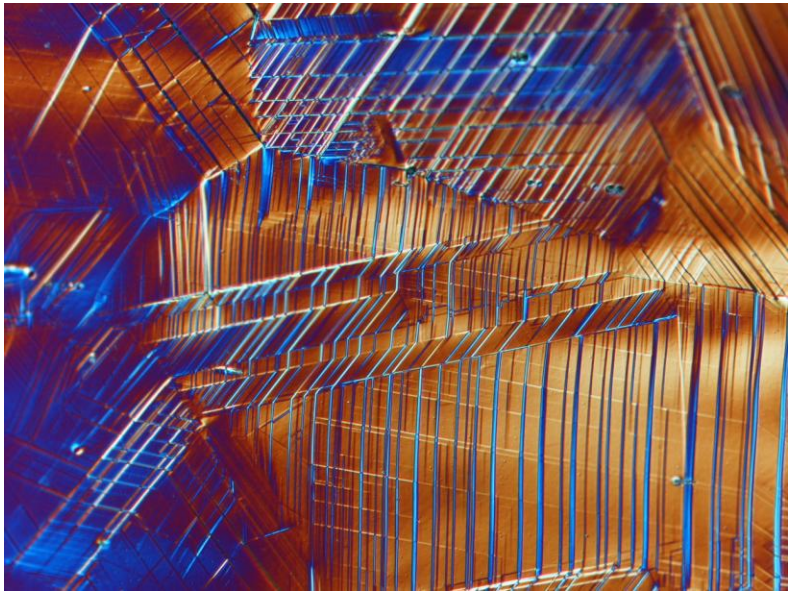
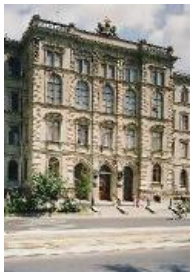
Probing the surface and bulk mechanical properties of NiTi shape memory alloys



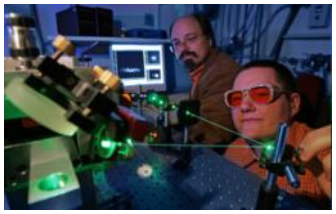
Martin F.-X. Wagner
Materials Engineering Group
Chemnitz University of Technology

A few words about Chemnitz, its university and our research at IWW

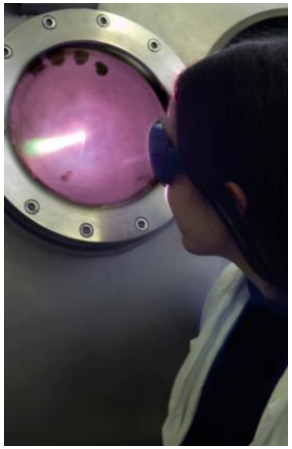
Chemnitz University of Technology

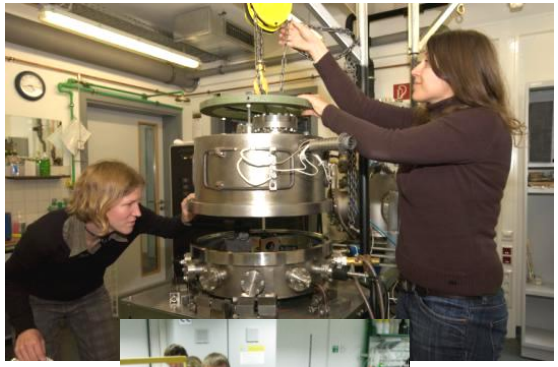


- >10.000 Students
- 8 Departments (Mech. Eng. 26 Full Professors)
- > 50 BSc/ MSc courses
- ***1 Collaborative Research Center (IWW)***
- international students from more than 50 countries
- Smart Systems Campus: Fraunhofer-Institutes IWU, ENAS and IZM
- „Saxon Excellence Research“ eniPROD; TUC + FhG
- ***Federal Cluster of Excellence MERGE***



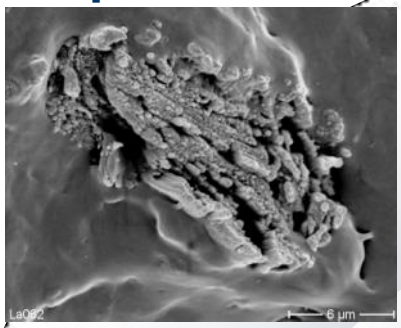

Department of Materials Science and Engineering (IWW)



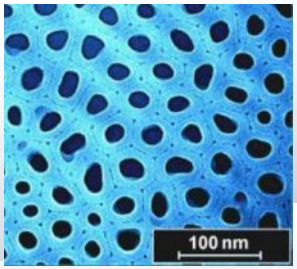


Research Profile

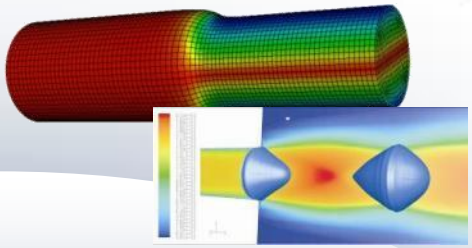
Composite Materials



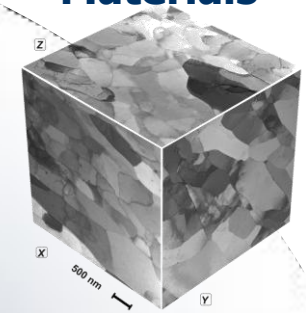
Electroplating



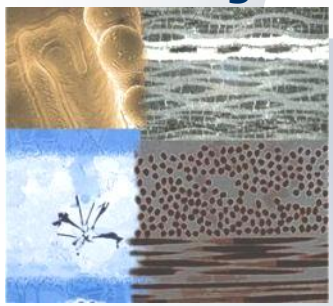
Modelling



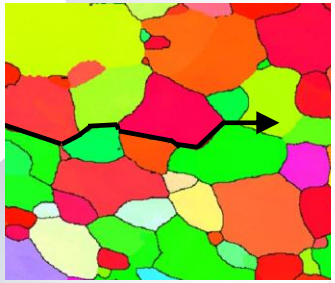
Ultrafine-grained Materials



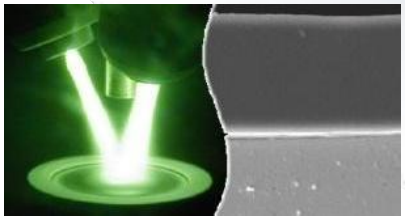
Brazing



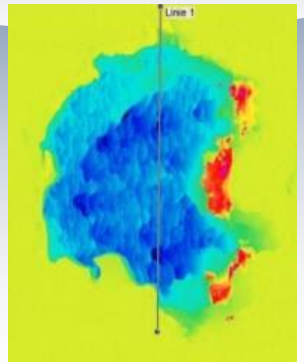
Microstructural Analysis



Thermal Spraying

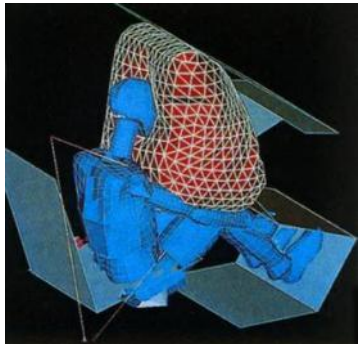


Corrosion and Tribology



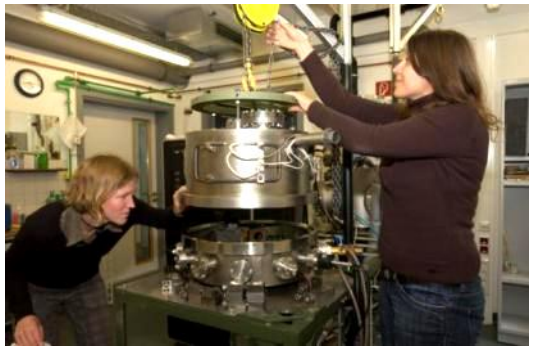
(Dynamic) Materials Testing

Research collaborations with industry


Our alumni work, among others, with

Audi 🌍 Mathys Orthopädie GmbH
Thyssen 🌍 MTU 🌍 Enthone-OMI
Thielert Aircraft Engines 🌍 Modine
Daimler 🌍 Hilti 🌍 Airbus 🌍 AMD
Volkswagen 🌍 Salzgitter Stahl AG

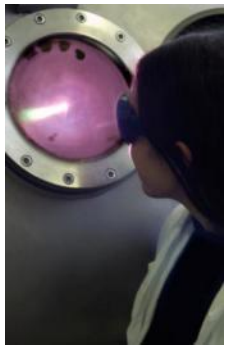


Degree Courses

- Mechanical Engineering/Production Technology
- Automobile Production, Medical Engineering
- Focus Areas:
  Materials Engineering, Surface Technology, Lightweight Construction

Further Activities

- Seminars
- Further training courses
- Post-graduate programmes
- Student projects



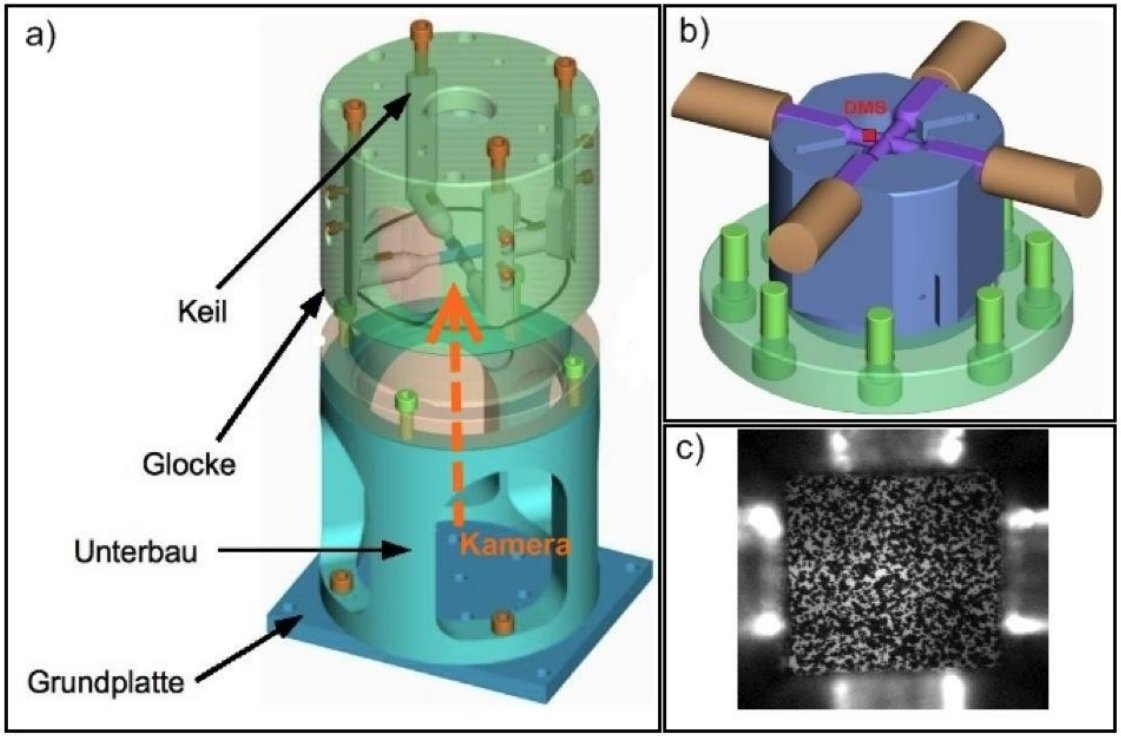
Research areas (general area of mechanical properties and microstructure)

