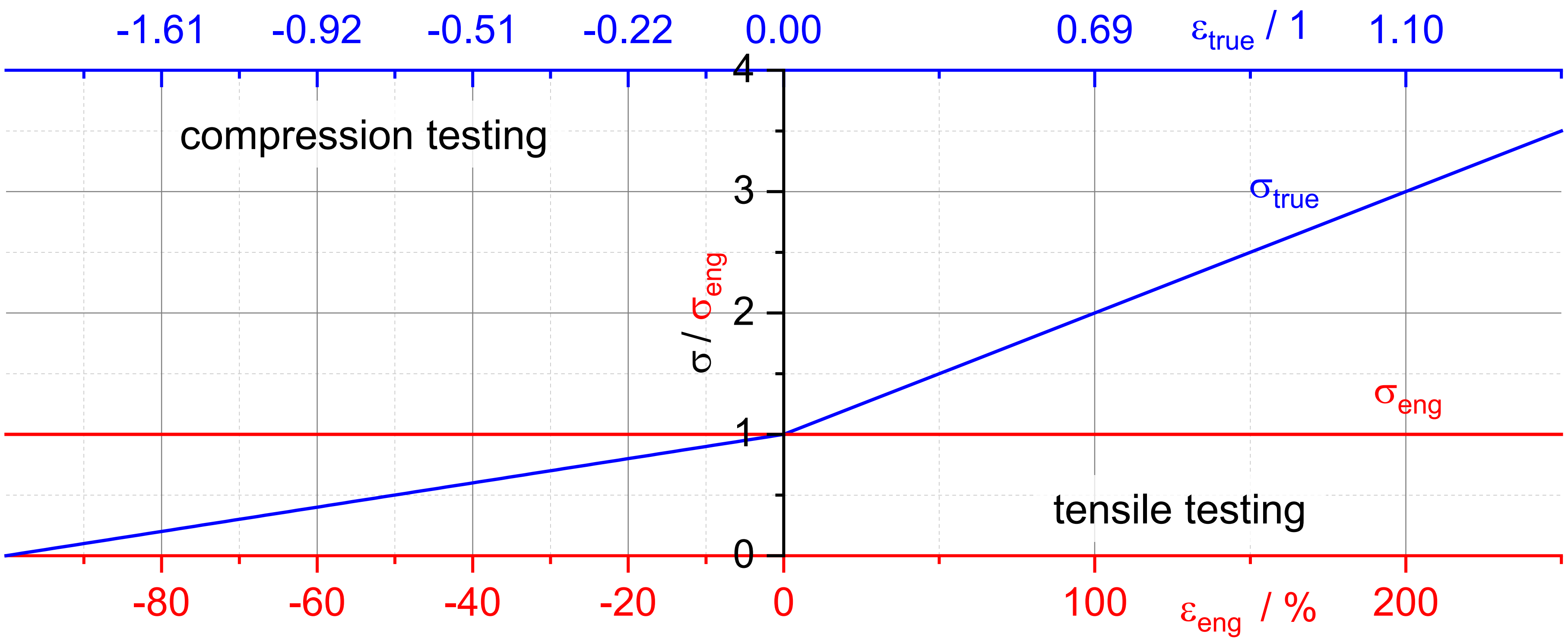
True Stress, True Strain

Direct comparison of $\varepsilon_{\mathrm{true}}$ and $\varepsilon_{\mathrm{eng}}$ as a function of $\varepsilon_{\mathrm{eng}}$.



True Stress, True Strain

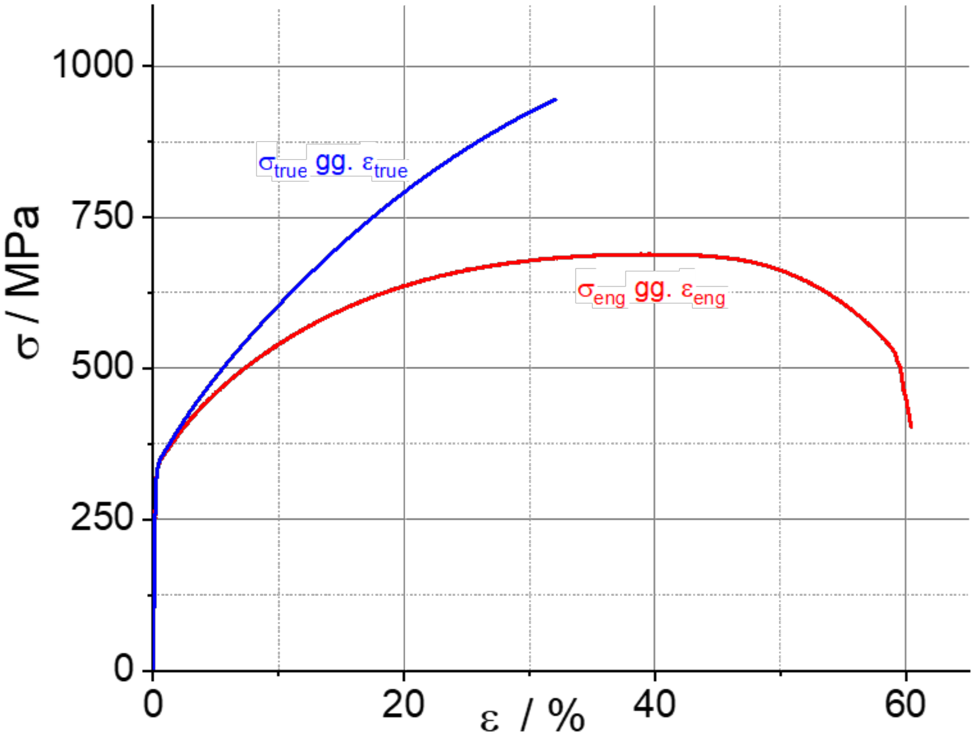
Direct comparison of σ_{true} and σ_{eng} as a function of ε_{eng}.



True Stress, True Strain

- **Volume conservation is an assumption not a prerequisite**, also for plastic deformation!
- Strictly, **volume conservation** requests a Poisson's ratio of $\nu = 0.5$. For the elastic region, ν is typically about 0.3, it continuously increases to 0.5 after yielding. **The deviations are usually neglected when converting from engineering to true quantities**.
- In the necking region, the analytical conversion from engineering to true quantities is not possible anymore. You need to locally resolve strain and stress, for example by DIC.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ °C$*/vacuum/*$1\ h$*/water-quenched,* $4\ mm$ *diameter) at room temperature*



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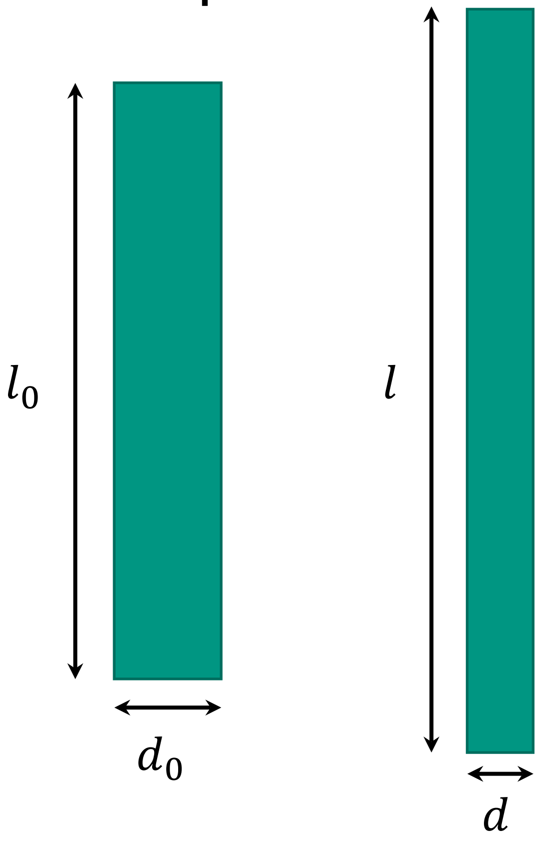
Poisson's Ratio

- Describes the negative ratio of axial strain ε_{ax} and transversal strain ε_{tr} under uniaxial tension/compression:

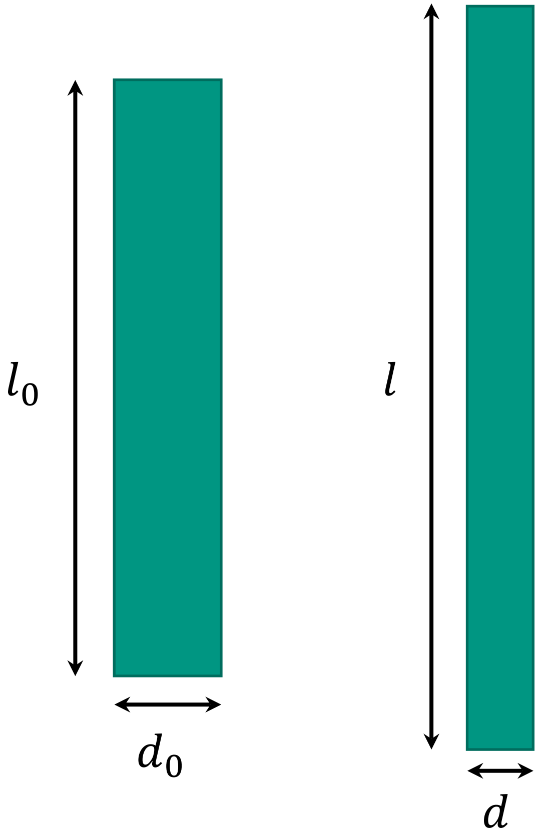


$$\varepsilon_{ax} = \frac{l - l_0}{l_0} \qquad \varepsilon_{tr} = \frac{d - d_0}{d_0}$$

$$\nu = -\frac{\varepsilon_{tr}}{\varepsilon_{ax}}$$

Poisson's Ratio

- Volume change during deformation:



$$V_0 = A_0\, l_0 \qquad V = A\, l$$

Assuming a prismatic rod shape:

