Karlsruhe Institute of Technology

Institute for Applied Materials

Plasticity

Lecture for “Mechanical Engineering” and “Materials Science and Engineering”

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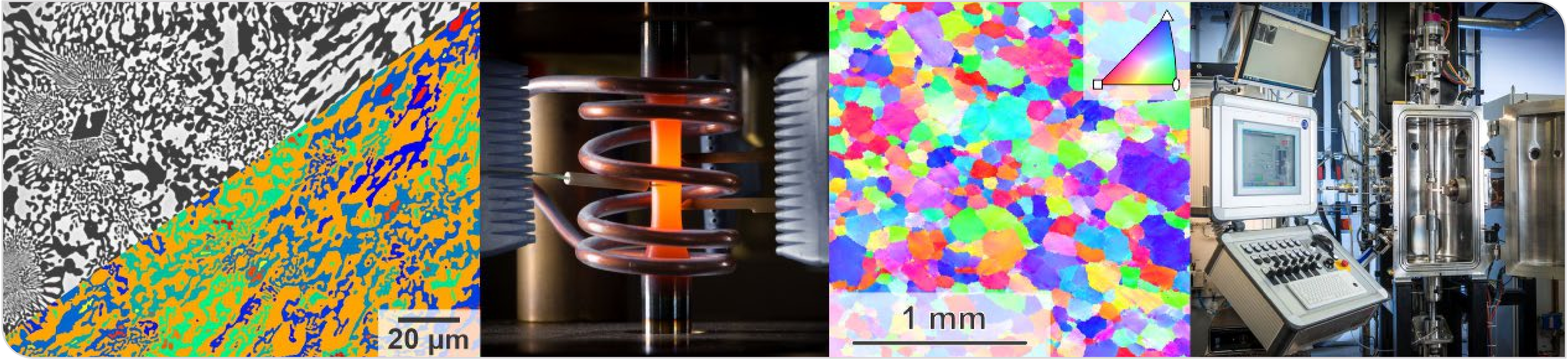

Topics

- Educational Objectives
- Relevance of Plasticity of Materials
  - General Aspects
  - Examples
    - Strength of Engineering Materials (Structural Materials)
    - Determination of Properties of Semi-Finished Parts
    - Severe Plastic Deformation
    - Mechanical Alloying
    - TWIP & TRIP Steels
    - Martensitic Transformation, Pseudo-Elasticity & Shape Memory Effect

Learning Objectives

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- Students are familiar with **macroscopic, mesoscopic and microscopic mechanisms of plastic deformation** in **metals, alloys and intermetallic compounds**.
- This includes **qualitative and quantitative description**.
- The students are able to **apply their knowledge** in order **to deduce and explain mechanism-property relationships** in this kind of materials and **their use in materials manufacturing and development**.

Relevance of Plasticity

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- The assessment of material behavior under mechanical load is important for following engineering problems:
  - **Design of parts and materials selection**
    (Apart from elastic stiffness considerations, design is typically with respect to onset of plastic deformation (yield) or small but tolerable strains (offset). In rare cases, necking might be decisive for designing (e.g. working).)
  - **Failure and damage analysis**
    (In general, considerations for high plastic strains and/or fracture have to be made.)
  - **Material manufacturing and processing**
    (Quality control issues might be related to plastic deformation.)
  - **Material development and optimization**

Relevance of Plasticity

- The assessment is typically based on material‘s resistances. These are tested in following experiments:
  - **Tensile tests**, compression tests, bending tests, torsion tests, …
  - **Upset tests**
  - **Creep tests**
  - Stress relaxation tests
  - **Fatigue testing**
  - **Fracture toughness tests**
  - **Charpy notch tests**
  - **Hardness testing**

Please note the difference between most common mechanical tests and tests for working/upset simulation.

Most common mechanical tests apply specific load conditions and shape change/deformation is depending on the plastic flow behavior of the material (at least in one direction). In contrast, upsetting and working aims at applying loads to achieve specific shape changes or deformation (sometimes in most of the directions).

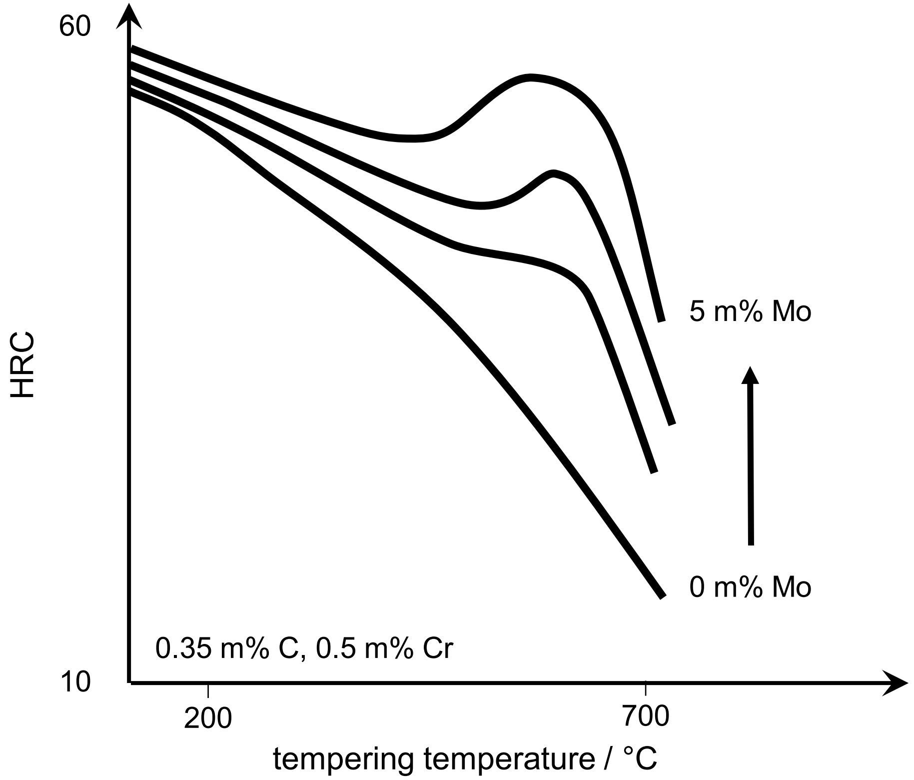
Relevance of Plasticity

- The resistances (can) depend on various parameters and conditions:
  - **Loading conditions**:
    - **Stress/strain state**
      (e.g. uniaxial/multiaxial)
    - **Loading direction**
      (e.g. tensile vs. compression)
    - **Loading sequence/strain rate**
      (e.g. static, quasi-static, dynamic, cyclic)
  - **Material condition**
    - **Crystal structure**
    - **Microstructure**
  - Geometry/dimensions
  - **Environmental influences**
    - **Temperature**
    - Corrosion
    - Radiation

Examples

Strengthening Mechanisms

- **Strength and hardness** of most structural materials are a result of a **complex, non-linear superposition of several strengthening mechanisms**.
- For the application of these strengthening mechanisms (reproducibility) and further improvement of materials (enhancement of strength while maintaining ductility), a **solid understanding of the microstructural details (defects) governing strength is necessary**.
- The **exact superposition of the individual strengthening contributions** including their limits are **still under investigation**.