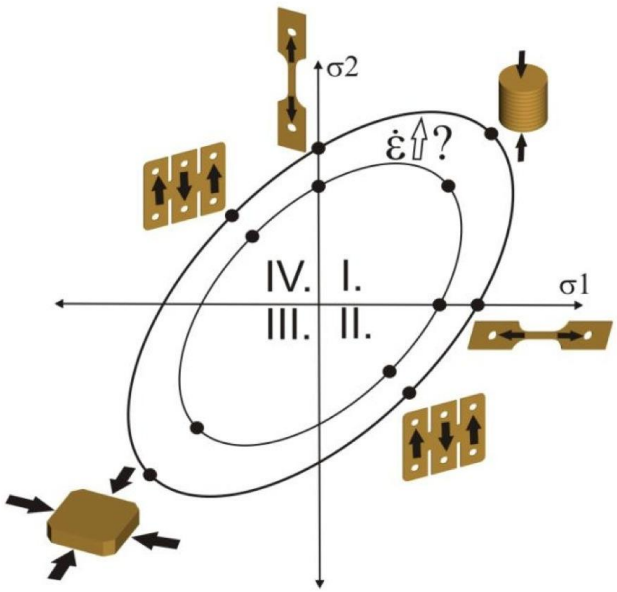
- NiTi shape memory alloys, martensites
- Al, Mg, Ti
- High strain rate deformation, shear bands
- Localization of deformation
- Thermo-mechanical optimization
- SPD: ECAP, cryo-forming

Methods, tools

- Mechanical testing, including strain mapping, thermal imaging
- Microstructural analysis (SEM, TEM, XRD...)
- High strain rate testing (drop tower, rotating wheel, Split Hopkinson)
- ECAP (different tools, 16 MN press)
- Modeling: atomistic, micromechanics, FEM

DFG PAK250: Biaxial compression testing





Univ.-Prof. Dr.-Ing. habil. B. Wielage
Professur Verbundwerkstoffe

Univ.-Prof. Dr.-Ing. habil. T. Lampke
Professur Oberflächentechnik/Funktionswerkstoffe

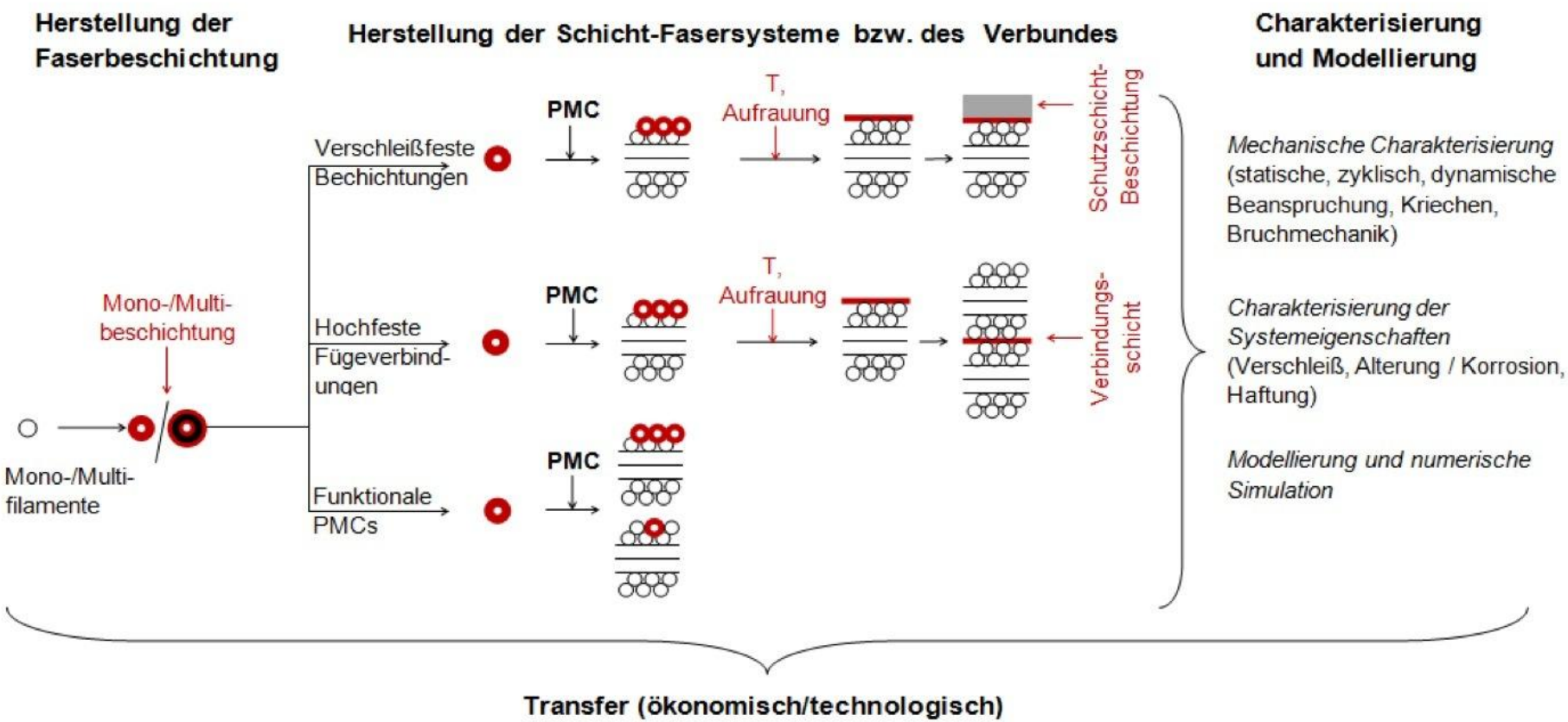
Univ.-Prof. Dr.-Ing. habil. M. Wagner
Professur Werkstofftechnik

Univ.-Prof. Dr. rer. pol. habil. U. Götze
Professur BWL III - Unternehmensrechnung und Controlling
(Fakultät für Wirtschaftswissenschaften)

Univ.-Prof. Dr.-Ing. M. Berger
Professur Montage- und Handhabungstechnik

TECHNISCHE UNIVERSITÄT CHEMNITZ
1836-2011
175 Jahre

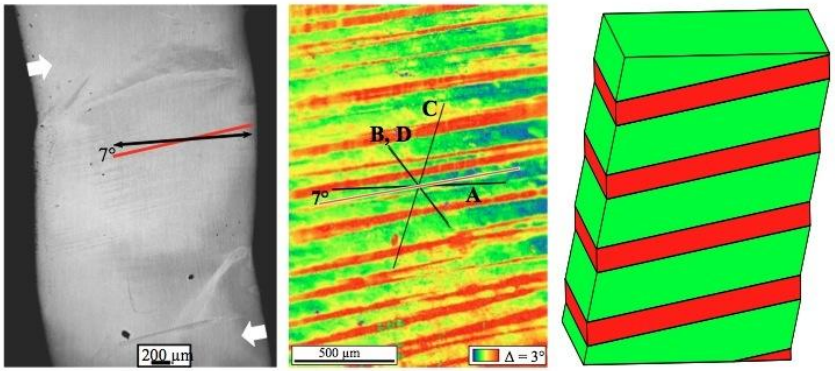
Strukturfonds in Sachsen.
ESF
Europäischer Sozialfonds
CCI-Nr.: 2007 DE 05 1 PO 004

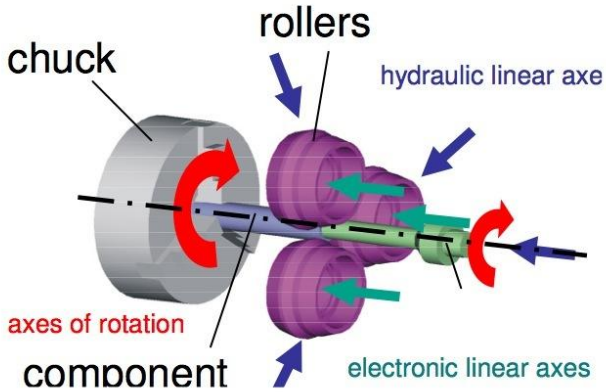


Ecological and economical machining

MICROPLAST

DFG-FOR797

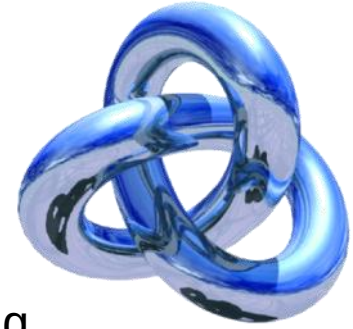




Prinzip Bohrungsdrücken

DFG-PAK292

Collaborative Research Center SFB 692

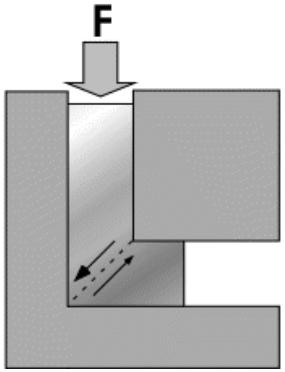


Optimization of high-strength aluminum alloys:

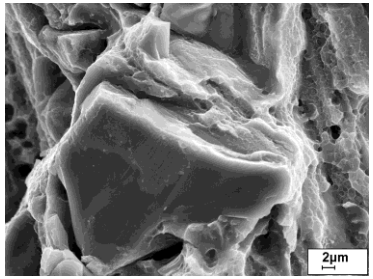
a) ECAP deformation and thermo-mechanical processing