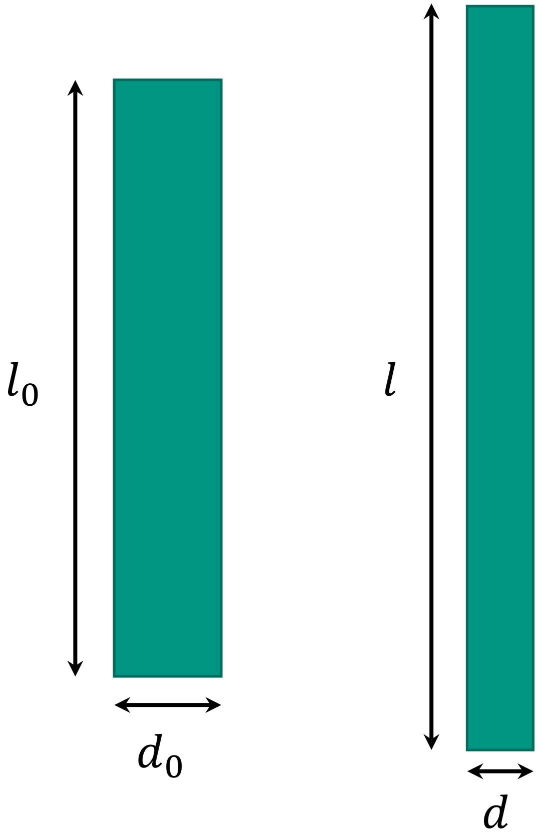
$$A_0 = \frac{\pi}{4}\, d_o^2 \qquad A = \frac{\pi}{4}\, d^2$$

$$V_0 = \frac{\pi}{4}\, d_0^2\, l_0 \quad V = \frac{\pi}{4}\, d^2\, l$$

$$\frac{V - V_0}{V_0} = \frac{d^2\, l - d_0^2\, l_0}{d_0^2\, l_0} = \frac{d^2\, l}{d_0^2\, l_0} - 1$$

Poisson's Ratio

- Volume change during deformation:



Assuming a prismatic rod shape:

$$\frac{V - V_0}{V_0} = \frac{d^2\, l}{d_0^2\, l_0} - 1$$

$$\frac{V - V_0}{V_0} = \frac{(\varepsilon_{tr} + 1)^2\, d_0^2\, (\varepsilon_{ax} + 1)\, l_0}{d_0^2\, l_0} - 1$$

$$= (\varepsilon_{tr} + 1)^2\, (\varepsilon_{ax} + 1) - 1$$

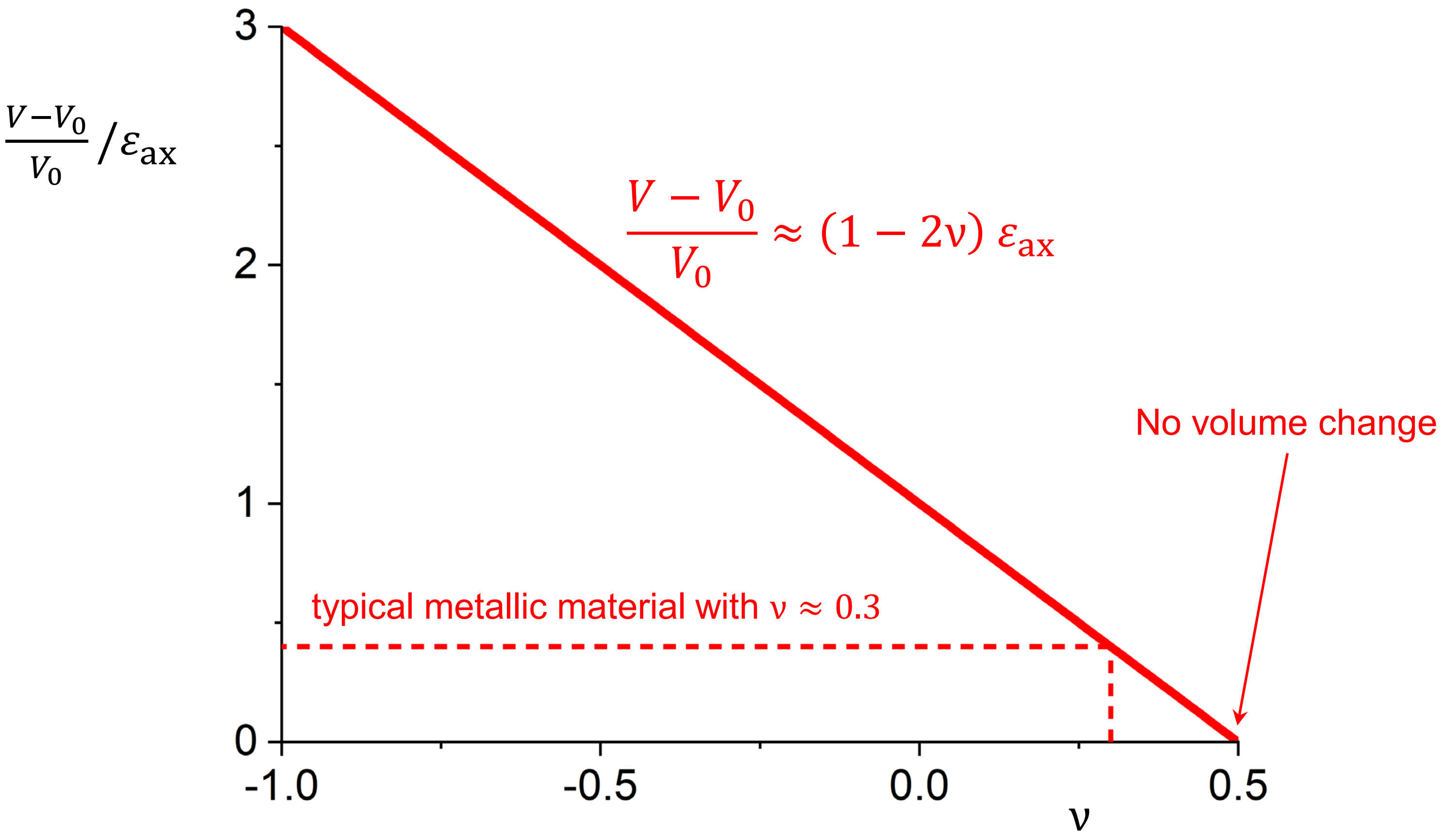
$$\frac{V - V_0}{V_0} = \varepsilon_{ax} - 2\nu\, \varepsilon_{ax} - 2\nu\, \varepsilon_{ax}^2 + \nu^2\, \varepsilon_{ax}^2 + \nu^2\, \varepsilon_{ax}^3$$

Assuming small strains $\varepsilon_{ax} \ll 1$:

$$\frac{V - V_0}{V_0} \approx (1 - 2\nu)\, \varepsilon_{ax}$$

Poisson's Ratio

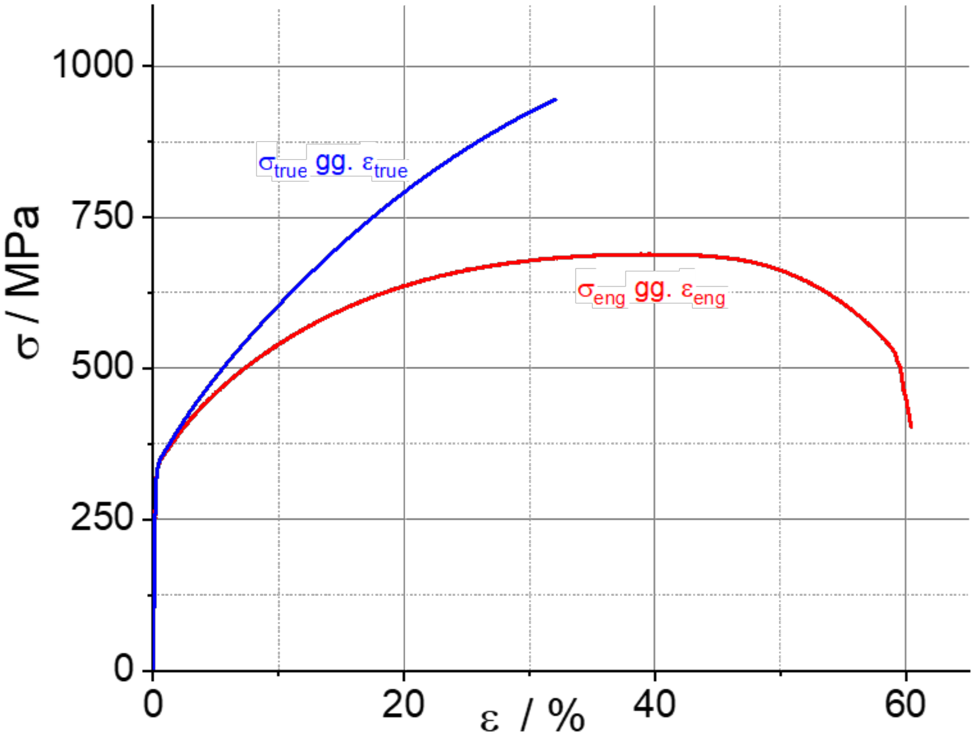
- Volume change during deformation:



Stability vs. Instability

- Loading of a sample in tensile geometry leads to two different contributions to the force:
  - **Geometrical softening**: during loading, the cross section of the sample becomes smaller. In case of nil resistance against further deformation, the force needed to deform would become smaller.
  - **Intrinsic strengthening**: The material itself work-hardens; its yield strength is continuously increasing.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*



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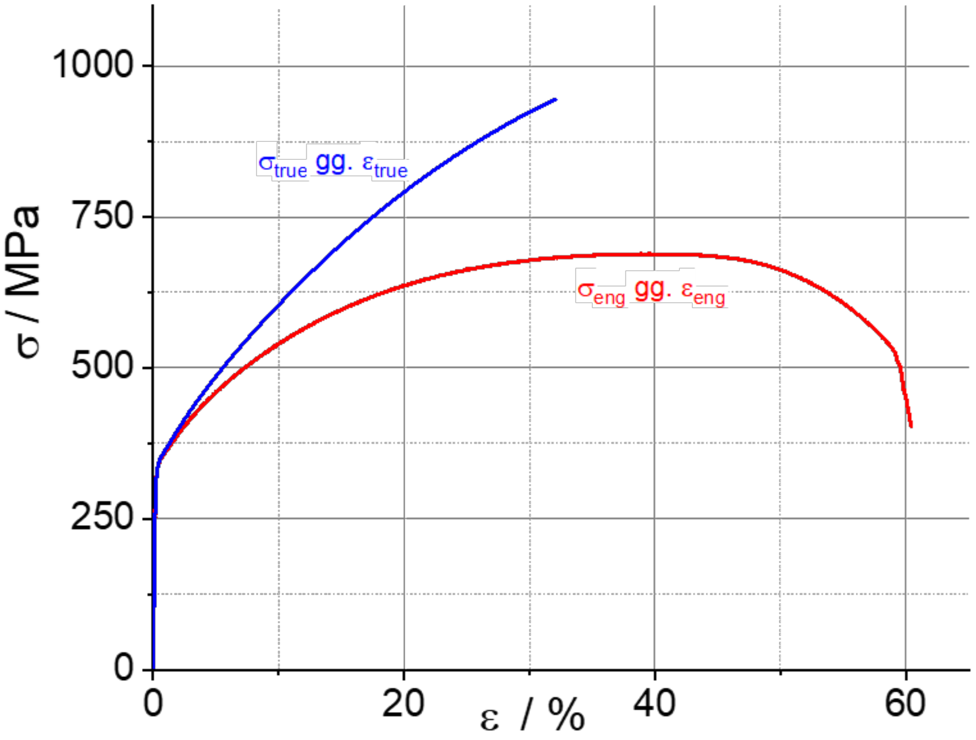
Stability vs. Instability

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C/vacuum/1 h/water-quenched, 4 mm diameter) at room temperature

- Up to the uniform strain, the tensile test is **stable**.
- Any **perturbation of the cross sectional area** results in **localized plastic deformation due to stress concentration**.
- The localized plastic deformation leads to a **sufficient work-hardening to prevent further localization**.
- Hence, the localization of plastic deformation is stopped by the intrinsic work-hardening.