Appearance of secondary hardness as a function of tempering temperature and Mo content of a martensitic steels.

E. C. Bain: “Alloying Elements in Steels”, Cleveland, USA: ASM (1939)

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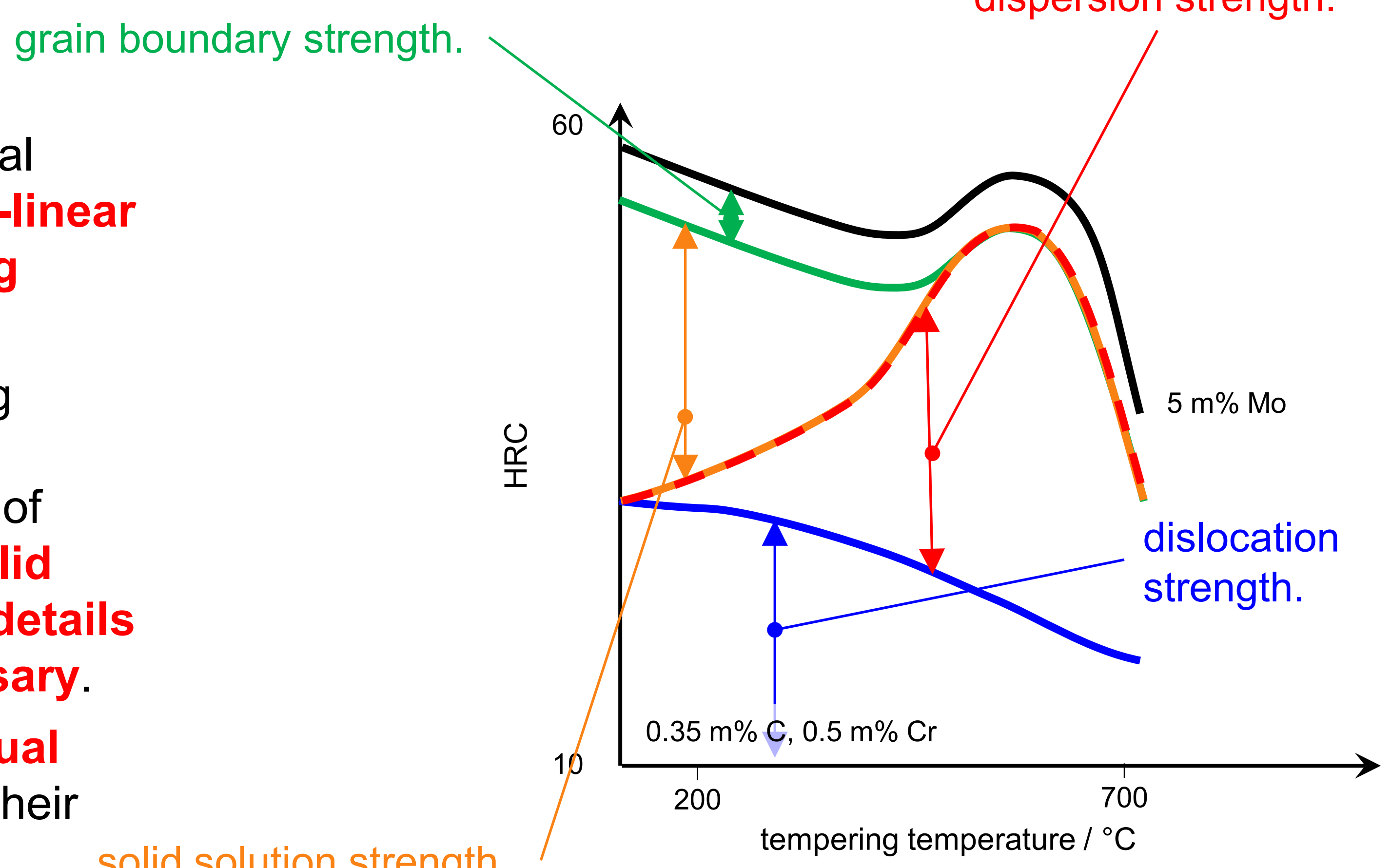

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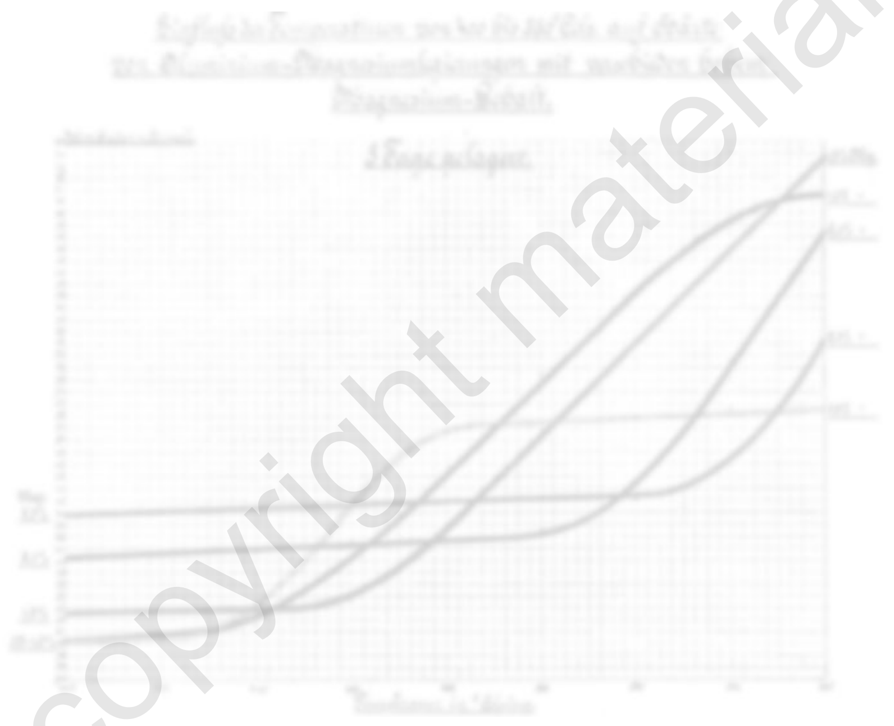
Strengthening Mechanisms

- Many alloying concepts and processing steps for improving strength were known way before the fundamental mechanisms were clear:
  - Historical development “Bronze age”, “Iron age”, “Damasqus steel”, etc.
  - Specific microstructures:
    - Naming of troostite, sorbite and martensite by F. Osmond (France, 1895)
    - Naming of ferrite, pearlite and cementite much earlier by H. M. Howe (USA, 1848-1922) and A. Ledebur (Germany, 1837-1906)
  - Age hardening of Al alloys:
    - Al-Cu-Mn-Mg by A. Wilm (1903)
- The **identification of fundamental mechanisms** followed **much later after development of suitable theoretical concepts and advanced characterization methods**. Most of these developments were linked with the fast development of quantum and solid state physics in the beginning of the 20th century.