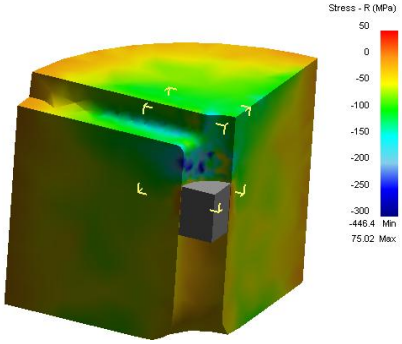
b) Aluminum matrix composites

c) Al-Mg-composites



„ECAP“ (Equal channel angular pressing)





The team of SFB 692, September 2013

WYSI(NN)WG

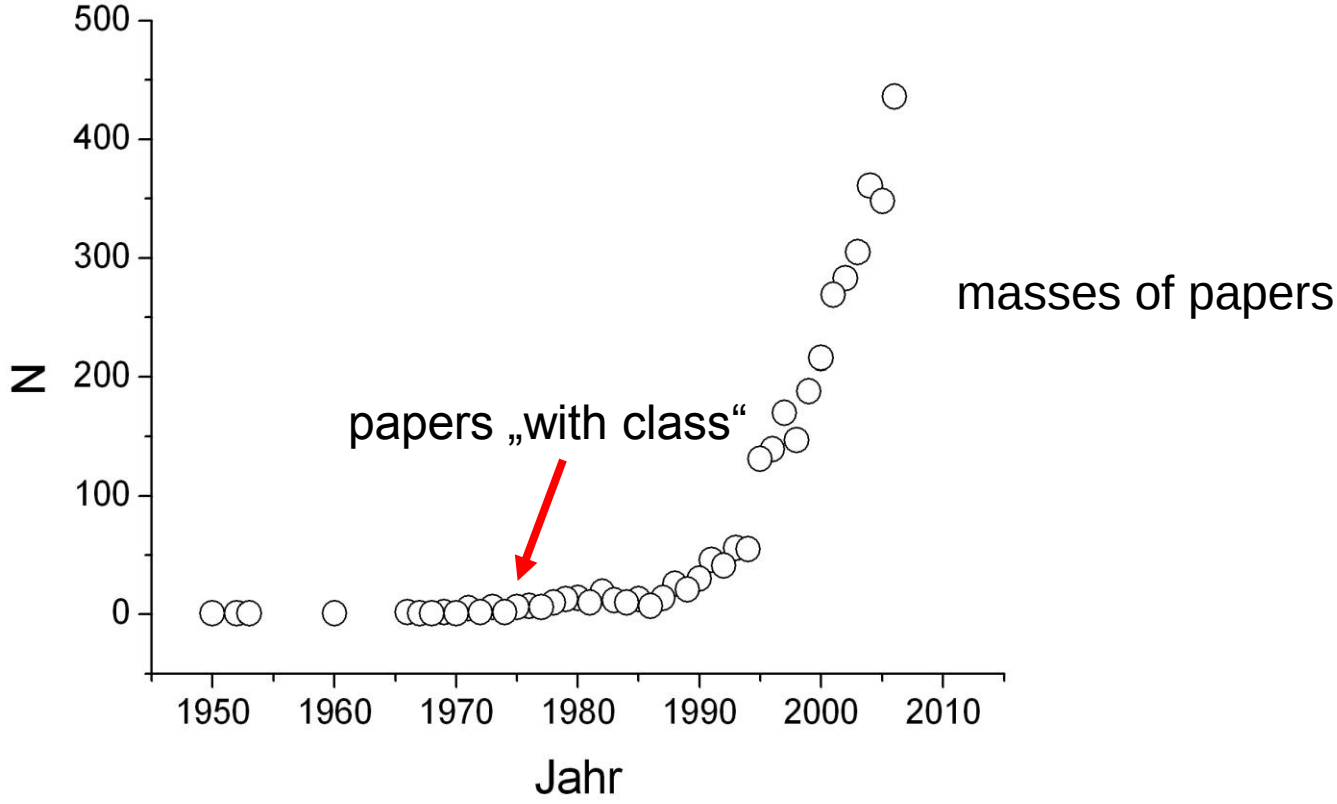
- „Materials that you can deform and that, when heated, recover their initial shape“

- Potential use (to be evaluated crititcally): healing dents in a car body, morphing wings, alternatives to complex motors and gears, sensor and actuator capabilities in one single part

- *Note: „Any sufficiently advanced technology is indistinguishable from magic....“ (A.C. Clarke)*

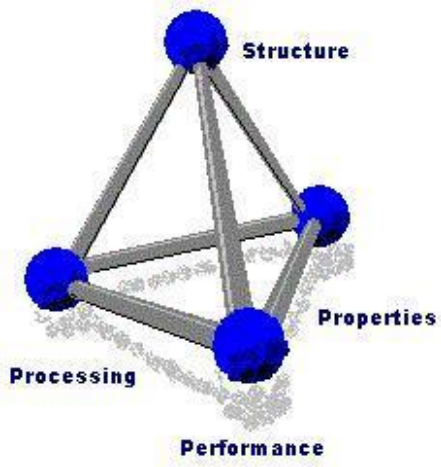
ISI Web of Science

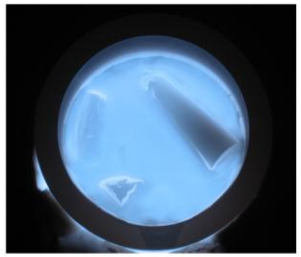
„NiTi OR Nitinol“ → 3513 search results, 1945 – 2007
„SMA“ → 7464 search results

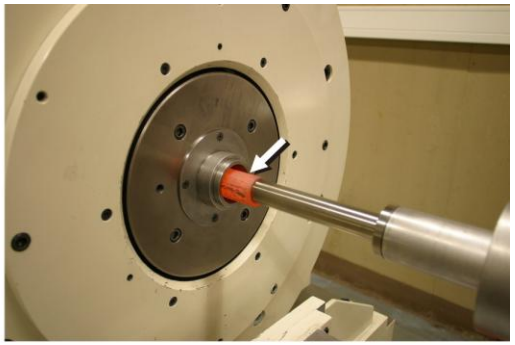


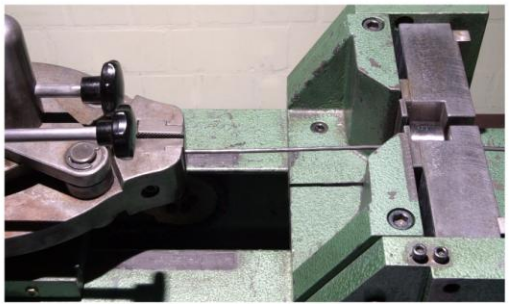
„If you want to teach materials science – teach shape memory alloys“

Jan van Humbeeck, Preface to Scripta Mater. Viewpoint No. 33 on Shape Memory Alloys, vol. 50 (2004)