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Stability vs. Instability

- Beyond the uniform strain, any perturbation of the cross sectional area still leads to localization of plastic deformation due to stress concentration.
- The **intrinsic work-hardening is not sufficient to prevent the further stress concentration by the further decreasing cross sectional area**. The test is unstable.
- The sample is **only deforming at the weakest perturbation** and **necking occurs**.
  (Note that the perturbation must not only be of geometrical nature, a locally smaller strength can also be point of necking initiation.)

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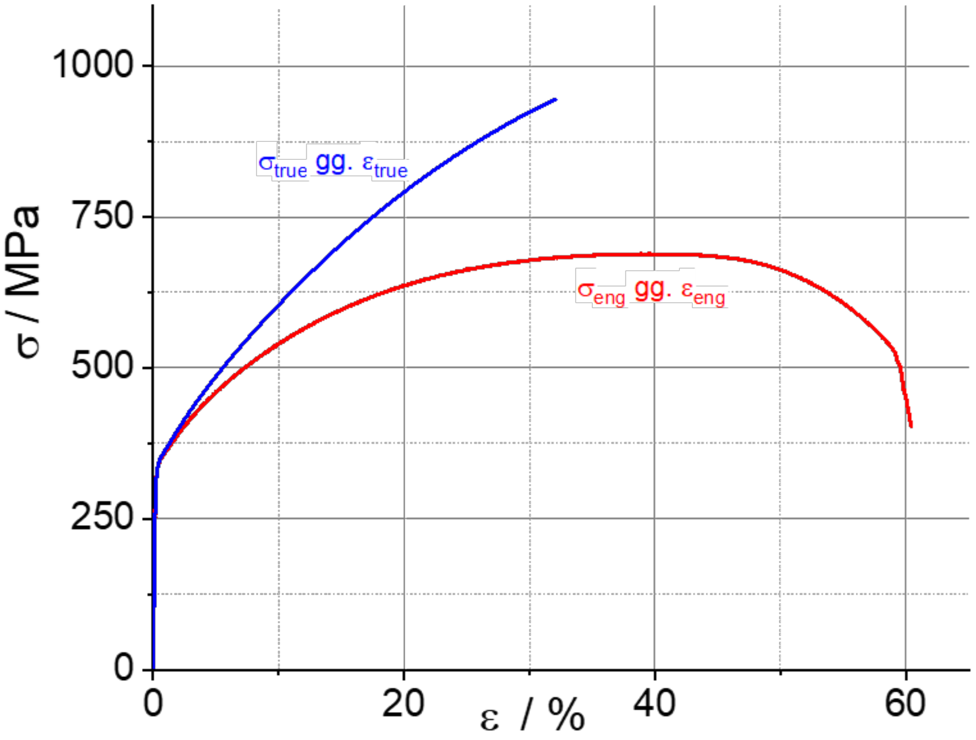

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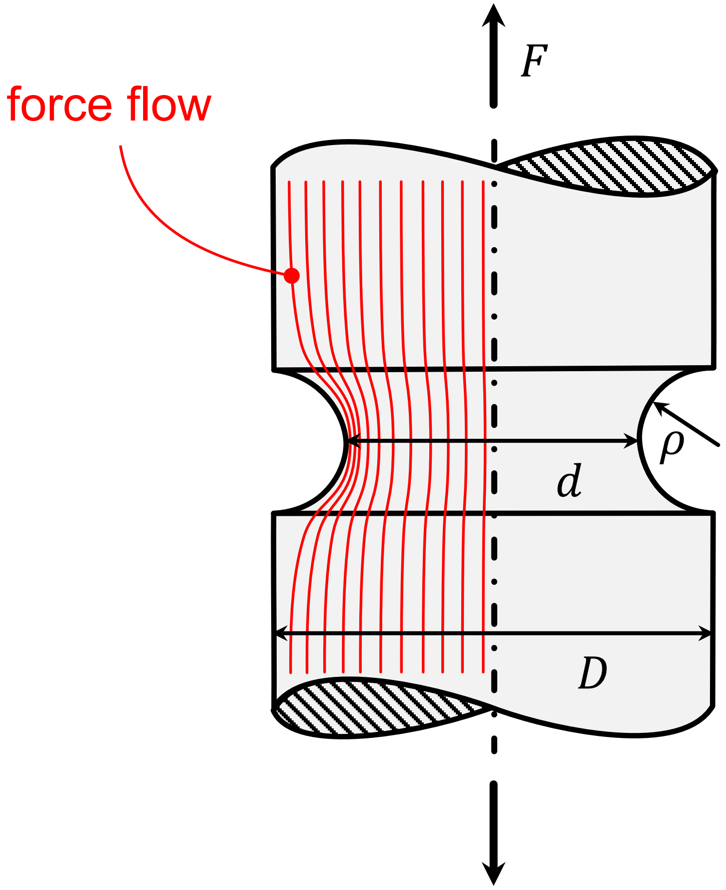
Notch Effect and Stress Concentration

- Example for force flow in a cylindrical sample with round notch under tension load.
- The flow lines follow the principle stress directions.
- The density of the flow lines corresponds to the local stress.
- The notch causes:
  - (1) **locally higher stress** $\sigma_k > \sigma_n$ due to the reduced cross sectional area
  - (2) a **stress concentration** $\sigma_{max} \gg \sigma_k > \sigma_n$ in the notch surface due to adoption of force flow
  - (3) **multiaxial stress state** in the notch region
- The detrimental effect of the notch depends on its sharpness ρ and depth $(D-d)/2$. The round notch ($\rho = (D-d)/2$) with $d = 90\ \%\ D$ results in a stress concentration of $\frac{\sigma_{max}}{\sigma_k} = 2.7$! Extreme cases of notches are cracks that exhibit essentially atomic sharp tip radii and depth according to the crack length.



Schematic of the force flow in a rod with circumferential notch loaded by the force F in axial direction.

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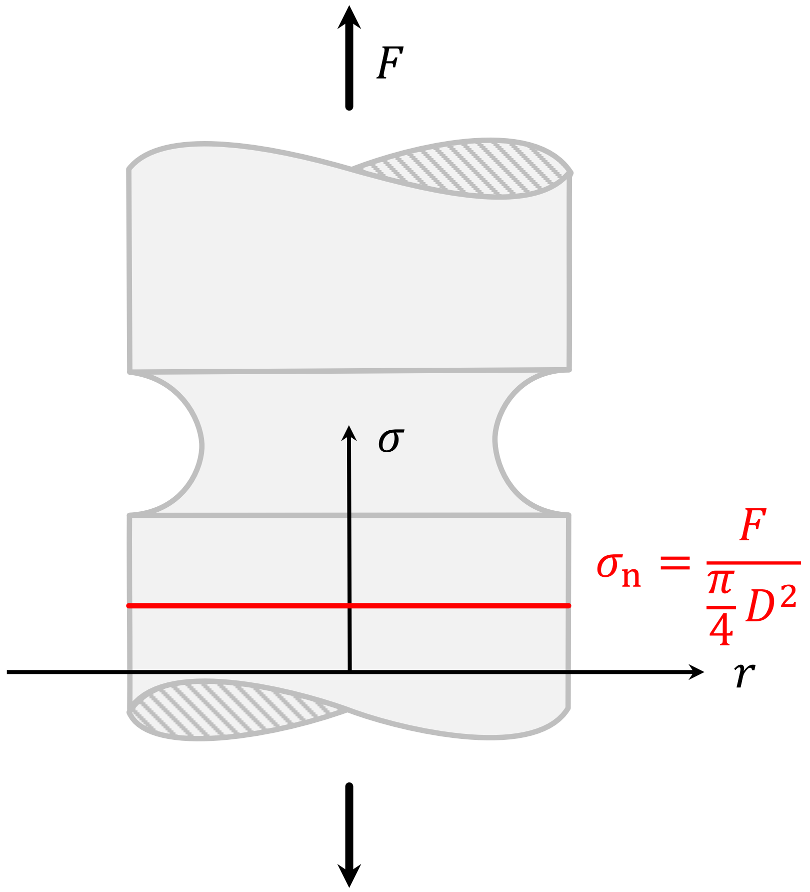

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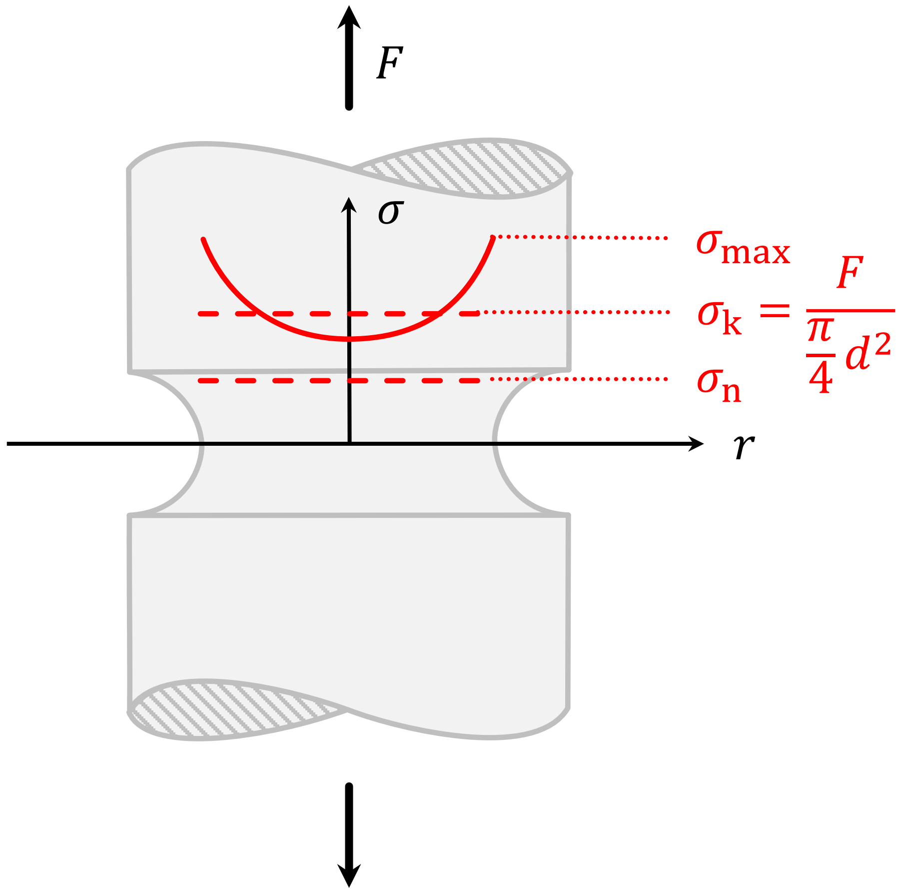
  - (1) **locally higher stress** $\sigma_\mathrm{k} > \sigma_\mathrm{n}$ due to the reduced cross sectional area
  - (2) a **stress concentration** $\sigma_\mathrm{max} \gg \sigma_\mathrm{k} > \sigma_\mathrm{n}$ in the notch surface due to adoption of force flow
  - (3) **multiaxial stress state** in the notch region
- The detrimental effect of the notch depends on its sharpness ρ and depth $(D-d)/2$. The round notch ($\rho = (D-d)/2$) with $d = 90\,\%\,D$ results in a stress concentration of $\frac{\sigma_\mathrm{max}}{\sigma_\mathrm{k}} = 2.7$! Extreme cases of notches are cracks that exhibit essentially atomic sharp tip radii and depth according to the crack length.