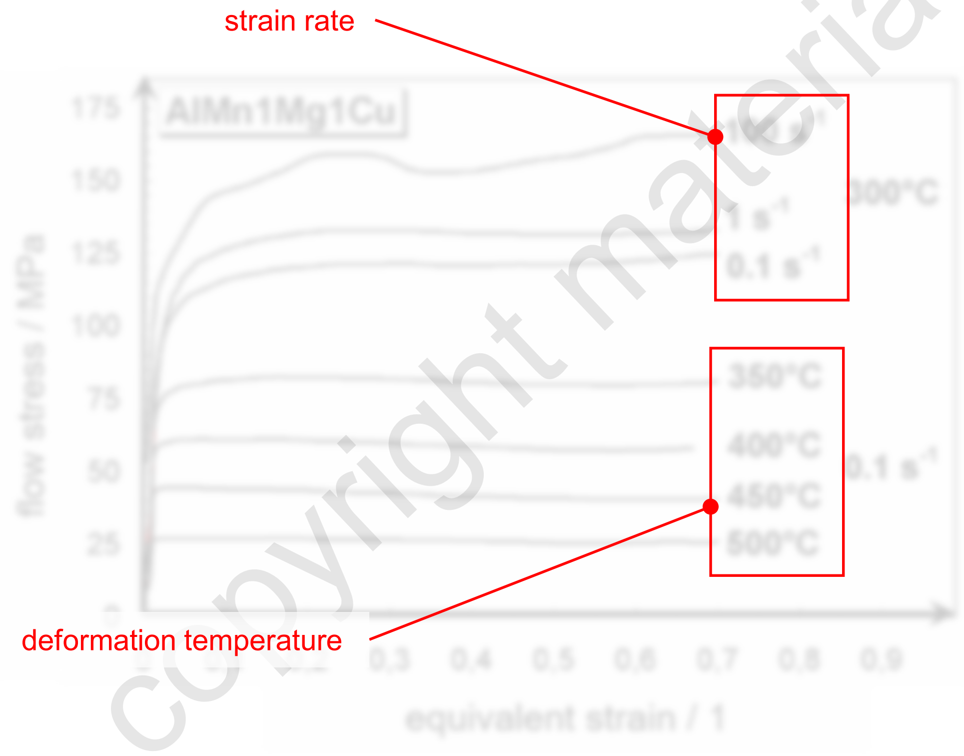
Lab report by A. Wilm (1906) for age hardening of AlCu4Mg.

taken from a reproduction of A. Wilm’s original work
in “Alfred Wilm und die Duraluminium-Erfindung”, Aluminium August (1937) 511 (no author claimed; signed with “hs”)

Examples

Manufacturing of Semi-Finished Parts

- While **microstructural conditions and properties of many steels can be largely recovered** by appropriate heat treatments, properties of **most semi-finished parts made from fcc & hcp metals/alloys, like Al, Cu, Ni, Ti, Mg, etc. strongly depend on their thermo-mechanical history**.
- In **most industrial applications**, **hot working processes** are applied in these cases in order to reduce processing steps.
- There is a **complex and large parameter space** for these manufacturing schemes.
- **High strength** is an obvious optimization goal. Nevertheless, there are also other criteria: **ductility, formability, bending radius, anisotropy** of these, etc. All these properties depend on the thermo-mechanical treatment of the alloys.



Upset testing of AlMn1Mg1Cu.

J. Hirsch, K. F. Karhausen, O. Engler: “Property Control in Production of Aluminum Sheet by Use of Simulation” in “Continuum Scale Simulation of Engineering Materials” D. Raabe, et al. (ed.), Weinheim: Wiley-VCH (2004)

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Inhomogeneous strain distribution (bottom) and microstructure (top) of AlMn1Mg1Cu after upset testing and partial recrystallization (10 s).

J. Hirsch, K. F. Karhausen, O. Engler: "Property Control in Production of Aluminum Sheet by Use of Simulation" in "Continuum Scale Simulation of Engineering Materials" D. Raabe, et al. (ed.), Weinheim: Wiley-VCH (2004)

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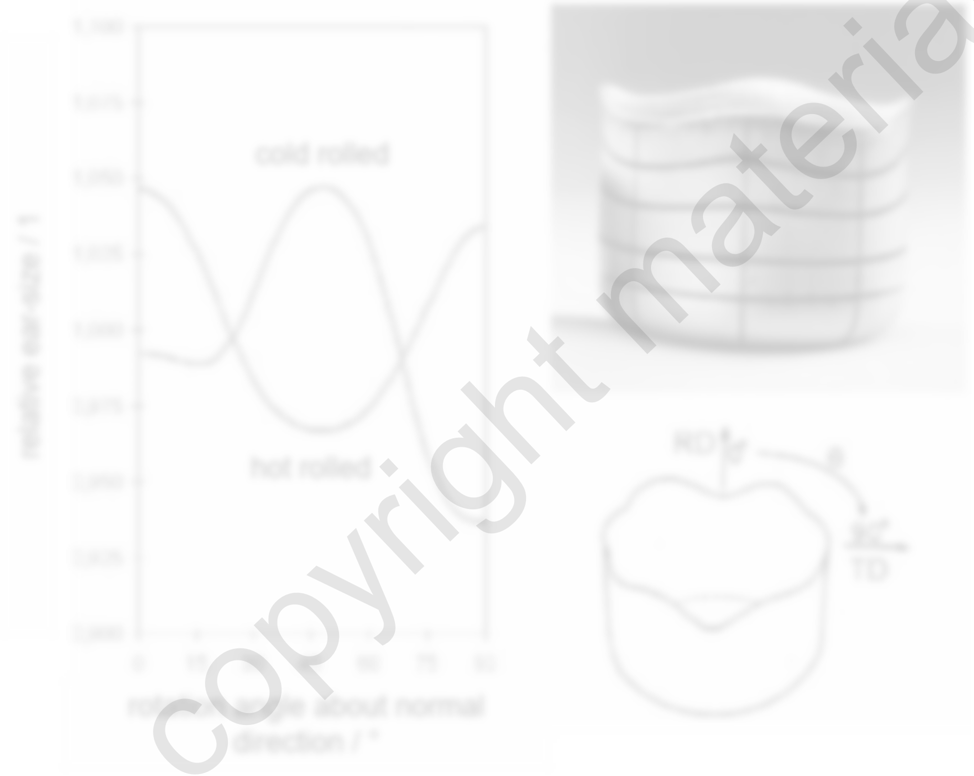


Anisotropy of plastic flow during die forming visualized by ear formation.