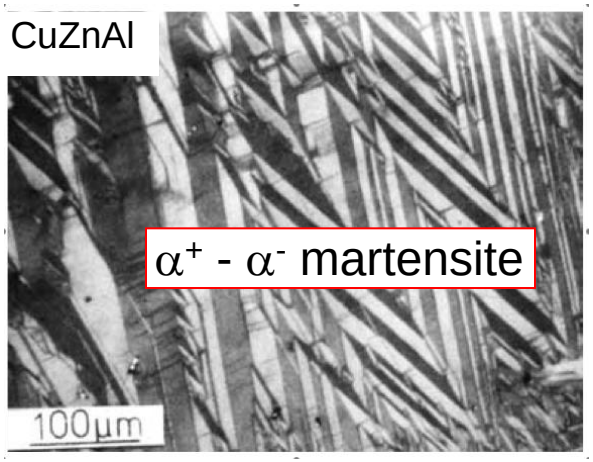


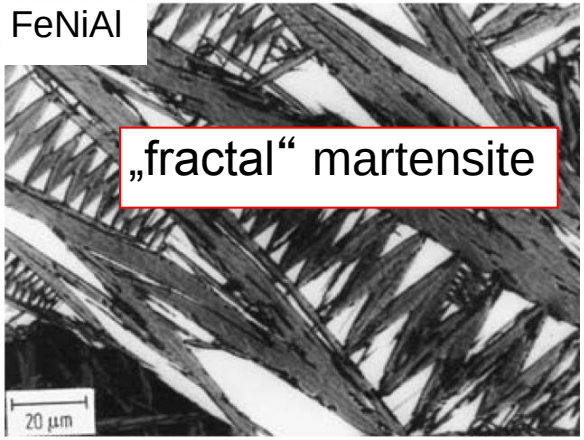


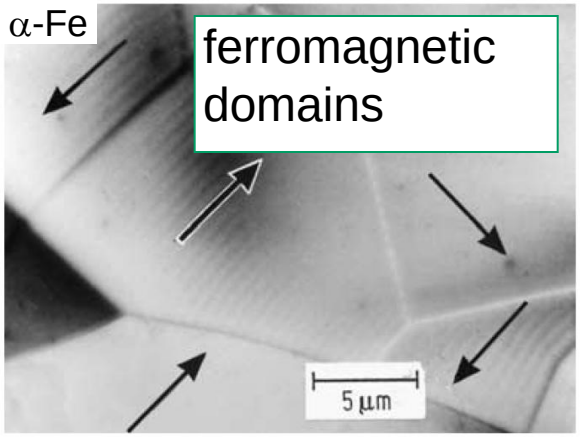


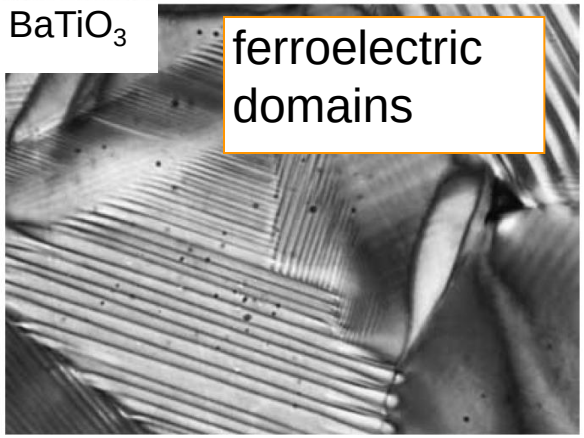


General class of materials: ferroics, domains



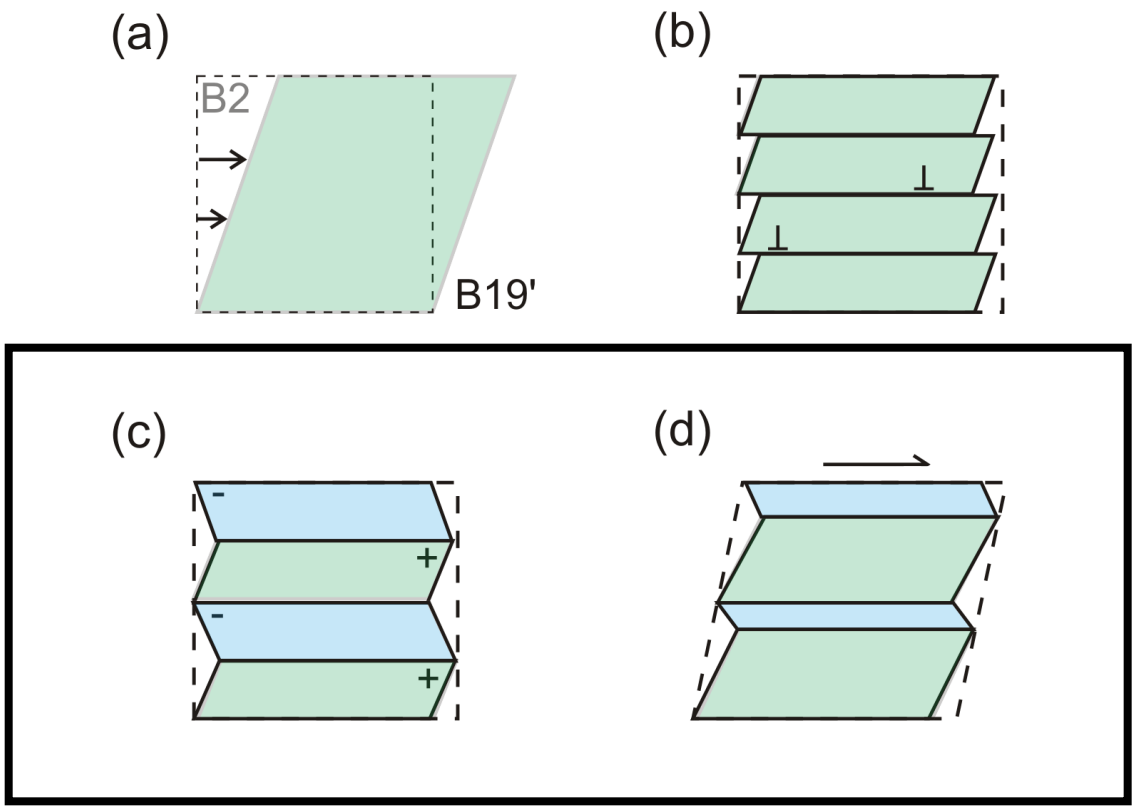






E. Hornbogen, Int. J. Mat. Res. 96 (2005), 316-324.

Rearrangement of domains...



Analogies

	ferro-		
elastic	magnetic	electric	*materials*
martensitic	ferromagnetic	ferroelectric	*effect/ domains*
~ 10 %	~ 1 %	~ 0.1 %	*strain*
temperature, stress	magnetic field H, stress	electric field E, stress	*stimuli*
large forces, but slow	small forces, fast	large forces, fast	*characteristics*

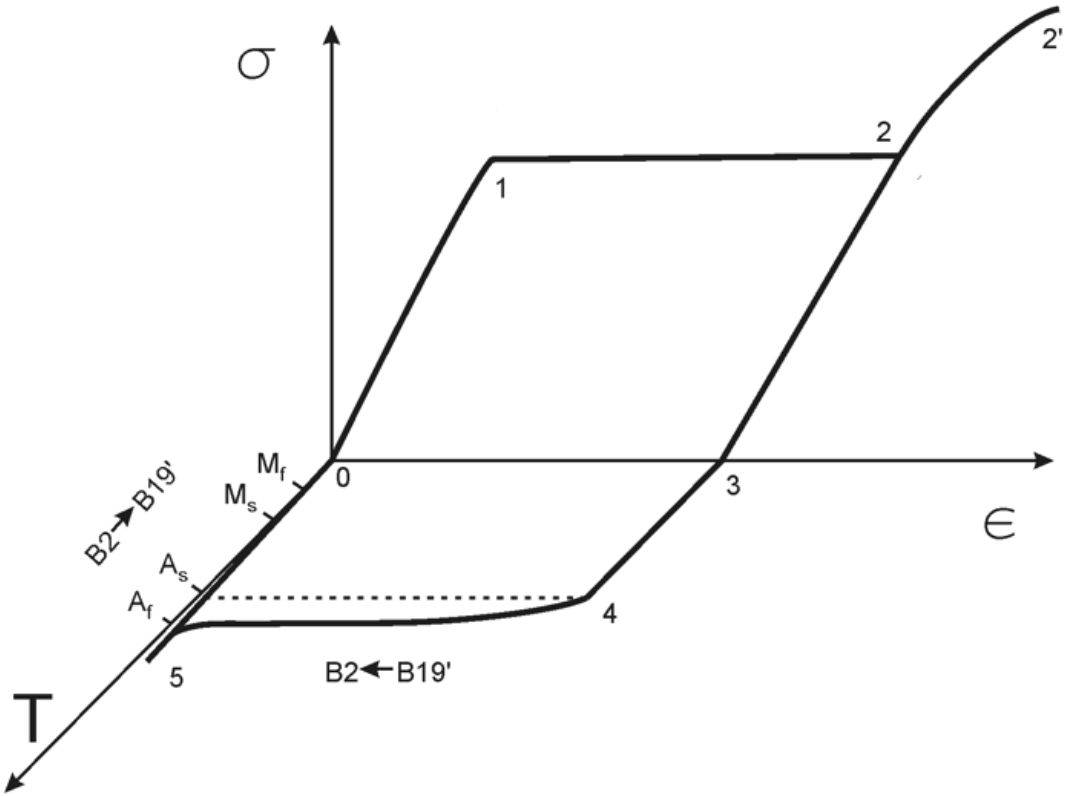
→ (thermal) shape memory alloys: Cu-based, Fe-based, NiTi

Why do research on NiTi ?

„The only successful shape memory alloy is the one least understood.“

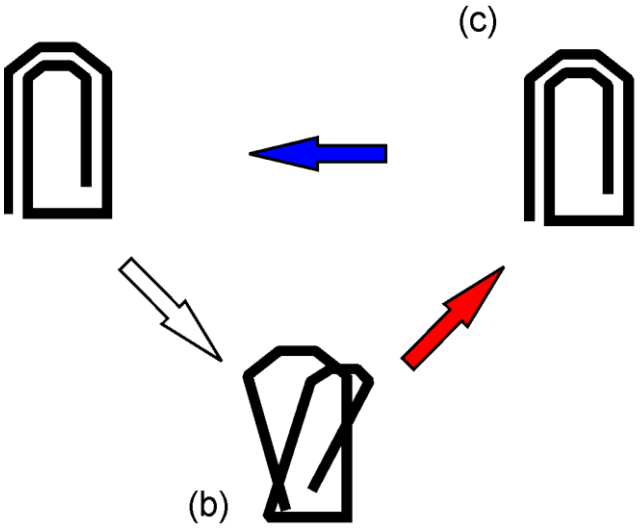
X. Ren, Bochum, 2003

SM Effects – Overview: Thermal SM

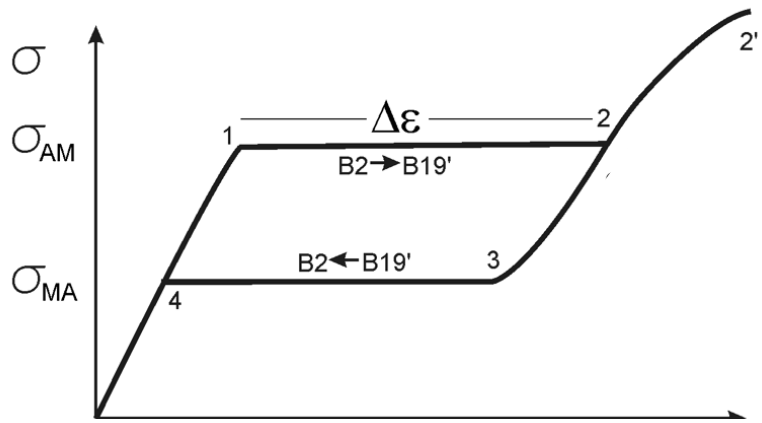


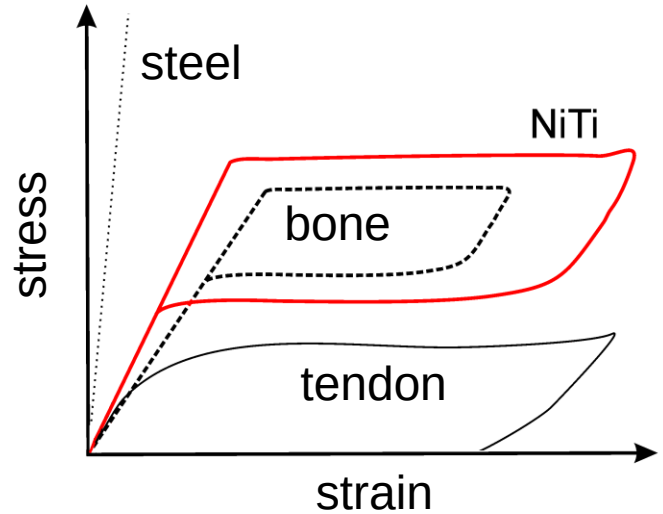
„one-way effect“

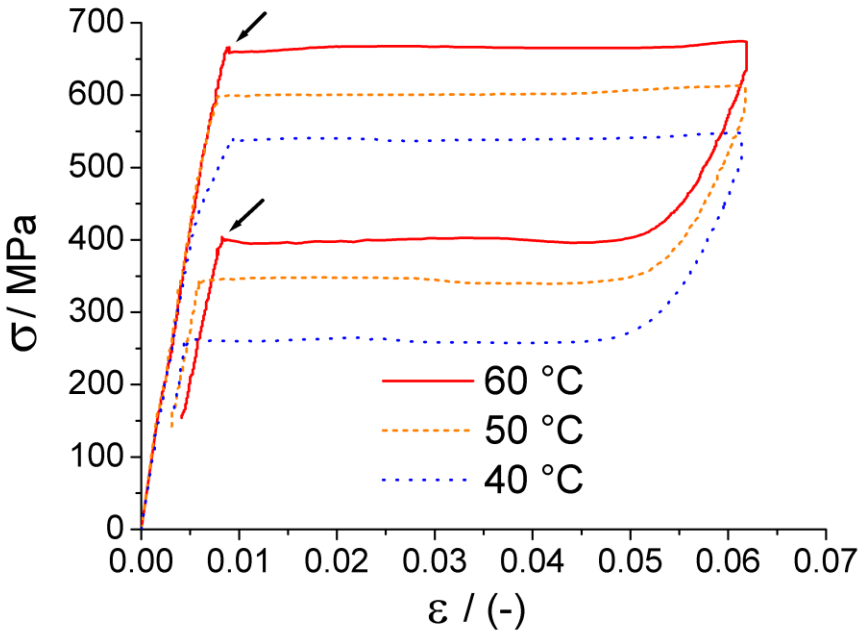
Engineering science, applications:
(no paper clips!)
actuators, thermostats
Forces, actuation frequency, design standards