Schematic of the force flow in a rod with circumferential notch loaded by the force F in axial direction.

Stability vs. Instability

- The stable test requests that the force carried along the sample axis x is constant:

$$F = \sigma_{\text{true}}(x) \cdot A(x) = \text{const.}\ \forall\, x$$

- The force needed for elongation changes during the test with:

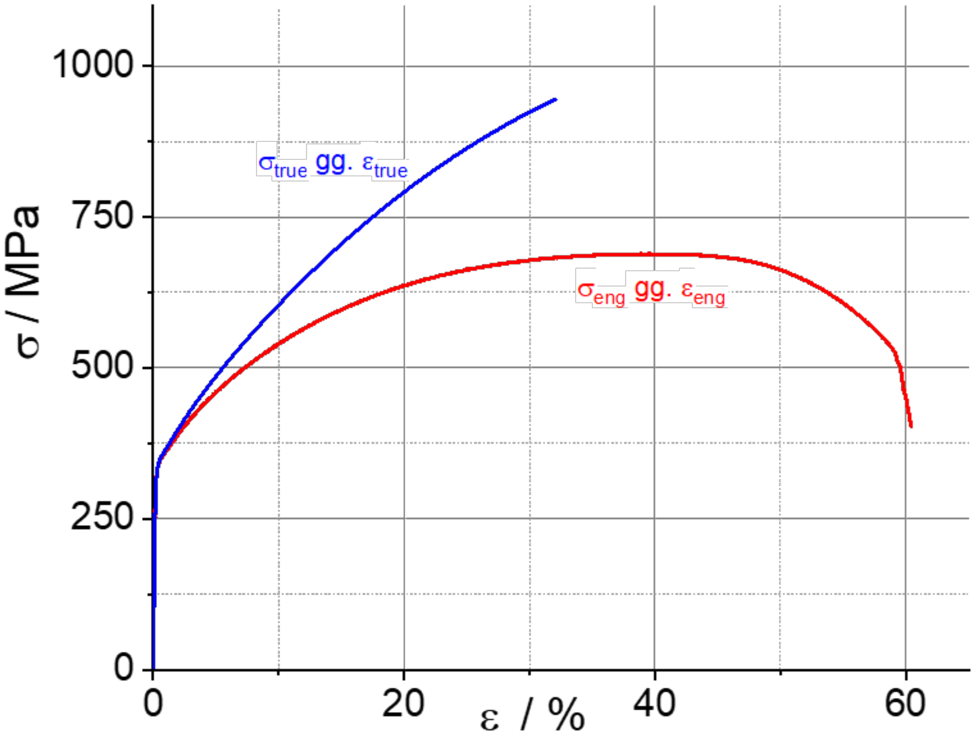
$$\frac{\mathrm{d}F}{\mathrm{d}\varepsilon_{\text{true}}} = A\,\frac{\mathrm{d}\sigma_{\text{true}}}{\mathrm{d}\varepsilon_{\text{true}}} + \sigma_{\text{true}}\,\frac{\mathrm{d}A}{\mathrm{d}\varepsilon_{\text{true}}}$$

$\frac{\mathrm{d}\sigma_{\text{true}}}{\mathrm{d}\varepsilon_{\text{true}}}$… intrinsic work-hardening of the material

$\frac{\mathrm{d}A}{\mathrm{d}\varepsilon_{\text{true}}}$… geometric softening

($\frac{\mathrm{d}A}{\mathrm{d}\varepsilon_{\text{true}}} < 0$ during tensile tests)

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ ^\circ\mathrm{C}$/vacuum/$1\ \mathrm{h}$/water-quenched, $4\ \mathrm{mm}$ diameter) at room temperature



A. S. Tirunilai: “Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures”, Journal of Materials Research 33 (2018) 3287-3300

Stability vs. Instability

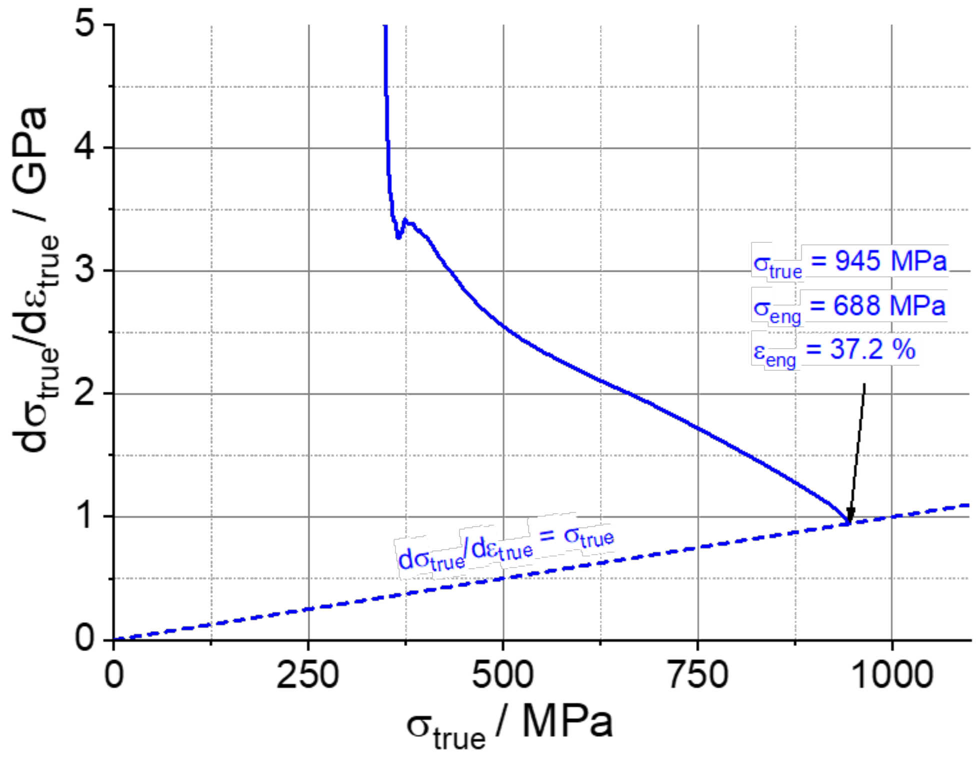
- A stable test request continuously increasing force:

$$\mathrm{d}F > 0$$
$$A\,\mathrm{d}\sigma_{\mathrm{true}} + \sigma_{\mathrm{true}}\,\mathrm{d}A > 0$$
$$A\,\mathrm{d}\sigma_{\mathrm{true}} - \sigma_{\mathrm{true}}\,A\,\frac{\mathrm{d}l}{l} > 0$$
$$\mathrm{d}\sigma_{\mathrm{true}} - \sigma_{\mathrm{true}}\,\mathrm{d}\varepsilon_{\mathrm{true}} > 0$$
$$\frac{\mathrm{d}\sigma_{\mathrm{true}}}{\mathrm{d}\varepsilon_{\mathrm{true}}} > \sigma_{\mathrm{true}}$$

Considère criterion

(should always be used for determination of the uniform strain, especially for materials with low work-hardening rates)

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*

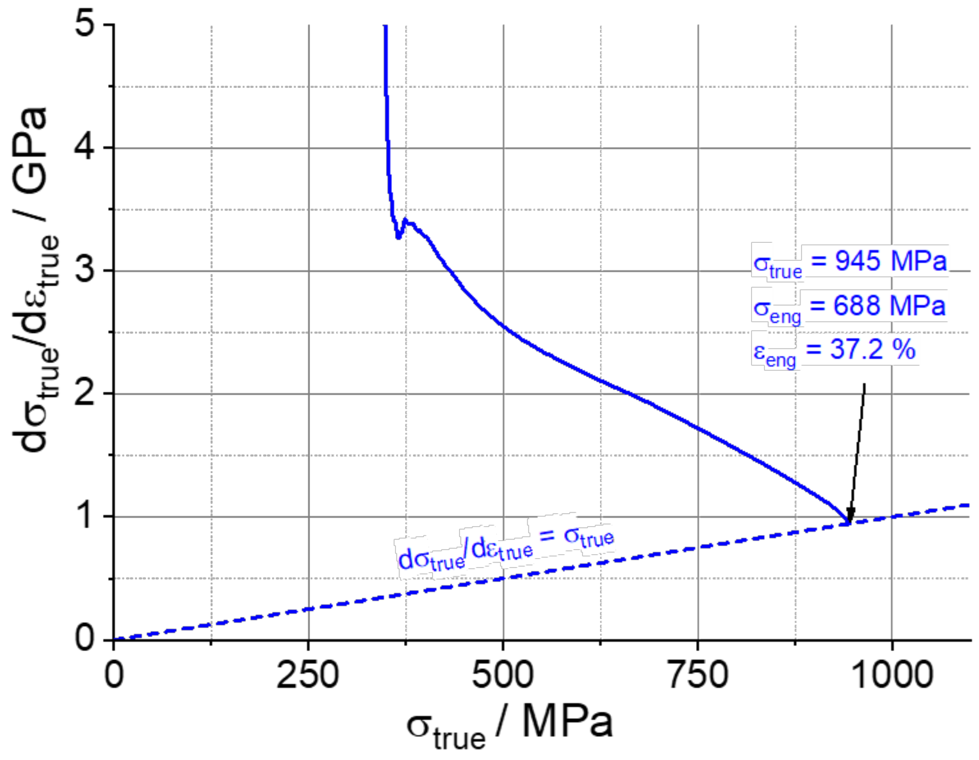


A. S. Tirunilai: "Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures", Journal of Materials Research 33 (2018) 3287-3300

Ductility

- This is counter-intuitive: **high ductility** (high ability to deform plastic) is observed **when work-hardening is high *and* remains high**.
- This is what excels TWIP and TRIP steels due to the dynamic refinement of the microstructure.
- Further contributions to work-hardening will be discussed in Chs. 4, 5 and 6.
- In some cases, details of plastic deformation might prevent reaching Considère criterion. Potential reasons are discussed in Ch. 6.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*