J. Hirsch, K. F. Karhausen, O. Engler: “Property Control in Production of Aluminum Sheet by Use of Simulation” in “Continuum Scale Simulation of Engineering Materials” D. Raabe, et al. (ed.), Weinheim: Wiley-VCH (2004)

Examples

High Strength, Ductile Materials for Safety-Relevant Applications

- In the 90's, several steel grades were developed which became attractive for potential light weight design in automotive industry through **significantly increased strength while ductility remained high**.
- The development succeeded in following classes of "**advanced high strength steels**" (AHSS):
  - **Dual phase (DP)**
  - **Complex phase (CP)**
  - **Ferritic-bainitic (FB)**
  - **Martensitic (MS)**
  - **Hot-formed (HF)**
  - **Twinning induced plasticity or transformation induced plasticity (TWIP & TRIP)**
- Some of these steels possess **strength well above 500 MPa in conjunction with ductility of beyond 10 % at high work hardening**. These steels are especially useful for **forming complex parts** (low necking ability) or in **crash-absorber applications** (high energy storage capacity until failure). Even density is rather high, the highest strengths in these steels allow for certain weight reduction.

Examples

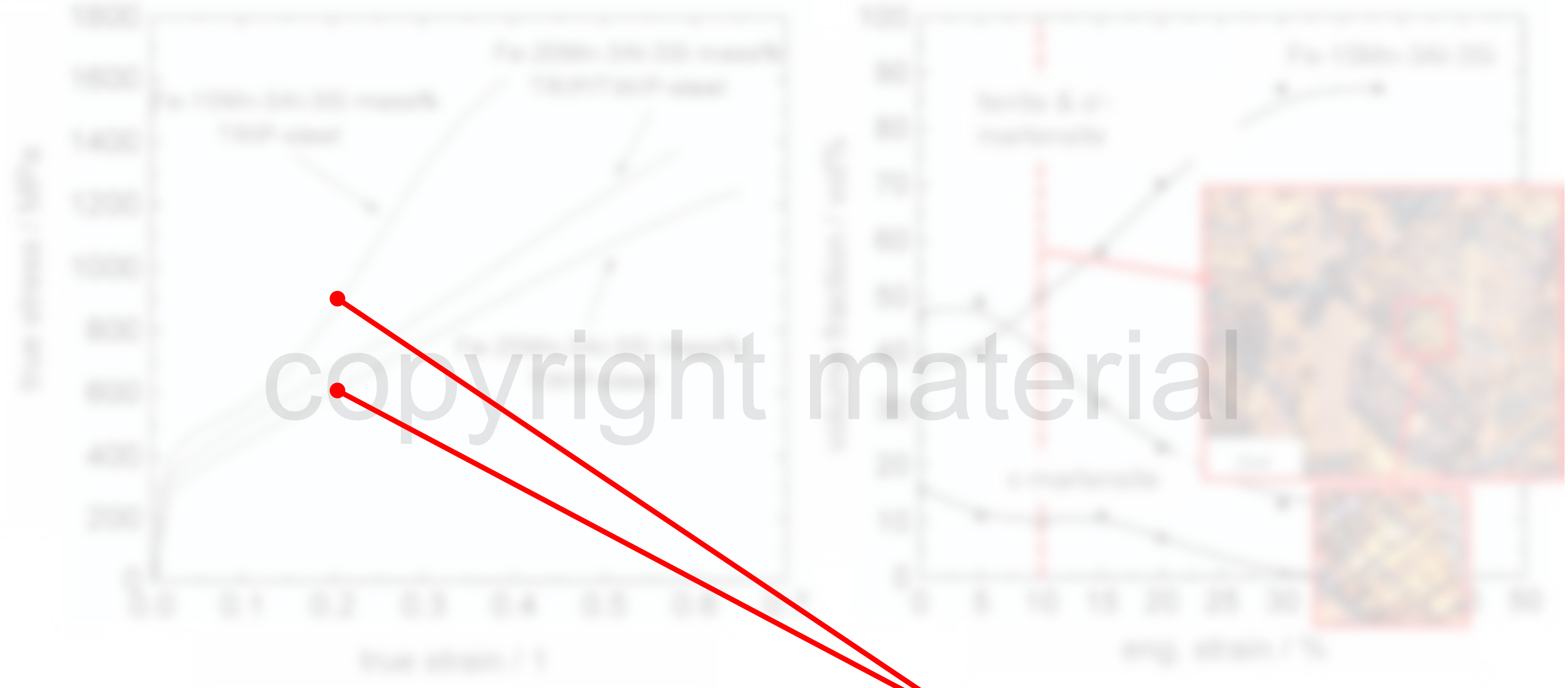
High Strength, Ductile Materials for Safety-Relevant Applications

The banana-shaped dependence is commonly referred to as **strength-ductility trade off**.

S. Keeler, M. Kimchi, P. J. Mooney: ”Advanced High-Strength Steels Application Guidelines, Version 6.0“ (2017)
https://www.worldautosteel.org/projects/advanced-high-strength-steel-application-guidelines/

Examples

High Strength, Ductile Materials for Safety-Relevant Applications



Stress-strain curves of TWIP and TRIP steels.

extended regions of stable or even increasing work/strain-hardening

G. Frommeyer, U. Brüx, P. Neumann: “Supra-Ductile and High-Strength Manganese-TRIP/TWIP Steels for High Energy Absorption Purposes”, ISIJ International 43 (2003) 438-446

Examples

Microstructure Refinement by Plastic Deformation

- Microstructural processes during **severe plastic deformation** (SPD) can be used to **significantly reduce grain size** down to submicron size or even smaller.
- There is a huge variety of SPD methods available. There are two which are developed to approximately industry scale: "**high pressure torsion**" (HPT) and "**equal channel angular pressing**" (ECAP).
- The challenging objectives in application of the methods are upscaling of most methods due to largely increasing friction forces and homogeneity of the materials produced.

R. Pippan: "Saturation of Fragmentation During Severe Plastic Deformation", Annual Review of Materials Research 40 (2010) 319-343
T. D. Horn: "Strain Localization during Equal-Channel Angular Pressing Analyzed by Finite Element Simulations", Metals 8 (2018) 55

Examples

Microstructure Refinement by Plastic Deformation

- Dislocation motion, multiplication and patterning
- Re-formation of microstructure
- Saturation grain size in the order of 100 nm

true strain

Microstructural changes in polycrystalline Ni during HPT as a function of true strain (orientation imaging by electron backscatter diffraction)

R. Pippan: “Saturation of Fragmentation During Severe Plastic Deformation”, Annual Review of Materials Research 40 (2010) 319-343

Examples

Microstructure Refinement by Plastic Deformation

- **Mechanical alloying** is a special kind of SPD process. **A metallic powder is high energy milled in ball mills or attritors.**
- **Extreme non-equilibrium microstructures** can be achieved through the severe plastic deformation:
  - **Nanocrystalline grain size**
    (usually smaller than by other SPD methods)
  - **Supersaturated solid solution**
    (way beyond the equilibrium limits)
  - Distribution of **dispersoids**
  - Quasi crystals and **amorphous alloys**
    (without an [obvious] liquid phase)
- Some materials are processed by this method in industrial scale. The extreme non-equilibrium states are difficult to be transferred into macroscopic components due to high driving forces for re-formation of the microstructure during consolidation. They are rather used for “bottom-up” synthesis of phases that are not accessible by cast metallurgy.