Effects II: Pseudoelasticity (mechanical memory)





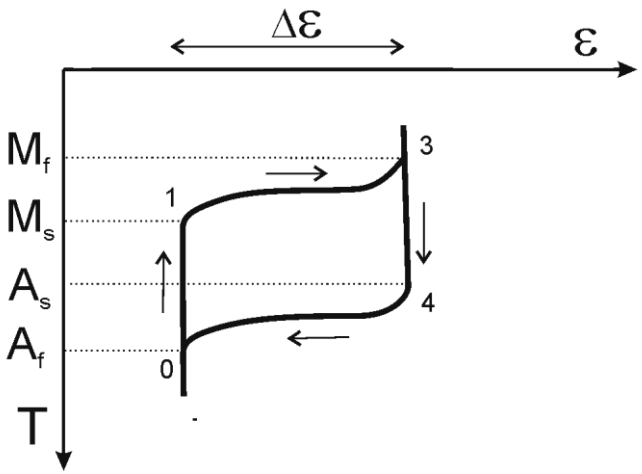


Focus on biomedical applications

Clausius-Clapeyron type relationship between (ambient) temperature and transformation stresses

c_{AM} = 5 - 15 MPa / K

Effects II ½ : two-way effect



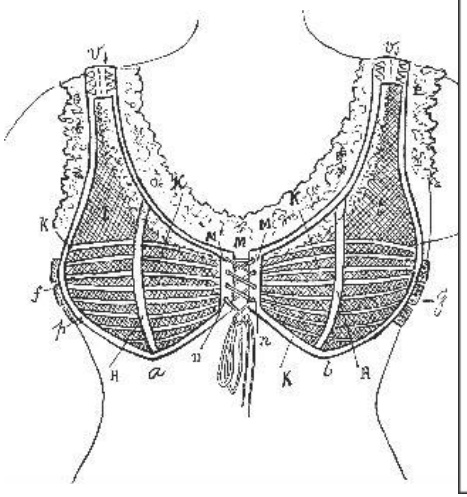
Requires „training“, fatigue, low (almost zero) forces allowed

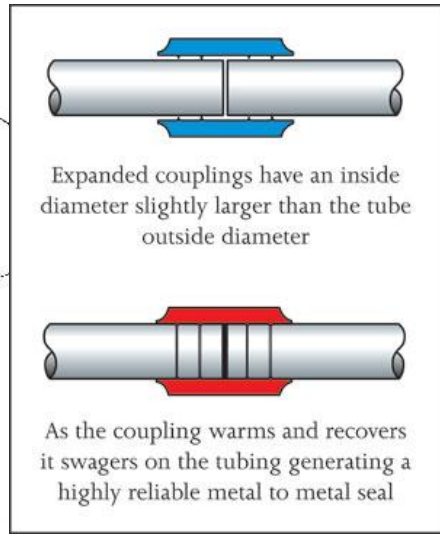
SMA applications

1. Fashion, decoration, gadgets
2. Couplings and fasteners
3. (Micro-) Actuators
4. Adaptive materials and hybrid composites
5. Damping apps

…

J. Van Humbeeck, Mat Sci Eng A 273-275, 1999, 134-148

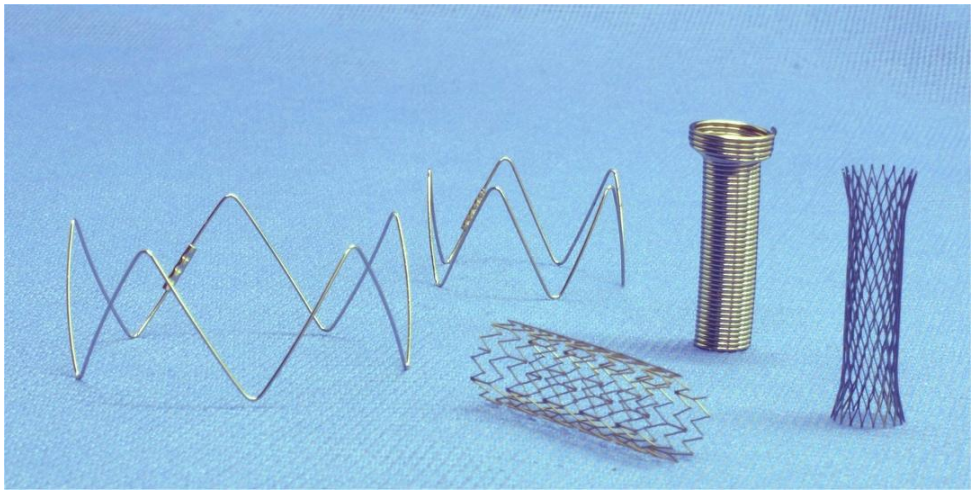




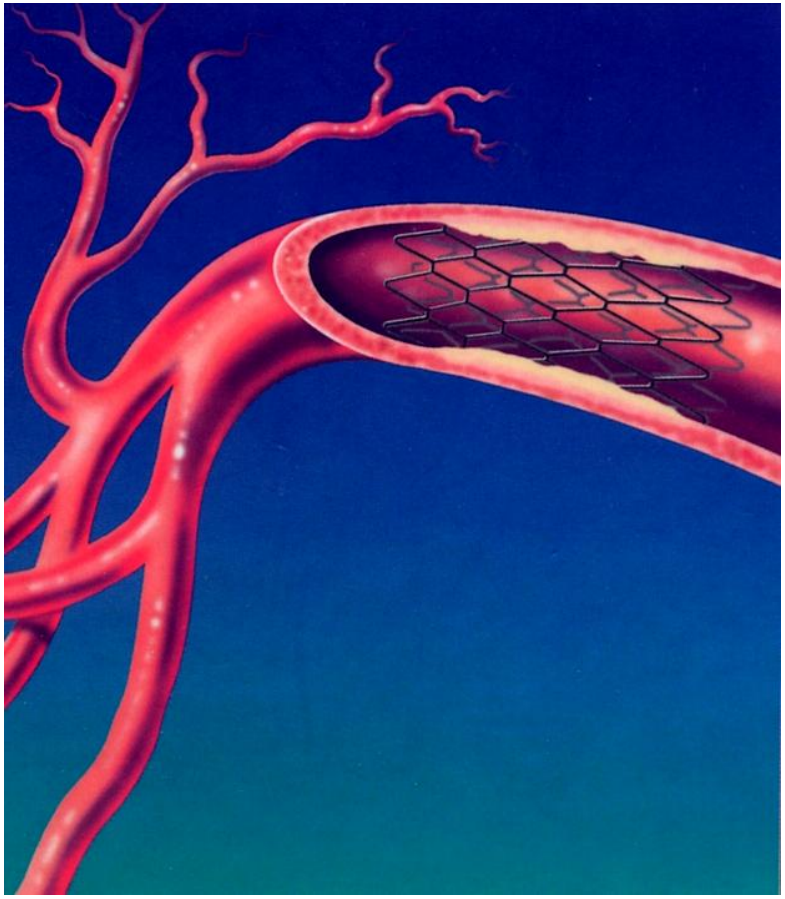
<u>Medical Applications (see paper by Duerig et al.)</u>