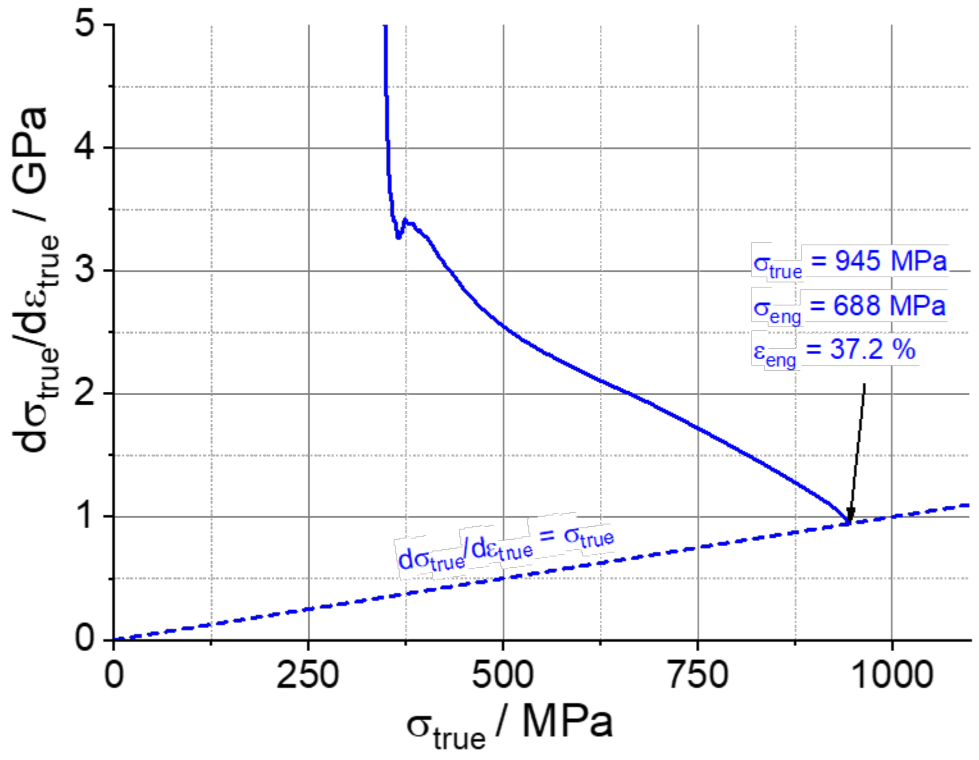


A. S. Tirunilai: "Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures", Journal of Materials Research 33 (2018) 3287-3300

Ductility

- In case mechanical tests are **free of geometrical softening**, e.g. compression tests and torsion tests, **no necking** due to geometrical-mechanical instability occurs!
- The **plastic strains** achieved in these tests are by definition **higher**.

Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized 800 °C*/vacuum/*1 h*/water-quenched,* 4 mm *diameter) at room temperature*

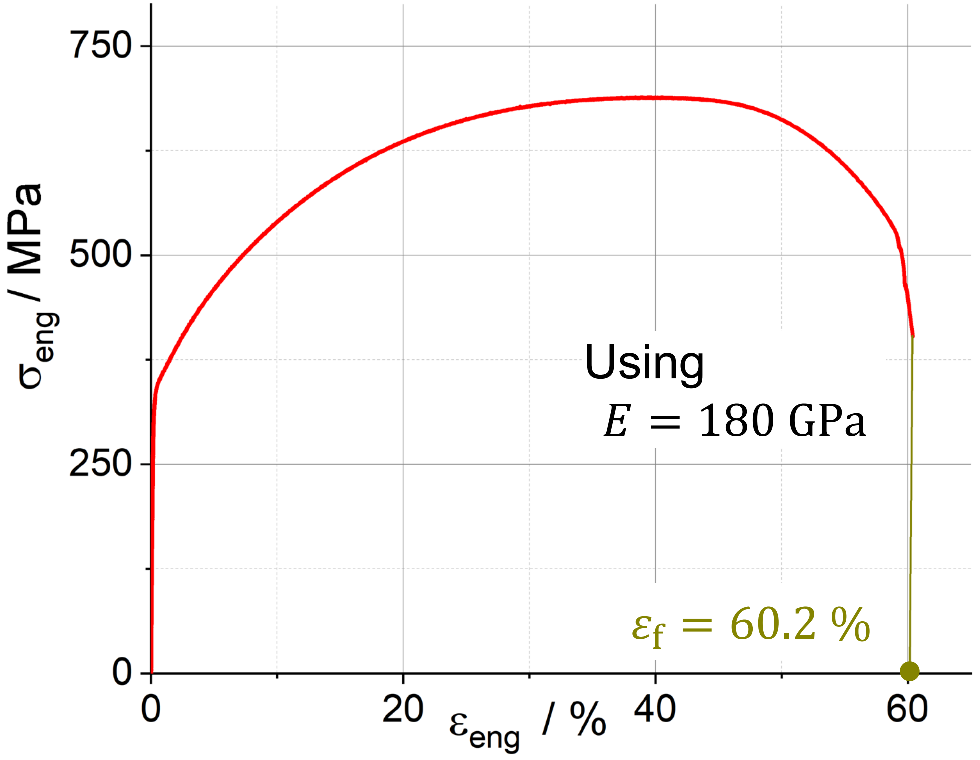


A. S. Tirunilai: "Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures", Journal of Materials Research 33 (2018) 3287-3300

Ductility

- In the engineering disciplines, ductility is often assessed based on **strains to fracture** ε_f.
- However, the **size of the necking region only depends on the cross sectional area** and **samples of different length exhibit different strains to fracture** while being equally ductile!
- Hence, **strain to fracture** is inappropriate to judge material's intrinsic ductility.
- Comparison of different samples requests constant $l_0/\sqrt{A_0}$ ratio.

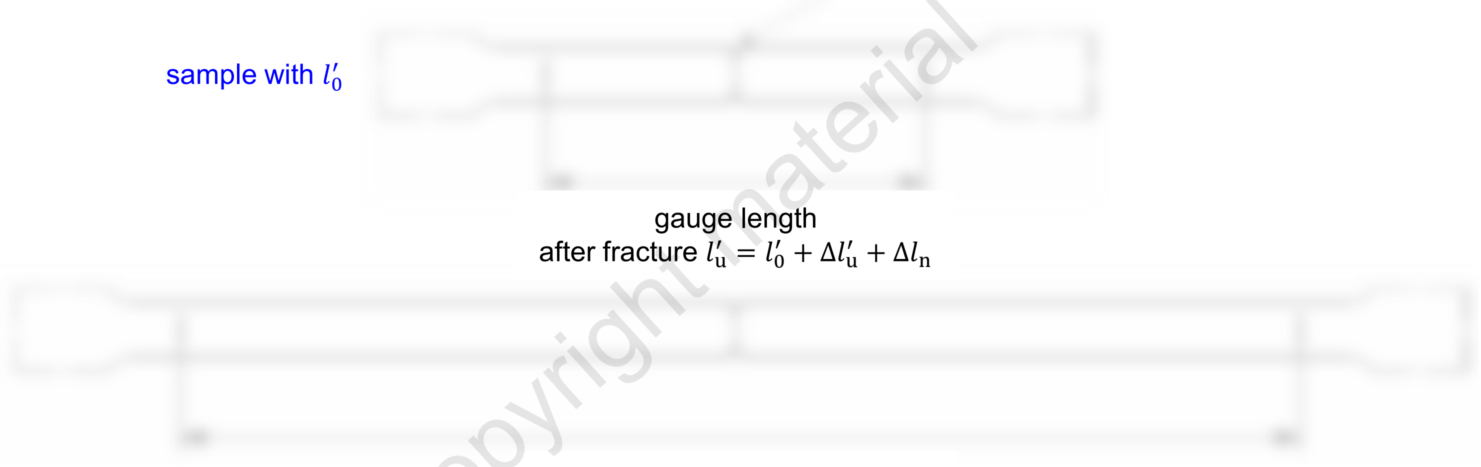
Example: tensile test conducted on A1 CoCrFeMnNi (recrystallized $800\ ^\circ\mathrm{C}$*/vacuum/*$1\ \mathrm{h}$*/water-quenched,* $4\ \mathrm{mm}$ *diameter) at room temperature*



A. S. Tirunilai: "Peculiarities of deformation of CoCrFeMnNi at cryogenic temperatures", Journal of Materials Research 33 (2018) 3287-3300

Ductility

- For samples of the same initial cross-sectional area, the same plastic elongation Δl_{n} within the necking region is achieved. For different initial length $l_0' < l_0''$, different strains to fracture $\varepsilon_{\mathrm{f}}' > \varepsilon_{\mathrm{f}}''$ are obtained since the uniform strains $\varepsilon_{\mathrm{u}} = \frac{\Delta l_{\mathrm{u}}'}{l_0'} = \frac{\Delta l_{\mathrm{u}}''}{l_0''}$ are unaffected by the total length:



$$\varepsilon_{\mathrm{f}}' = \frac{\Delta l_{\mathrm{u}}' + \Delta l_{\mathrm{n}}}{l_0'} = \varepsilon_{\mathrm{u}} + \frac{\Delta l_{\mathrm{n}}}{l_0'}$$

$$>$$

$$\varepsilon_{\mathrm{f}}'' = \frac{\Delta l_{\mathrm{u}}'' + \Delta l_{\mathrm{n}}}{l_0''} = \varepsilon_{\mathrm{u}} + \frac{\Delta l_{\mathrm{n}}}{l_0''}$$

DIN e.V.: DIN EN ISO 6892-1: Metallische Werkstoffe – Zugversuch - Teil 1, Berlin: Beuth Verlag GmbH (2009)