Examples

Microstructure Refinement by Plastic Deformation

- The movement of the balls and the powder result in a high frequency of impact events.
- Depending on the ductility of the used materials, plastic deformation and the heat associated with it result in consecutive cold welding and fracture of the particles.

Sketch of the consecutive cold welding and fracture of powder particles leading to intense intermixing of species.

C. Suryanarayana: “Mechanical Alloying and Milling”, Progress in Materials Science 46 (2001) 1-184

Examples

Microstructure Refinement by Plastic Deformation

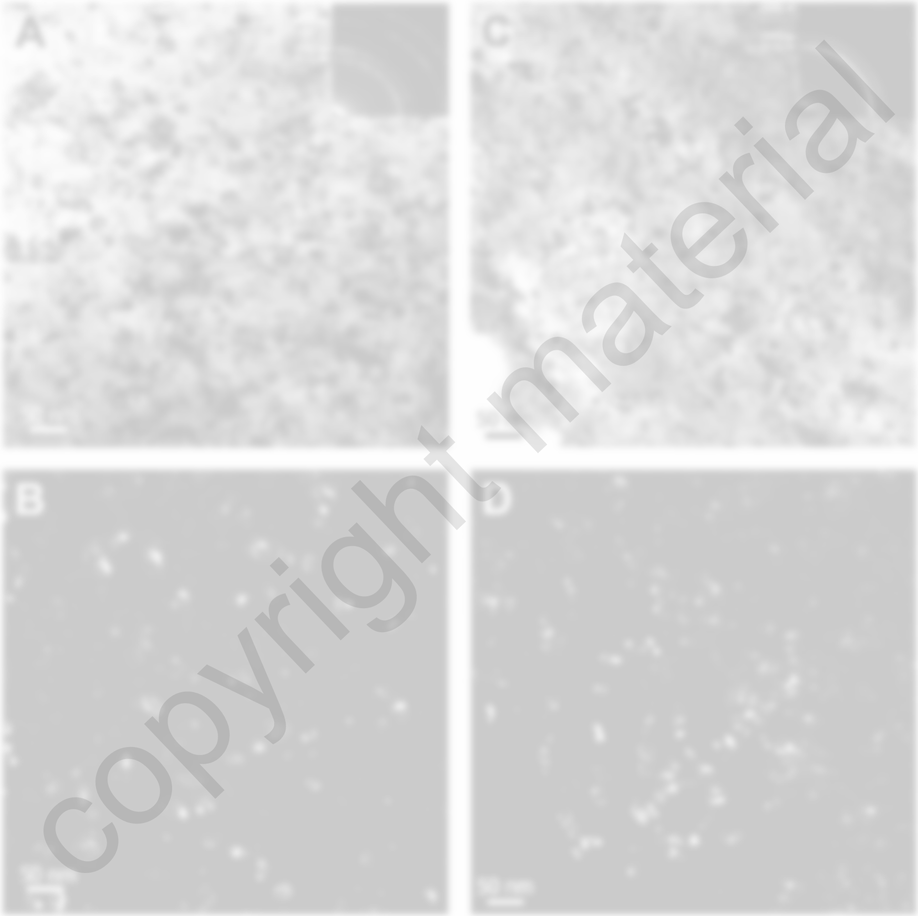
- The grain size that can be achieved scales with melting temperature (or solidus temperature in case of alloys).
- Solute drag on grain boundaries can further reduce the grain size subsequent to mechanical alloying.

Minimum grain size subsequent to mechanical alloying as a function of melting temperature of metallic elements.

C. C. Koch: "Mechanical Properties of Nanocrystalline Materials Produced by in situ Consolidation Ball Milling", Materials Science Forum 579 (2008) 15-28

Examples

Microstructure Refinement by Plastic Deformation



Transmission electron micrographs (bright field) of in-situ consolidated Cu (A) und Cu-1at.%Nb (C).

TEM bright field is used to assess the entire microstructure.

Nb exhibits negligible solubility in Cu in equilibrium conditions. During mechanical alloying up to 10 at.% Nb can be dissolved allowing for an effective precipitation strengthening and grain boundary stabilization afterwards.

Transmission electron micrographs (dark field) of in-situ consolidated Cu (B) und Cu-1at.%Nb (D).

TEM dark field is used to observe individual grains and to determine the grain size of the material.

K. M. Youssef: "High strength, ductility, and electrical conductivity of in-situ consolidated nanocrystalline Cu-1%Nb", Materials Science and Engineering A 711 (2018) 350-355

Examples

Borderline Phenomena: Martensitic Transformations

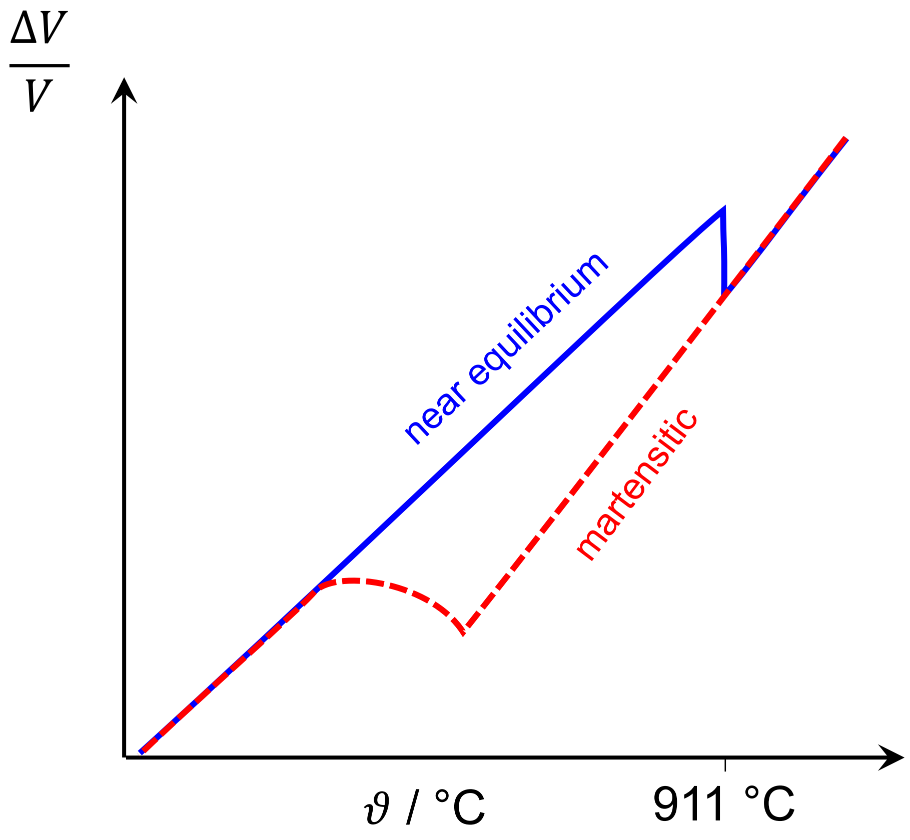
- In many system, **structural transitions** occur.
- The **transformation is reconstructive** under near equilibrium conditions: long-range diffusion of atoms allows transformation via nucleation and growth.
- In case diffusion is suppressed by sufficiently high cooling rates (higher than critical cooling rate) to sufficiently low temperatures (upper critical temperature), the **transformation becomes displacive**: it is mediated by **cooperative movement of the atoms**, which means neighboring atoms before and after the transformation are the same. The transformation is **diffusionless**.
- In multicomponent systems with largely different diffusion coefficients, intermediate transformations can occur.