1. Stents
2. Guide wires
3. Vena cava filters
4. Orthodontic drills and braces

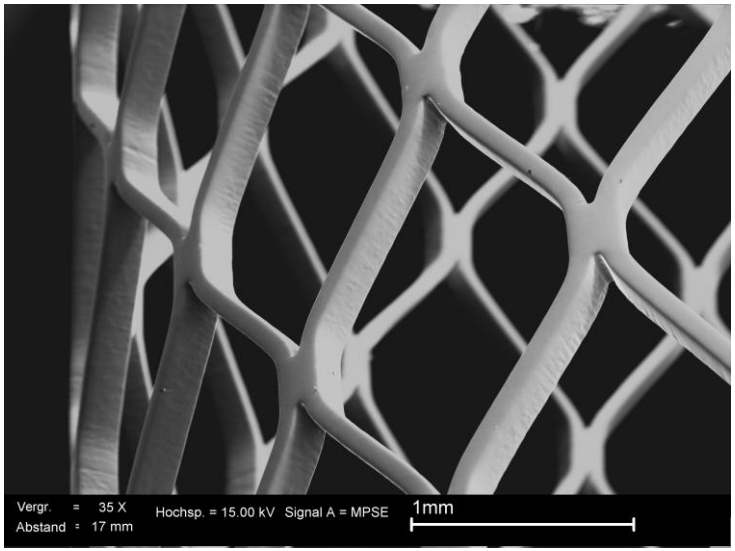
Medical market dominated by NiTi

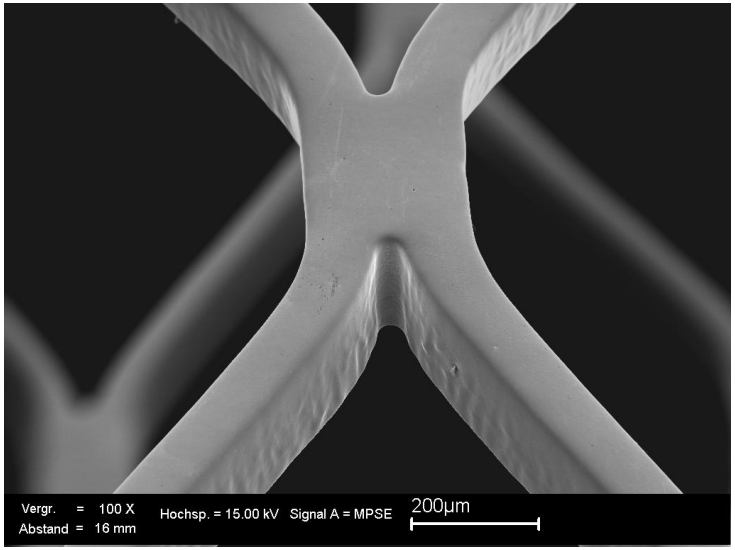


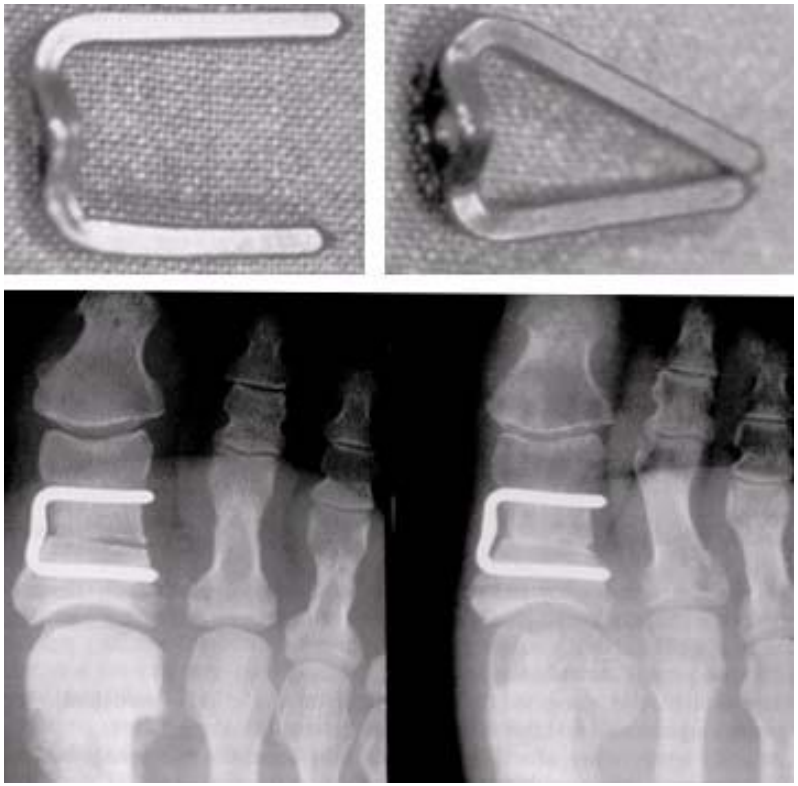
Stents: fine structures and cyclic loading