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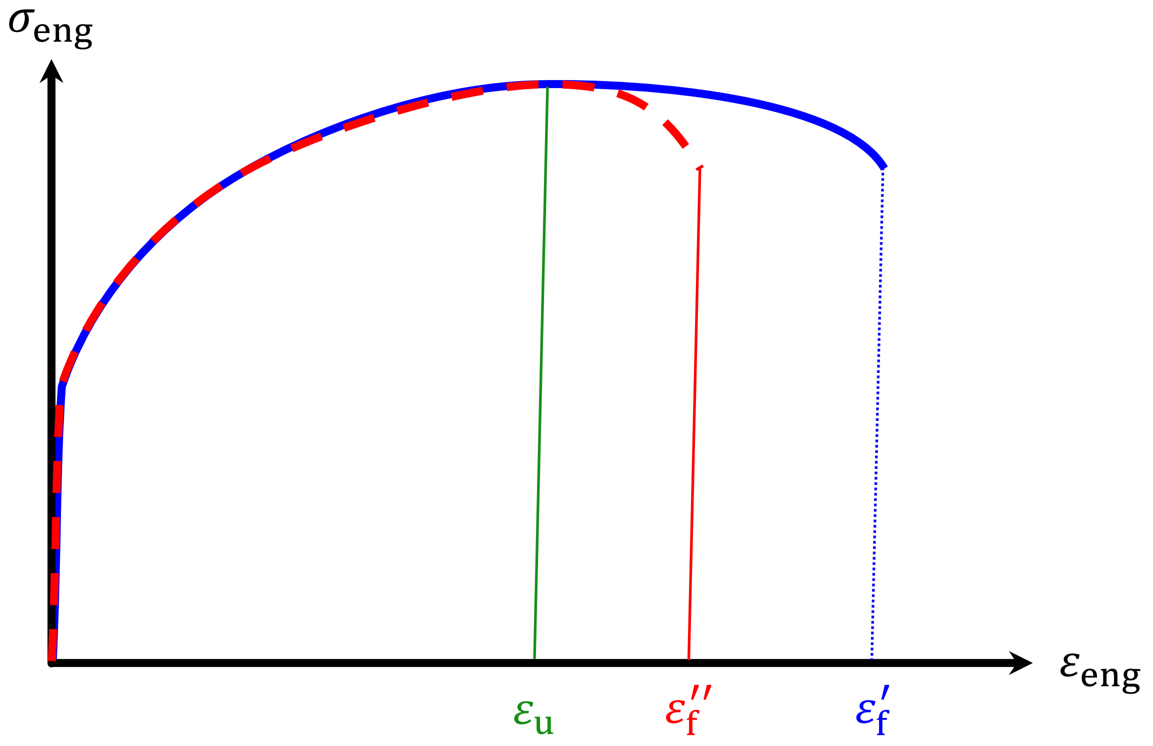


$$\varepsilon_\mathrm{f}' = \frac{\Delta l_\mathrm{u}' + \Delta l_\mathrm{n}}{l_0'} = \varepsilon_\mathrm{u} + \frac{\Delta l_\mathrm{n}}{l_0'}$$

$$>$$

$$\varepsilon_\mathrm{f}'' = \frac{\Delta l_\mathrm{u}'' + \Delta l_\mathrm{n}}{l_0''} = \varepsilon_\mathrm{u} + \frac{\Delta l_\mathrm{n}}{l_0''}$$

Mechanical Properties

Karlsruhe Institute of Technology

Material	Condition			σ_y or $\sigma_{y,u}$ or $\sigma_{0.2}$ /MPa	σ_m/MPa	σ_m/σ_y	$\varepsilon_f/\%$
C45	Normalized	• 840 … 880 °C/air-cooled	$d \leq 16$ mm $t \leq 16$ mm	> 340	> 620	≈ 1.8	> 14
	Quenched & tempered	• 820 … 860 °C/oil- or water-quenched • 550 … 660 °C	$d \leq 16$ mm $t \leq 8$ mm	> 490	700 … 850	≈ 1.7	> 14
42CrMo4	Quenched & tempered	• 820 … 860 °C/oil- or water-quenched • 540 … 680 °C	$d \leq 16$ mm $t \leq 8$ mm	> 900	1100 … 1300	≈ 1.4	> 10
X2CrNiMo17-12-2	Solution Treated	• 1030 … 1100 °C/air- or water-cooled	$d \leq 8$ mm	> 240	530 … 680	≈ 2.8	> 40
Cu-OF	R200	• well annealed	$d \leq 5$ mm	< 100	200 … 250	> 2.0	> 42
	R290	• deformed	$d \leq 15$ mm	> 250	290 … 360	> 1.2	> 6
CuZn30	R270	• well annealed	$d \leq 5$ mm	< 160	270 … 350	> 1.7	> 50
	R410	• deformed	$d \leq 5$ mm	> 260	410 … 490	> 1.6	> 15

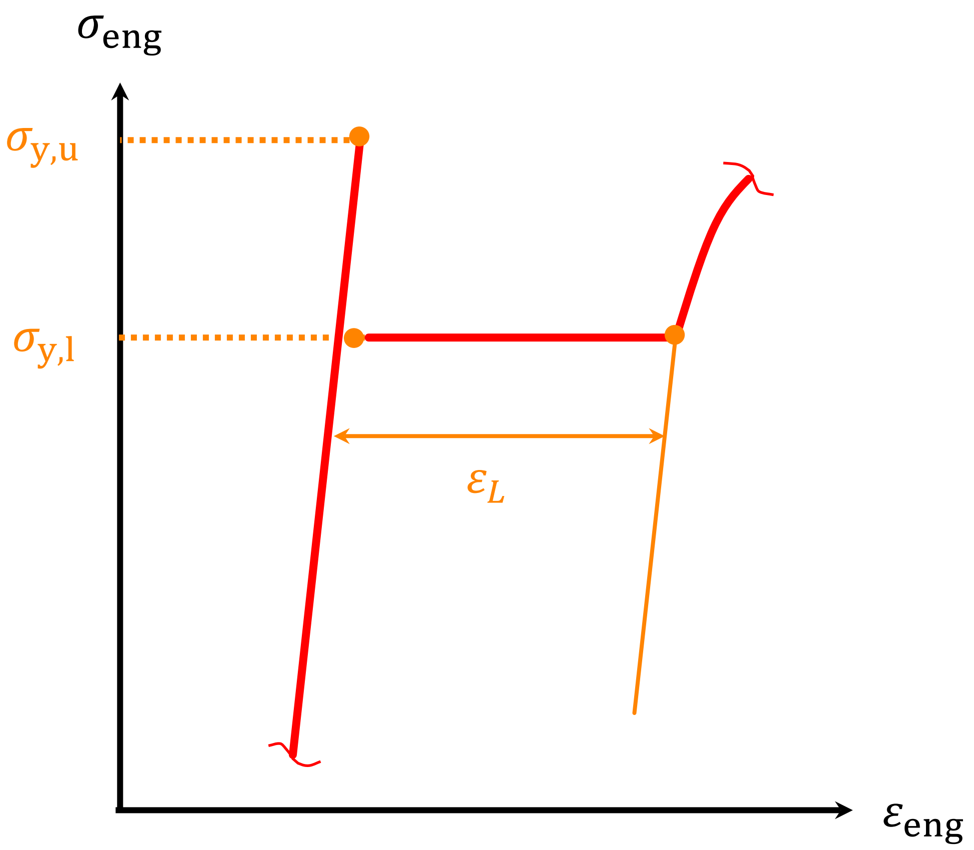
DIN EN ISO 683-1: Für eine Wärmebehandlung bestimmte Stähle, legierte Stähle und Automatenstähle – Teil 1: Unlegierte Vergütungsstähle
DIN EN ISO 683-2: Für eine Wärmebehandlung bestimmte Stähle, legierte Stähle und Automatenstähle – Teil 2: Legierte Vergütungsstähle
DIN EN 10088-2: Nichtrostende Stähle – Teil 2: Technische Lieferbedingungen für Blech und Band aus korrosionsbeständigen Stählen für allgemeine Verwendung
DIN EN 1652: Kupfer und Kupferlegierungen, Platten, Bleche, Bänder, Streifen und Ronden zur allgemeinen Verwendung

All by DIN e.V. and published Berlin: Beuth Verlag GmbH

Pronounced Yielding

- Localized deformation does not only contribute to effects at high plastic strains.
- It can also play a vital role in yielding. **Pronounced yielding** occurs when **two distinct strength values** occur: **higher** (onset of any plasticity) and **lower** (maintain plasticity).
- At yield point, a characteristic (plastic) **Lüders strain** is released.

Schematic illustration of a pronounced yield point phenomenon:



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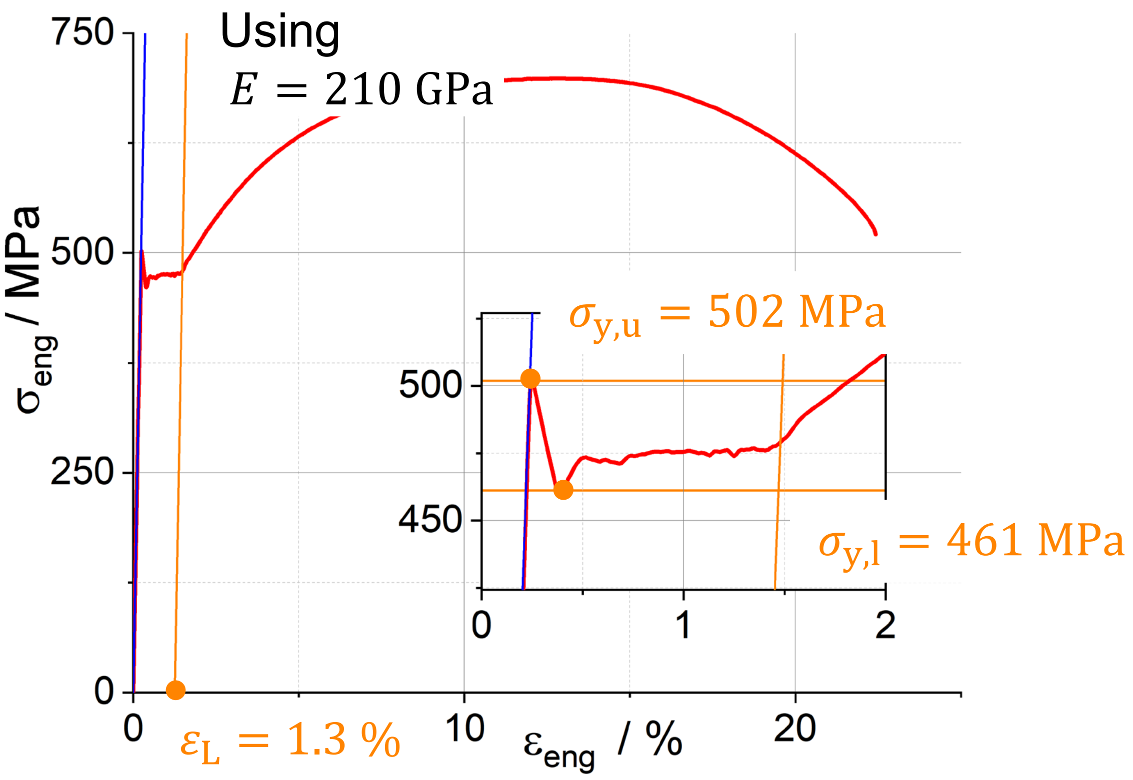
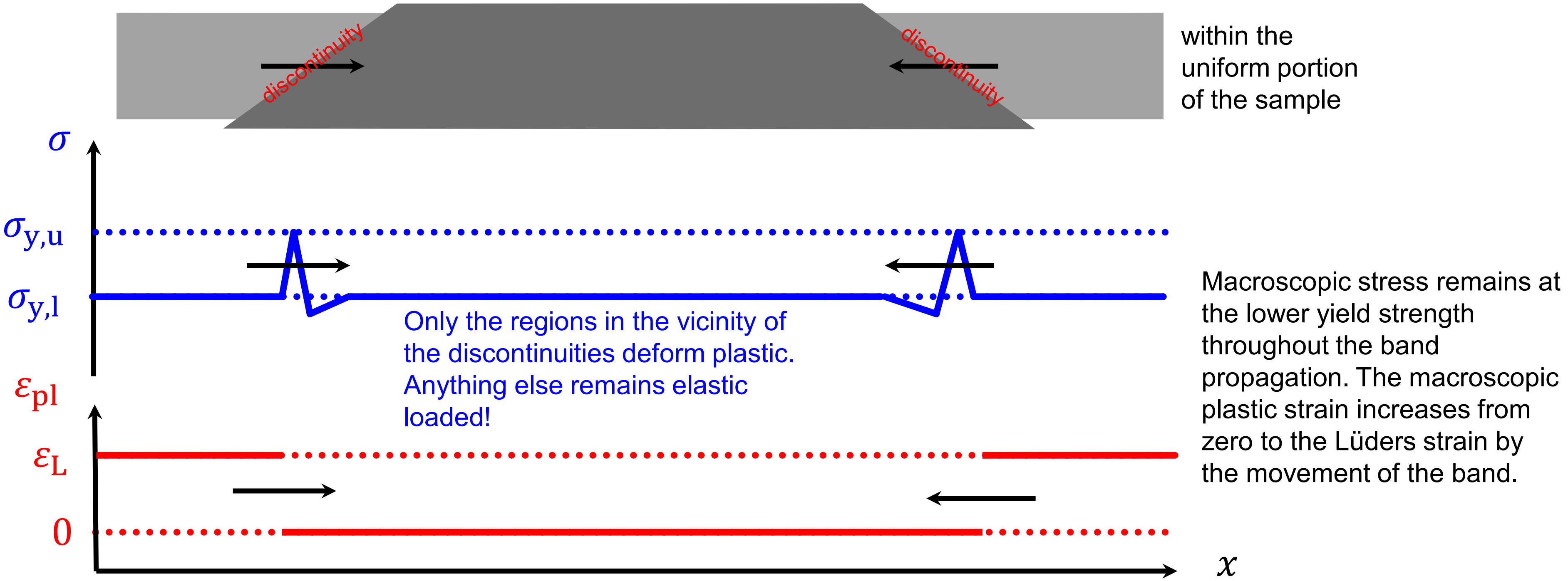
- At yield point, a characteristic (plastic) **Lüders strain** is released.