- Note that in multi-component systems, diffusionless structural transformations can occur with only short-range rearrangement of atoms (thus, not displacive in nature) at constant composition, e.g. massive transformations. For further details see the lecture “Phase Transformations in Materials”.

Examples

Borderline Phenomena: Martensitic Transformations

- Under equilibrium conditions, Fe exhibits a **volume change during** $\gamma \rightarrow \alpha$ due to the change in atomic packing factor and binding state of the atoms.
- The **volume change** that has to be accommodated by the transformation **increases with increasing super cooling** due to the different thermal expansion coefficients of the structures.
- At about $10^4\ \mathrm{K/s}$ (v_{crit}) and cooling to at least $550\ °\mathrm{C}$ (M_s), the martensitic transformation of Fe takes place. The necessary strain is accommodated by mainly plastic deformation, e.g. dislocation movement and generation.
- Accordingly, the hardness of martensitic transformed Fe is higher than that of reconstructive transformed Fe.
- C increases the volume change to be accommodated during the transformation. At high C contents, twinning occurs as additional and major accommodation mechanism.

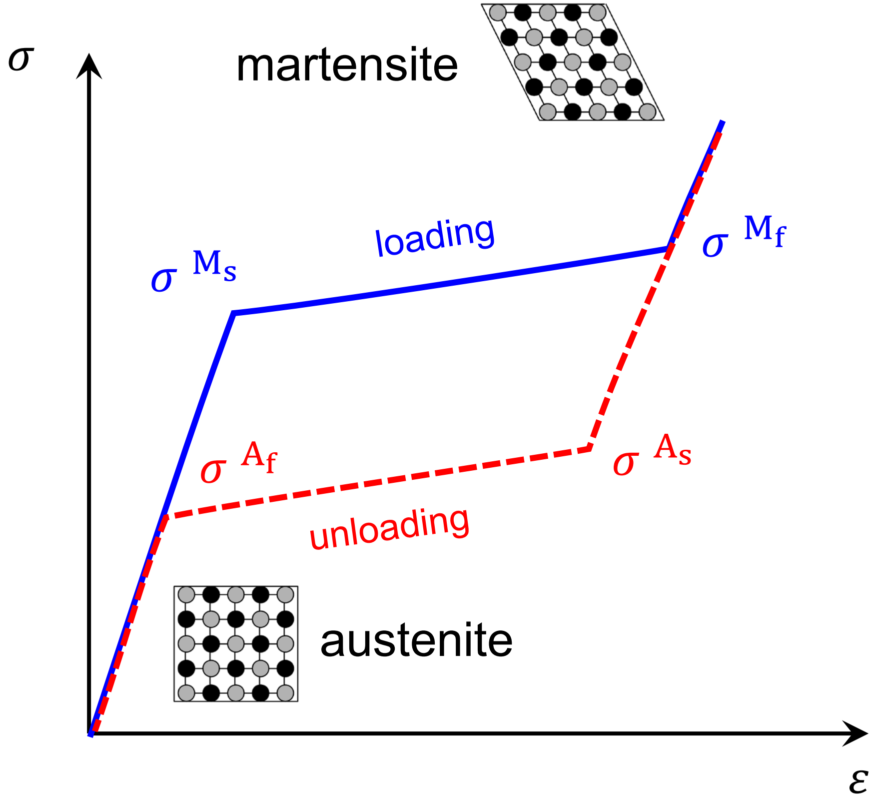


Volume change as a function of temperature in Fe.

Examples

Borderline Phenomena: Pseudo-Elasticity and Shape Memory Effect

- **Martensitic transformation is the origin of pseudo-elasticity and shape memory effects.**
- Pseudo-elasticity allows for large strains at rather low stresses.
- The shape memory effect allows for temperature induced recovery of a shape.
- Both phenomena are closely related to plastic deformation phenomena like twinning. If the operation is not fully reversible, functional fatigue occurs.



Stress-strain diagram for loading and unloading of a material exhibiting pseudo-elasticity.

D.C. Lagoudas: "Shape Memory Alloys – Modeling and Engineering Applications", New York, USA: Springer (2008)

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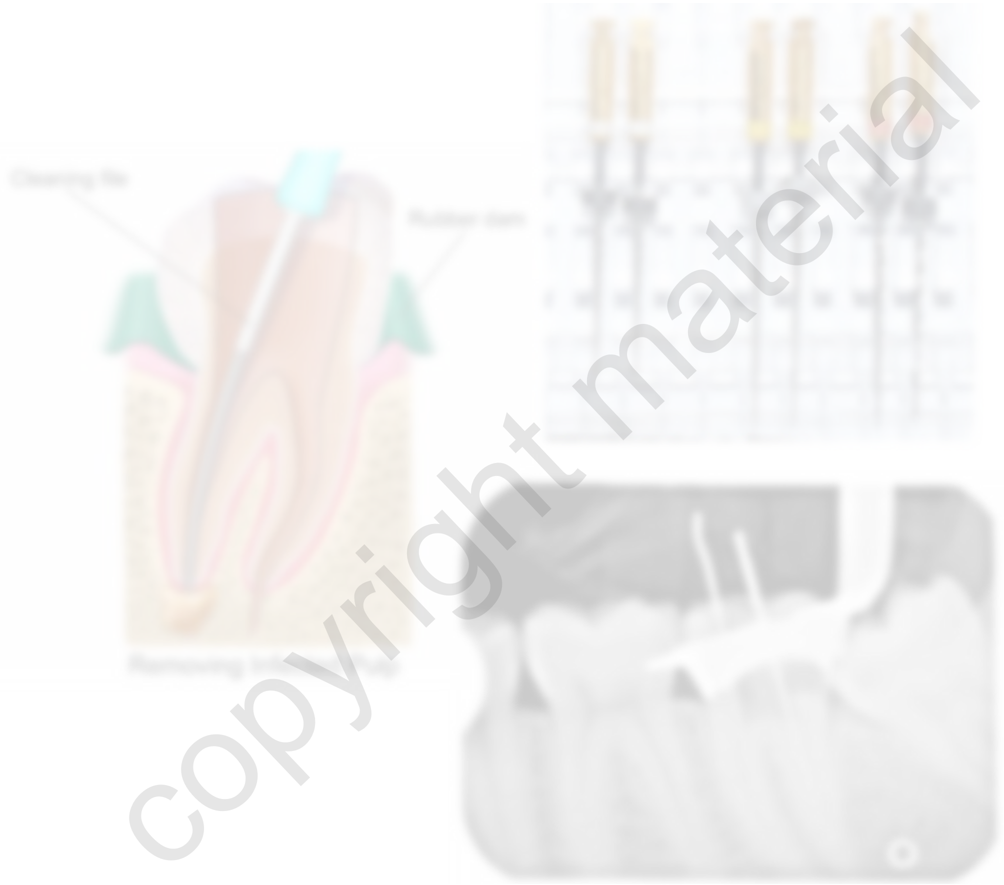