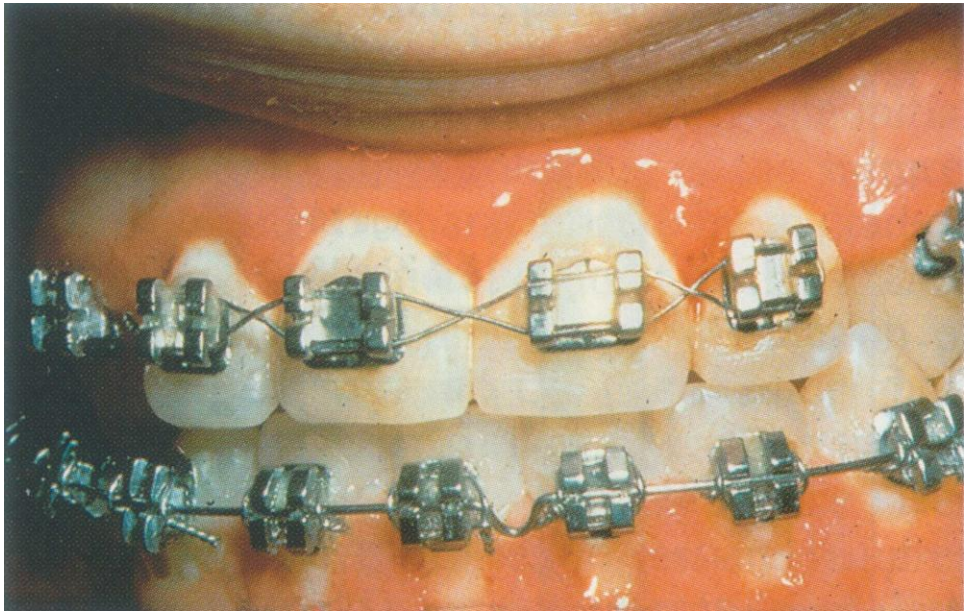


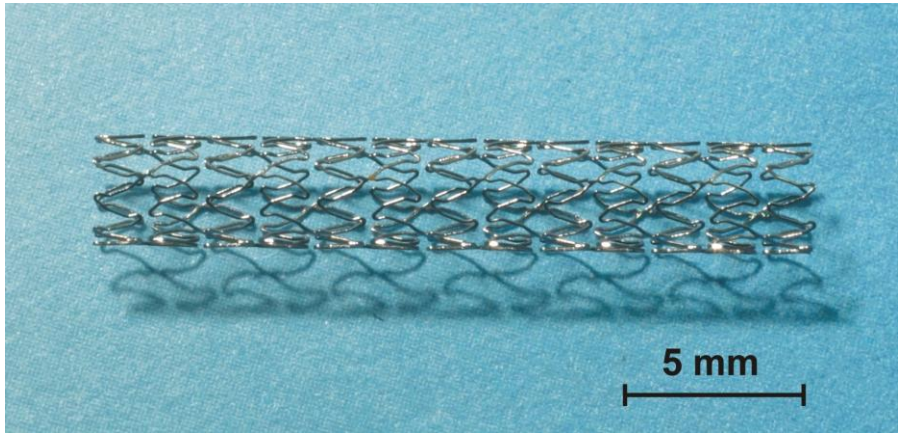
FDA: 4×10^8 cycles



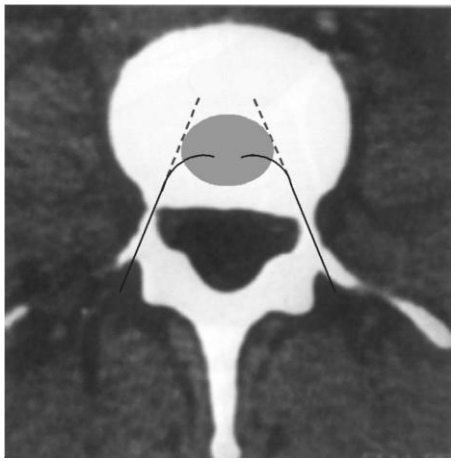


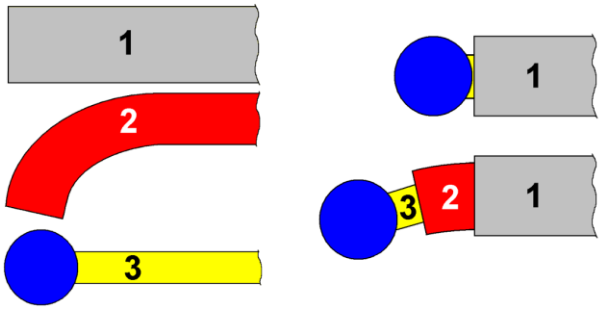


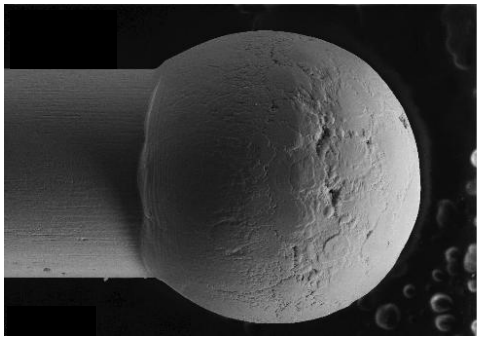



5 mm

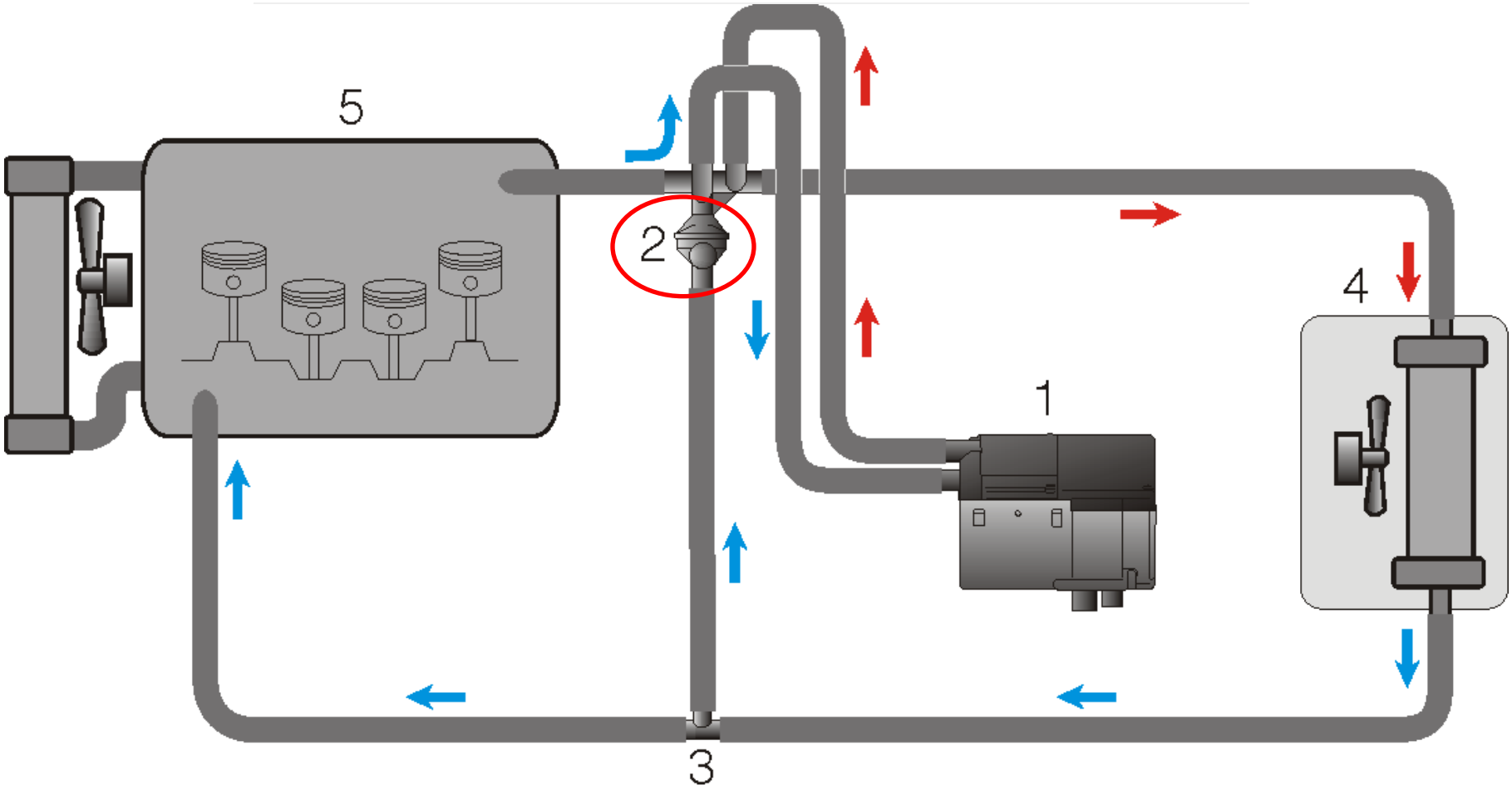
A non-linear drilling device







Examples of applications: Thermostat



(c) Eberspächer

Examples of applications: Thermostat

10 minutes

15 minutes

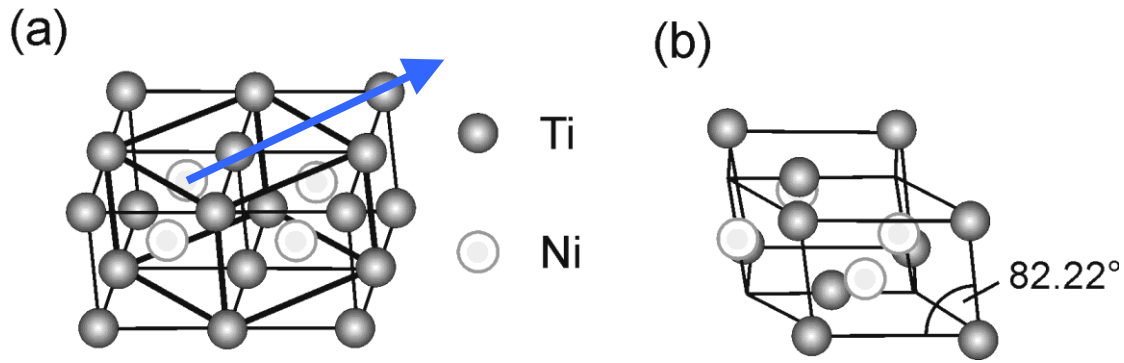
20 minutes

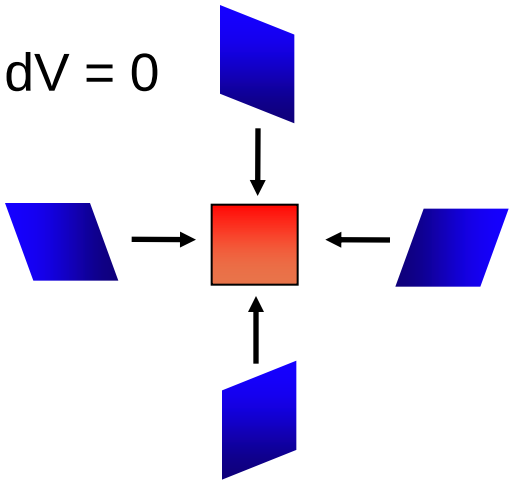
(c) Eberspächer

Limitations and Issues

Origin of Shape Memory

→ martensitic phase transformation





Higher symmetry of austenite:
<u>all</u> martensite variants
have to return to the <u>one distinct</u> austenite configuration

Martensitic Transformations

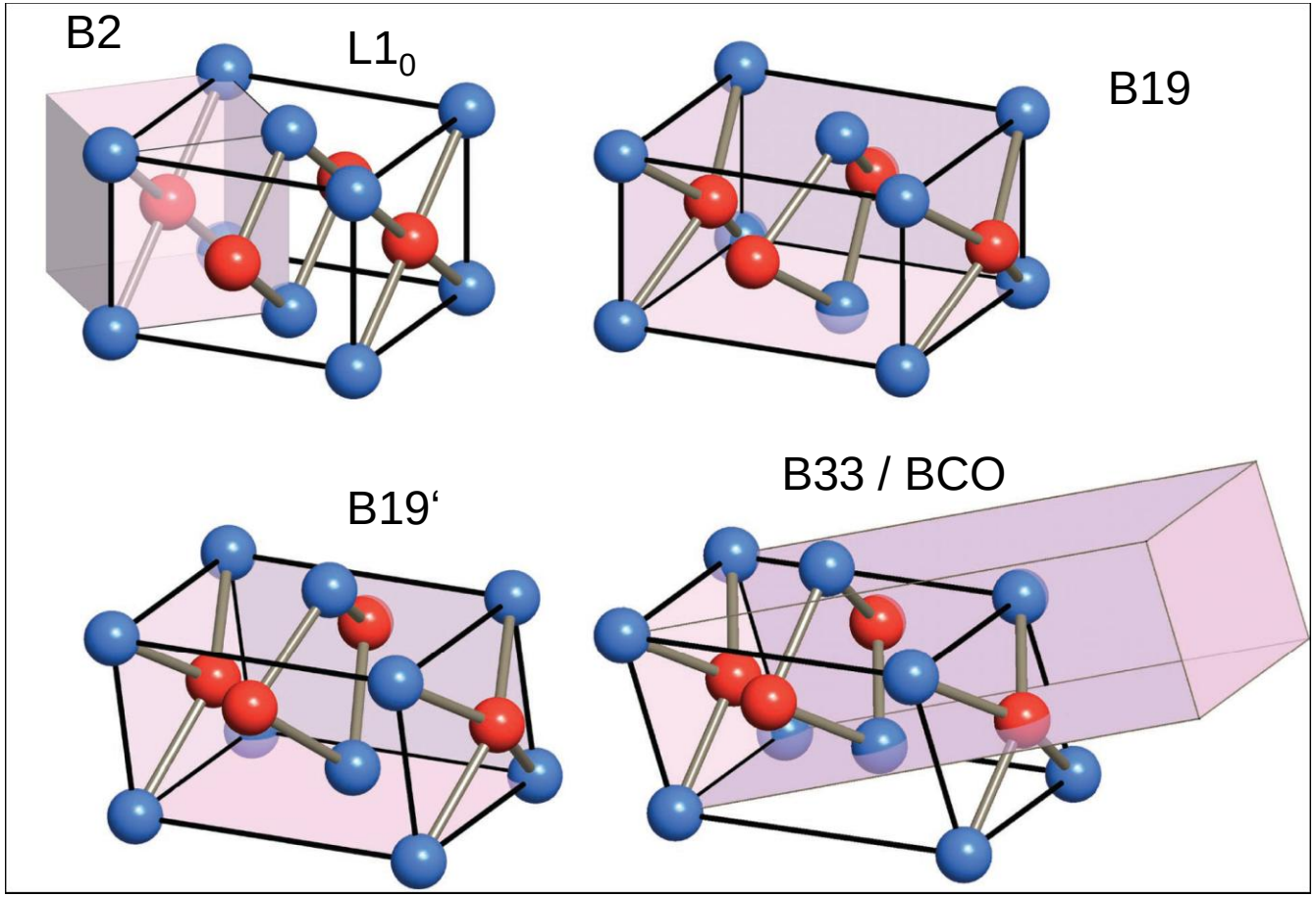
Adolf Martens

historically: Fe-C, tetragonal distortion

today: ALL diffusionless phase transformations

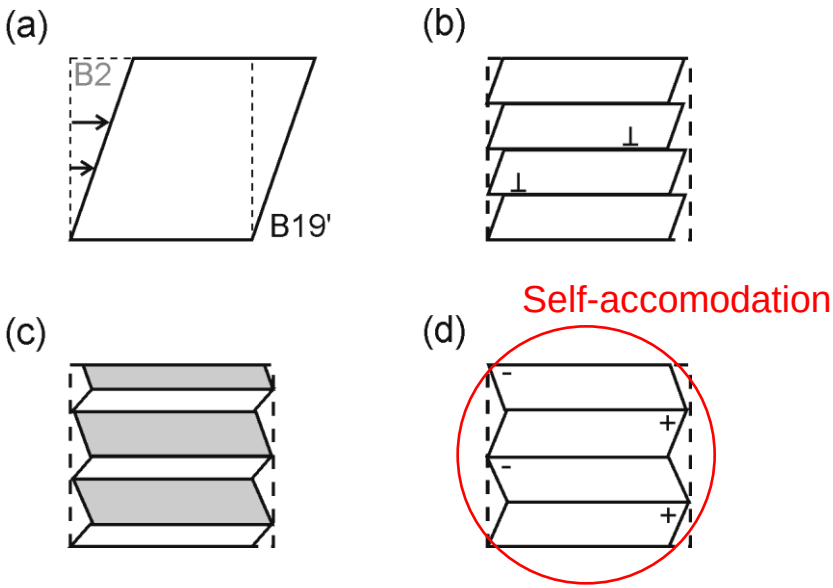
- chemical composition remains unchanged
- cooperative shear deformation in the lattice, lattice constants change only a little
- nearest neighbors remain the same
- considerable deformation, up to 15 % in single crystals
- habit plane between austenite and martensite
- well-defined orientation-relationships