Example: tensile test conducted on normalized C45 plain carbon steel (880 °C/air/30 min/air-cooled, 4 mm diameter) at room temperature



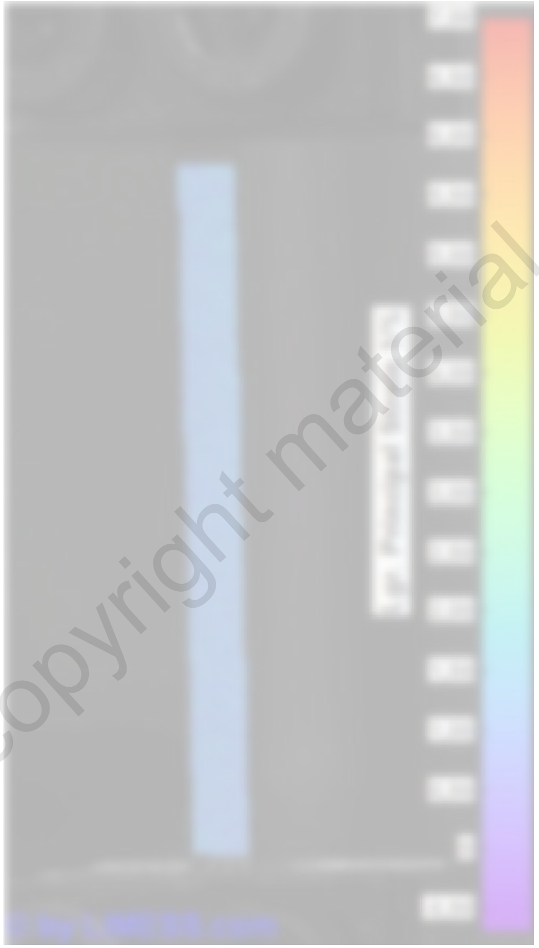
Pronounced Yielding

- Discontinuities/perturbations of the cross sectional area (usually at the transition radii) lead to **stress concentrations sufficient to initiate local plastic** deformation by surpassing the upper yield strength.
- The **discontinuities move** through the sample while leaving material behind that is deformed up to the **Lüders strain**.



Pronounced Yielding

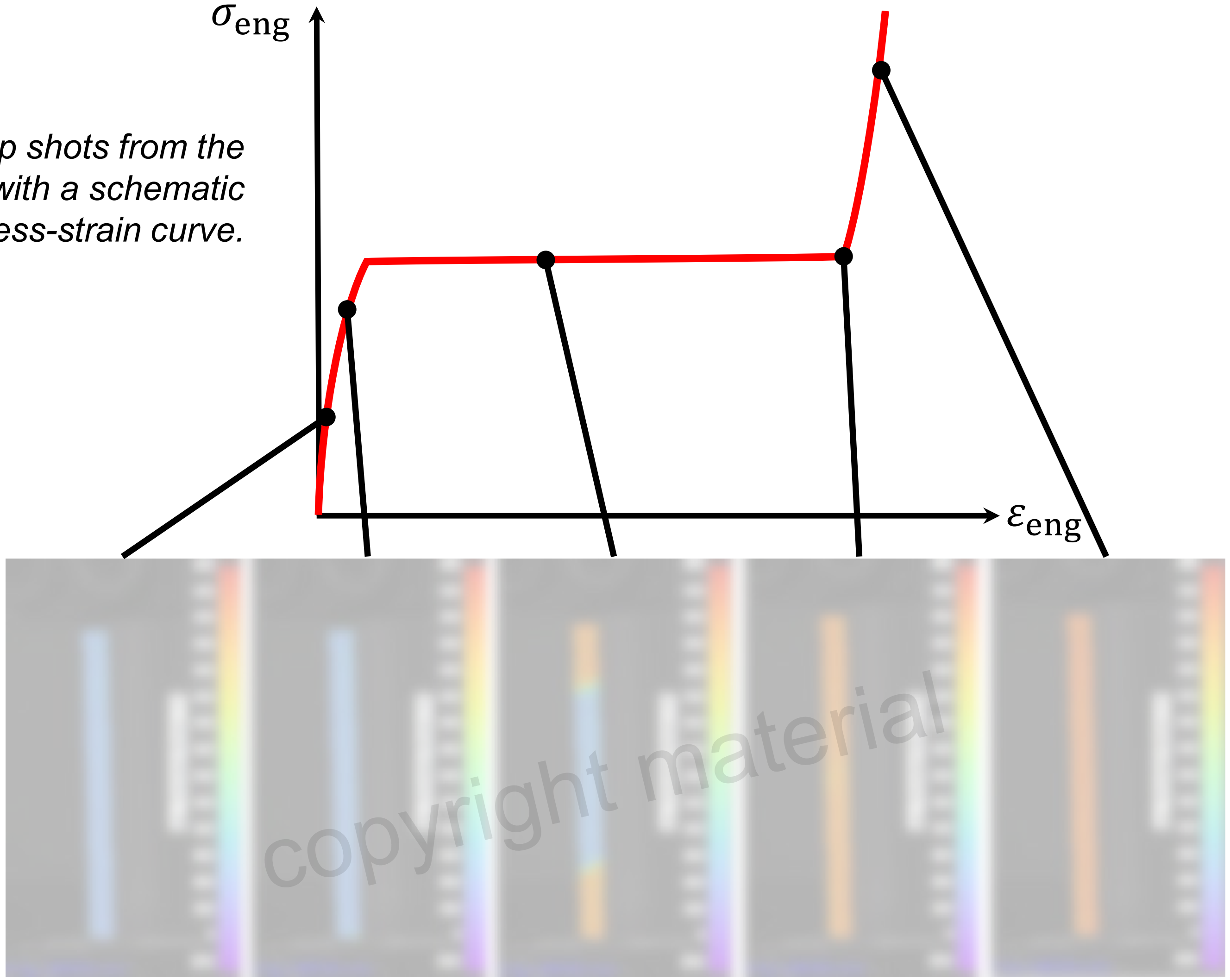
- Lüders bands of different nature exist. The commonly known pairs of bands or single bands running trough the entire sample are only one possibility.
- The nature of the band is closely related to the microscopic details of localization and plastic deformation. After formation of bands, the propagation can also be stopped due to various reasons. Discontinuous plastic flow might occur. These mechanisms are discussed in Chs. 5 and 6.



Example: Lüders band propagation through a shape memory alloy (note the grips in the upper part of the image for loading and unloading)

https://en.wikipedia.org/wiki/File:L%C3%BCdersband_measured_with_digital_image_correlation_(DIC)_from_LIMESS.gif

Pronounced Yielding



Snap shots from the gif with a schematic stress-strain curve.

https://en.wikipedia.org/wiki/File:L%C3%BCdersband_measured_with_digital_image_correlation_(DIC)_from_LIMESS.gif

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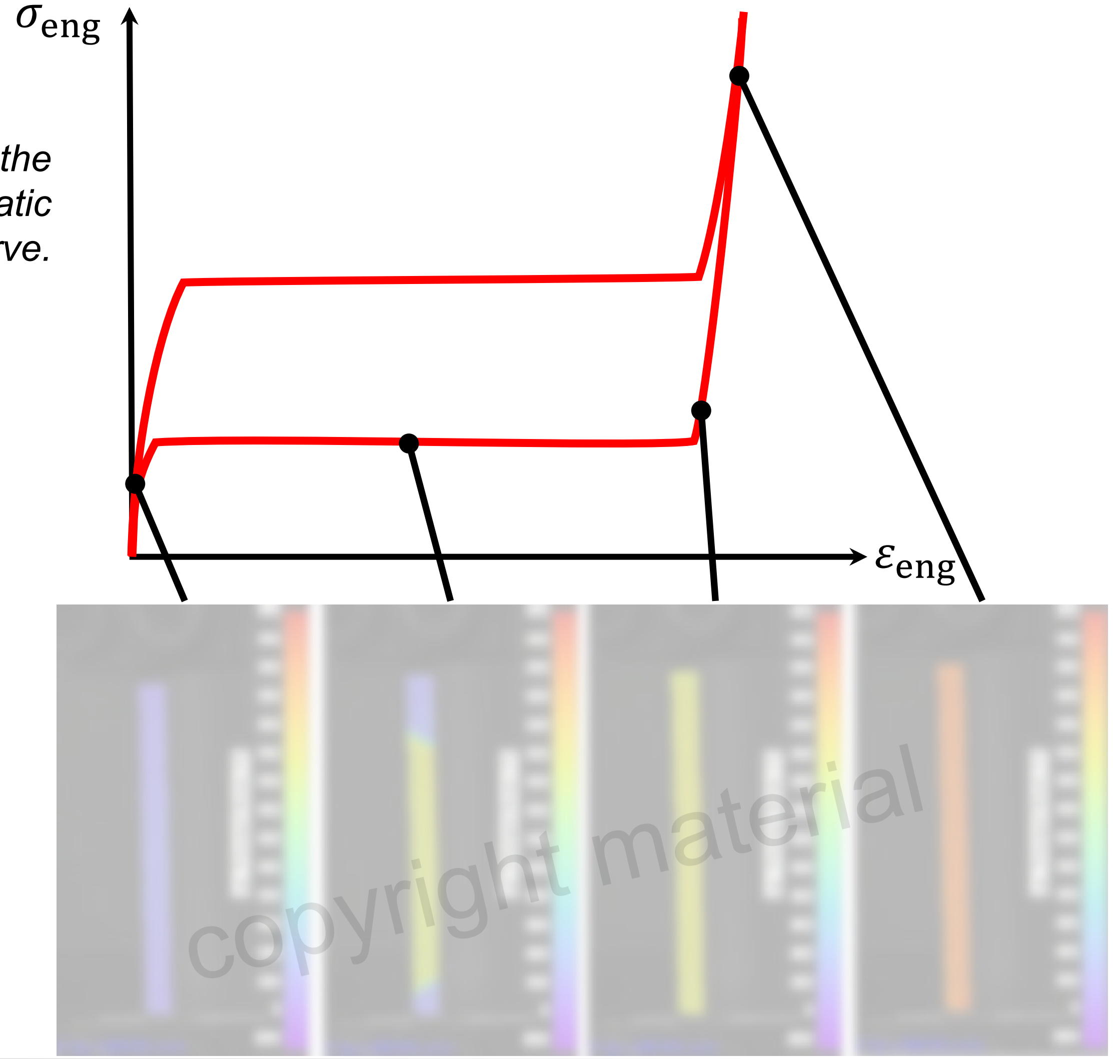
Snap shots from the gif with a schematic stress-strain curve.