Some images on the use and shape of endodontic files for root canal treatment.

https://en.wikipedia.org/wiki/Root_canal_treatment
https://en.wikipedia.org/wiki/Endodontic_files_and_reamers

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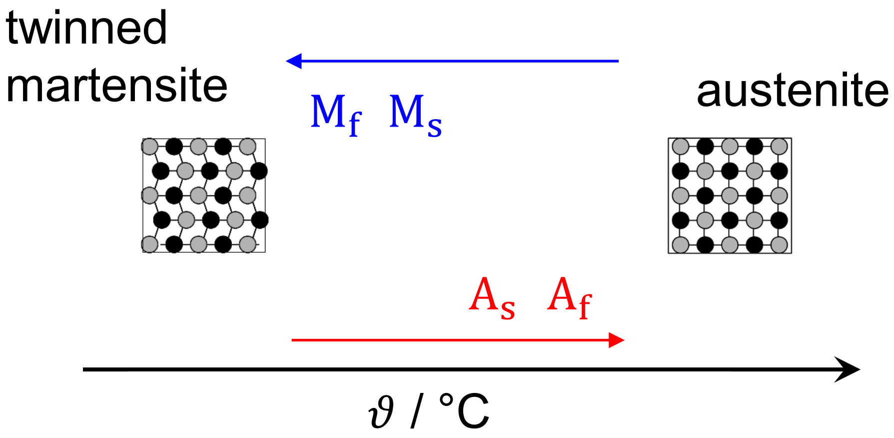

Temperature-induced transformation without external load and external shape change. The deformation between austenite and martensite is accommodated by twinning.

D.C. Lagoudas: "Shape Memory Alloys – Modeling and Engineering Applications", New York, USA: Springer (2008)

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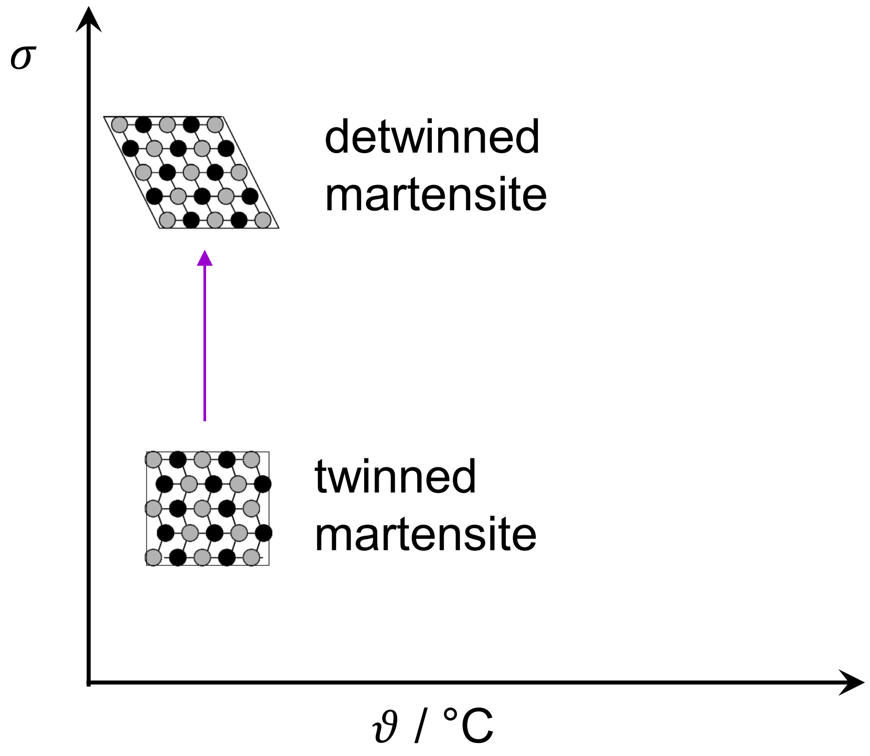

Deformation of the twinned martensite by detwinning.

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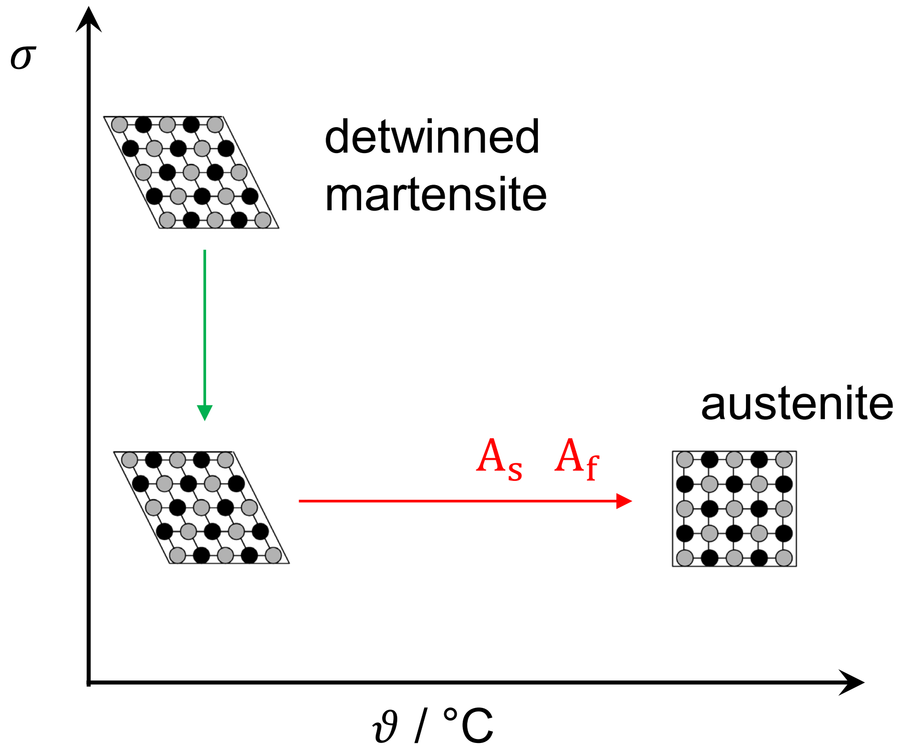

The detwinning process is irreversible and stays during unloading.
After heating above austenite finish temperature, the original shape recovers.

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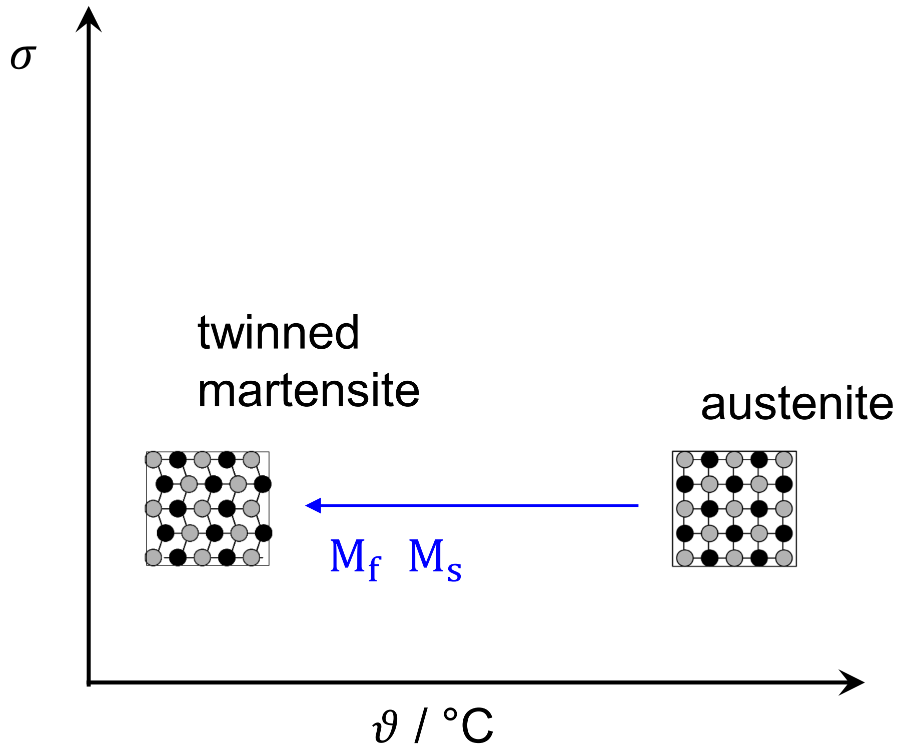

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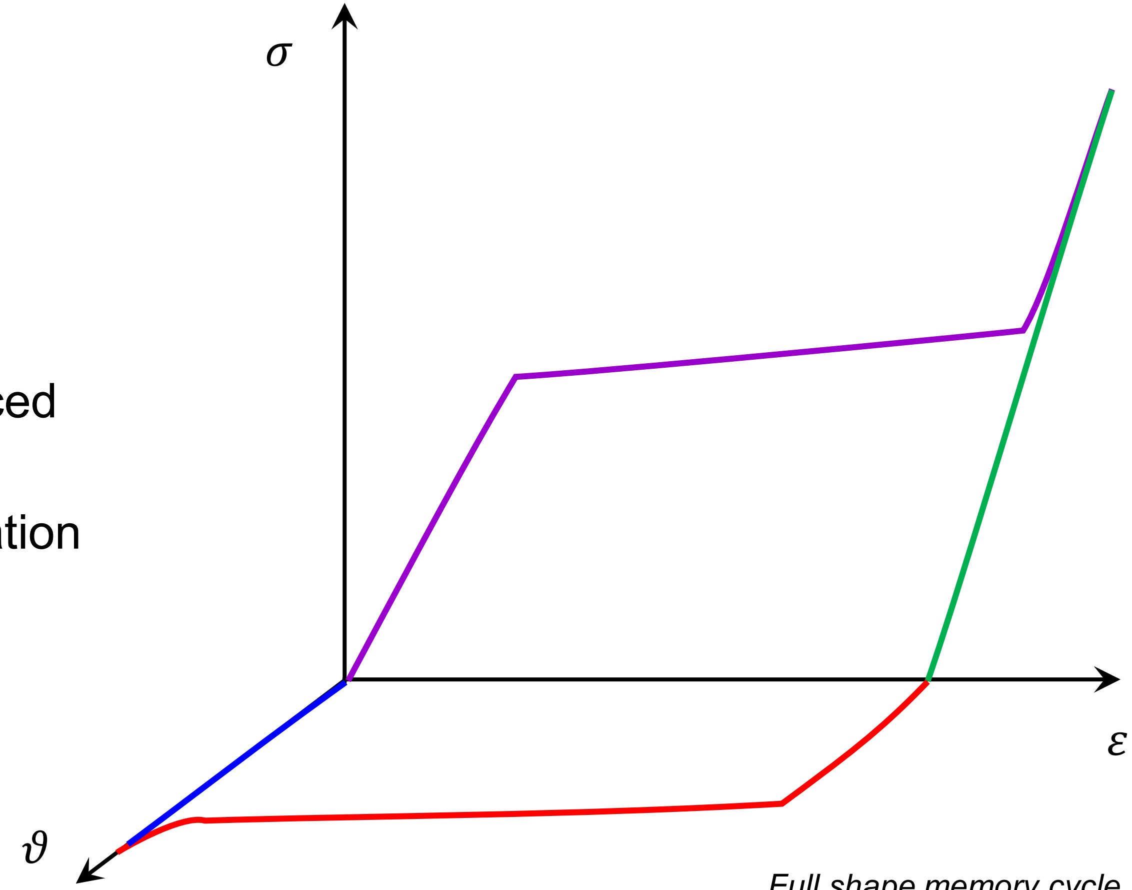

Full shape memory cycle.

D.C. Lagoudas: "Shape Memory Alloys – Modeling and Engineering Applications", New York, USA: Springer (2008)

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Self-expanding shape memory stent:
(above) deployed and (below) constrained like within the catheter.

D.C. Lagoudas: “Shape Memory Alloys – Modeling and Engineering Applications”, New York, USA: Springer (2008)

Summary

- Plasticity plays a major role for development and application of metals, alloys and intermetallic compounds in mechanical engineering.
- Microstructure determines the plastic deformation behavior and plastic deformation alters the microstructure leading to a complex feedback loop of the two.