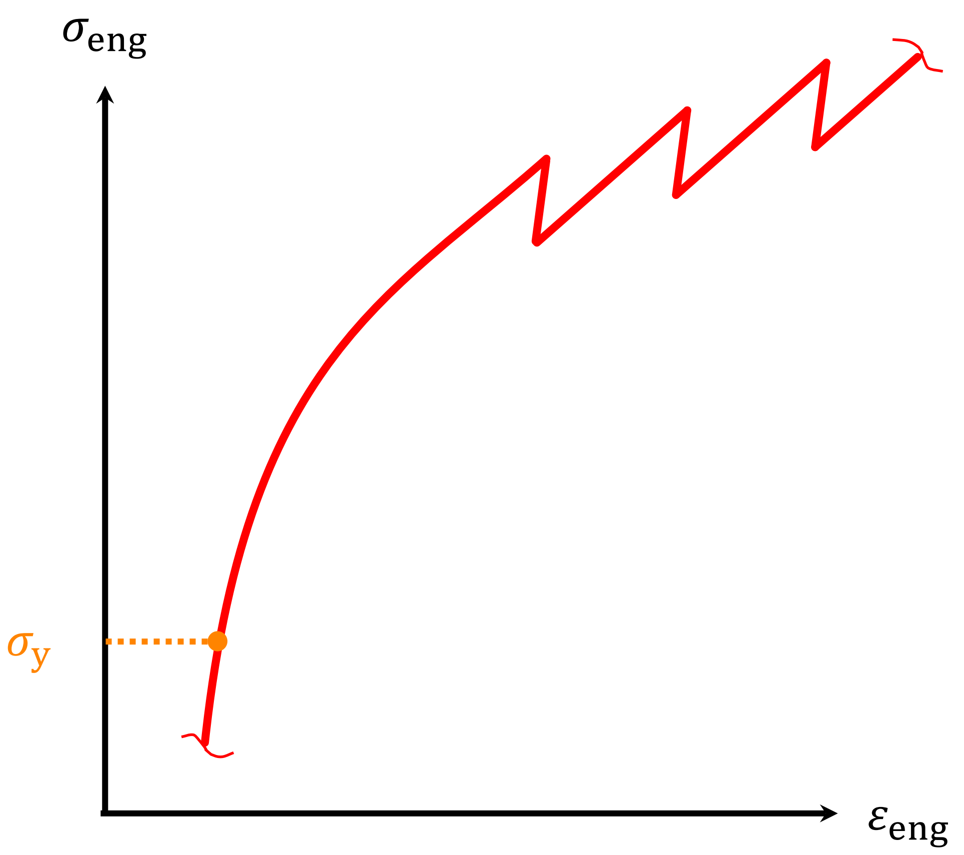


https://en.wikipedia.org/wiki/File:L%C3%BCdersband_measured_with_digital_image_correlation_(DIC)_from_LIMESS.gif

Portevin-Le-Chatelier Effect

- Another type of localized deformation occurs in some alloys in the work hardening region of alloys with dissolved alloying elements.
- The Portevin-Le-Chatelier effect occurs in distinct temperature and strain rate ranges beyond a certain critical strain as a consequence of solute-dislocation interaction. The mobility of solutes contribute the temperature dependence while dislocation motion is strain rate depending.

Schematic illustration of jerky plastic flow by the Portevin-Le-Chatelier effect:



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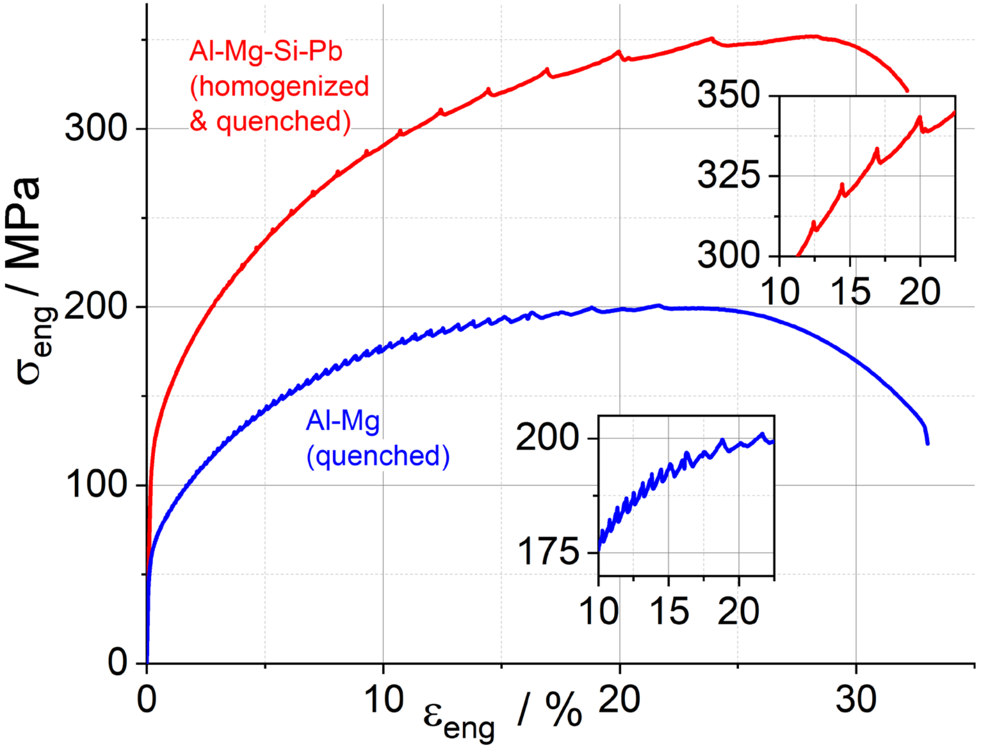
Example: tensile tests conducted on solid solution strengthened Al-Mg (AW-5754, 450 °C/air/1 h/quenched, 4 mm diameter) and a homogenized Al-Mg-Si-Pb (AW-6012, 530 °C/air/4 h/quenched, 4 mm dia.)



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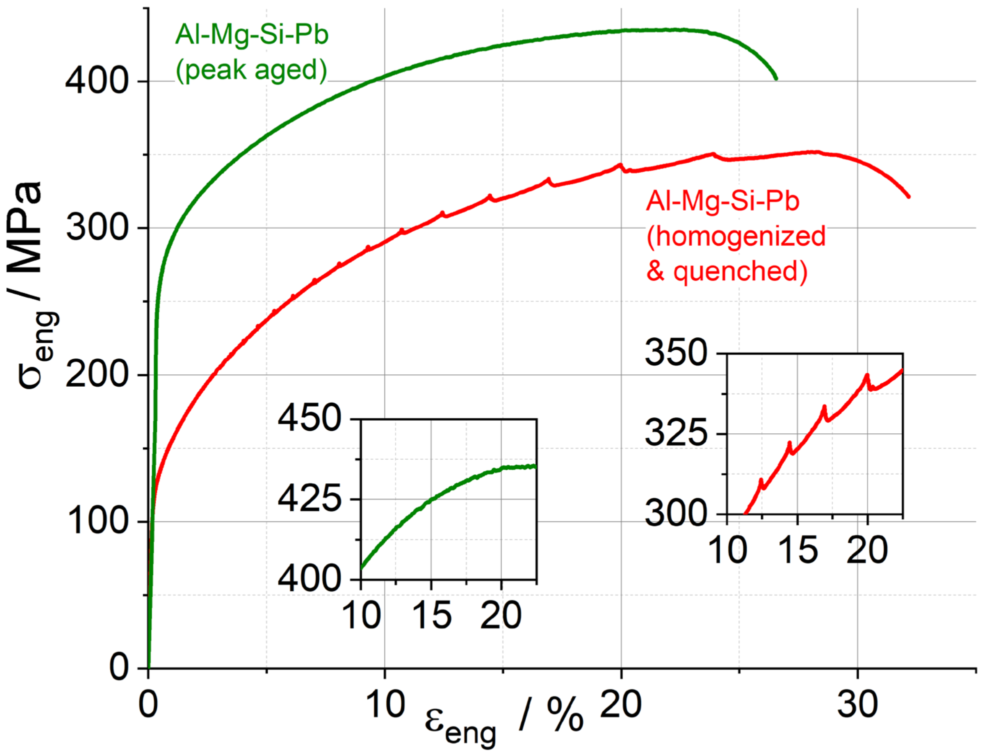
Example: tensile tests conducted on homogenized (530 °C/air/4 h/quenched) and subsequently peak aged (160 °C/air/20 h) Al-Mg-Si-Pb (AW-6012, 4 mm dia.)



Note that the PLC effect vanishes when the solute atoms are removed from the solid solution by the precipitation.

Summary

- Simple mechanical tests provide information about **stiffness** (resist. against elastic def.), **strength** (resist. against yielding, certain plastic strain or necking), **work-hardening** (increase of strength during plastic def.), **ductility** (ability to deform plastic), and **toughness** (energy consumption during plastic def.).
- Depending on the loading conditions, **localization of deformation** must be considered in order to describe the macroscopic deformation behavior.