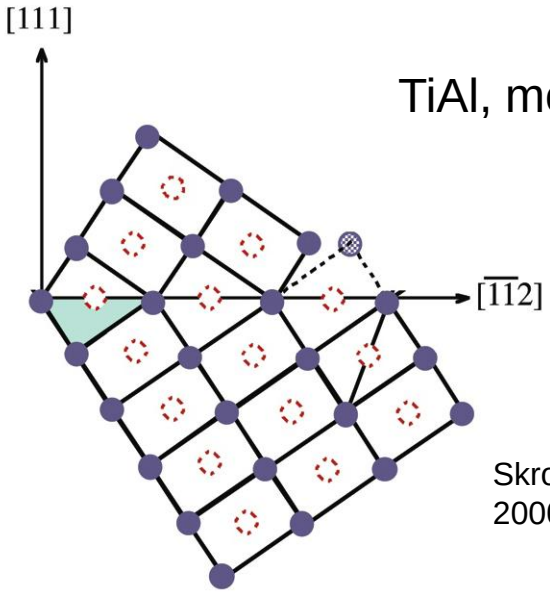
Important NiTi crystal structures



Huang, Ackland, Rabe, Nature Materials, 2003, 307- 311

Martensitic transformation in SMAs

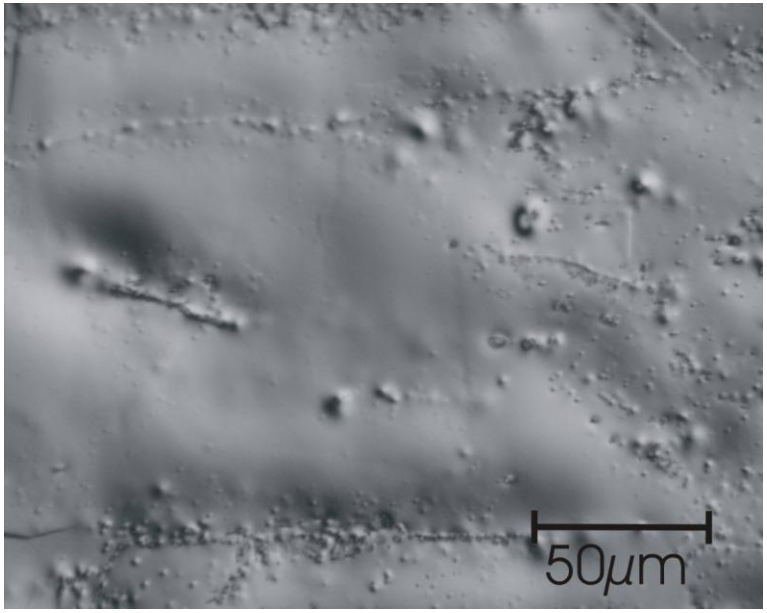




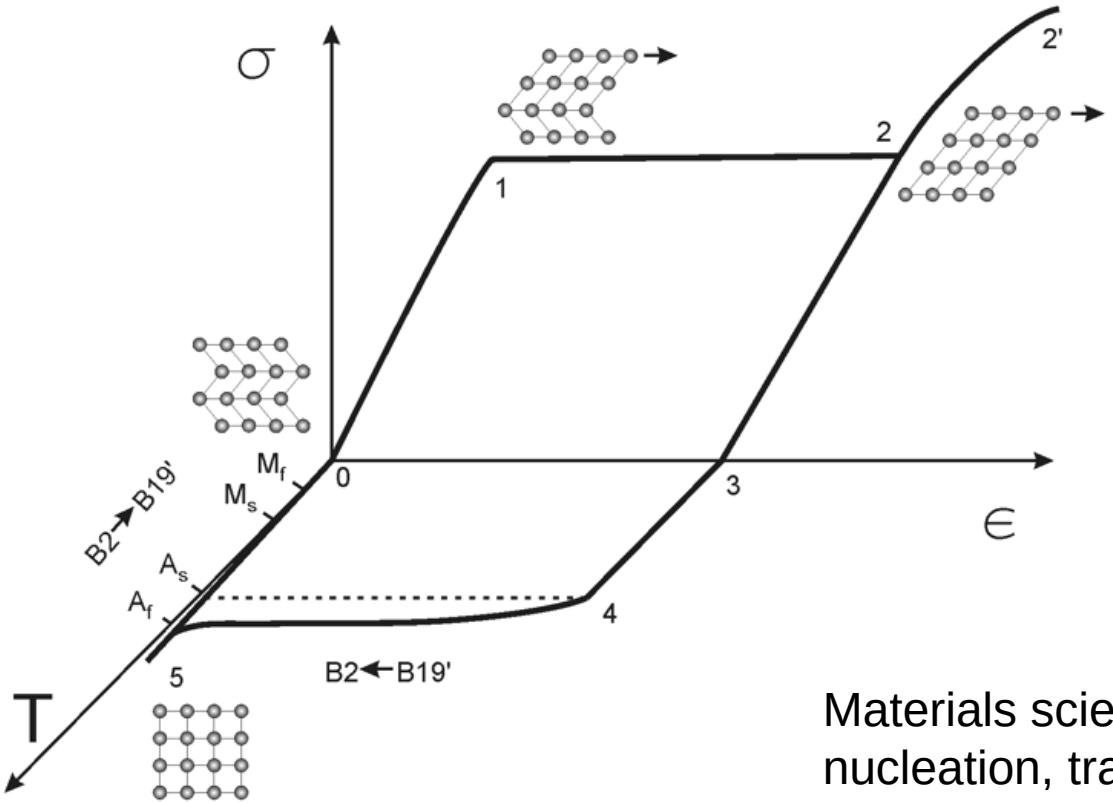
TiAl, mechanical twin

Skrotzki, Acta Mat, 2000, 851-862

Martensitic transformation in SMAs

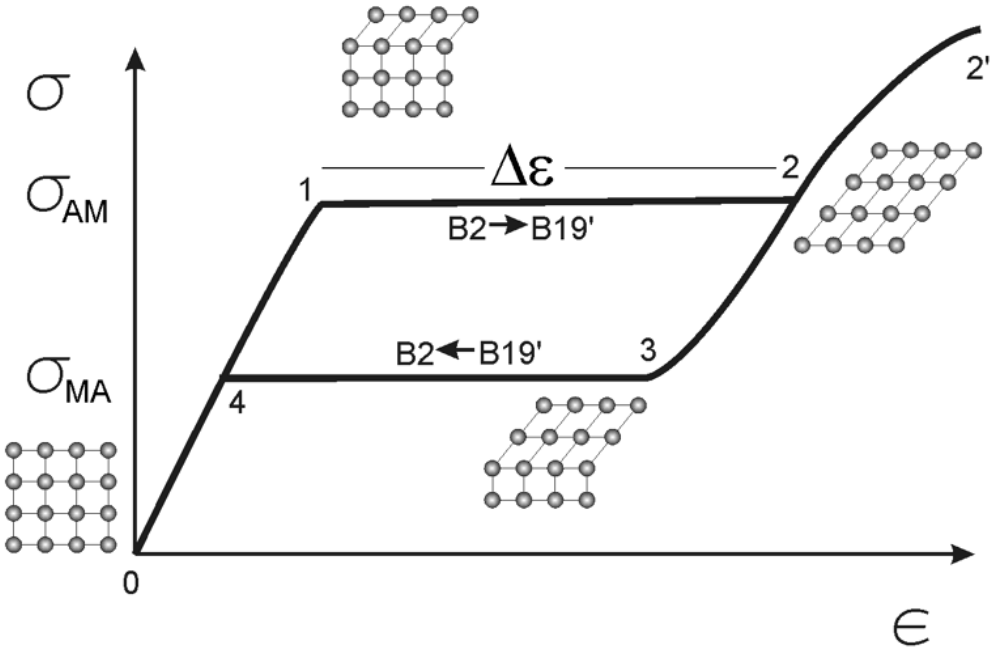


SM effects - again: EWE

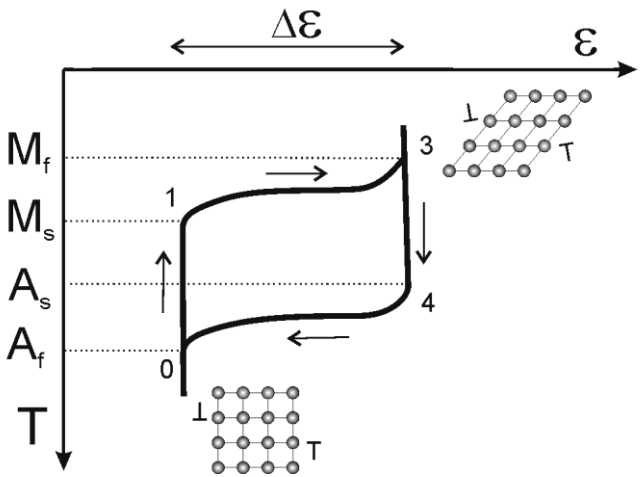


Materials science: twinning, detwinning, nucleation, transformation...

Pseudoelasticity

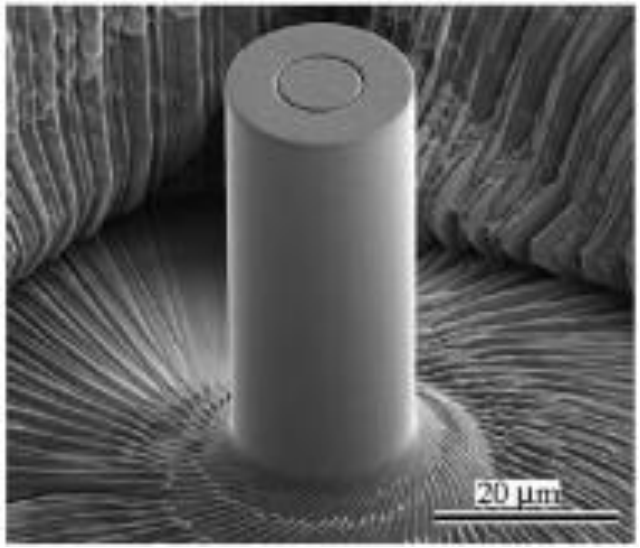


TWE

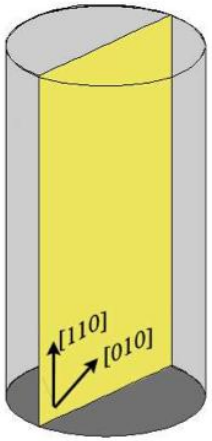


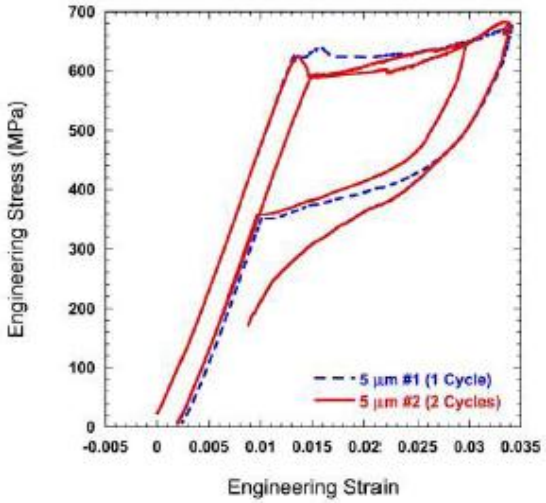
Training generates lattice defects

Microstructure: recent advances



D. Norfleet et al., Acta Mater. 57(2009), 3549



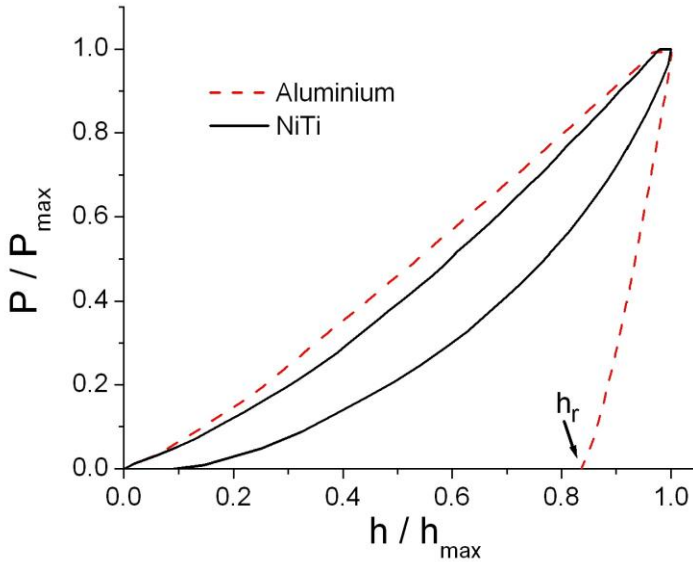


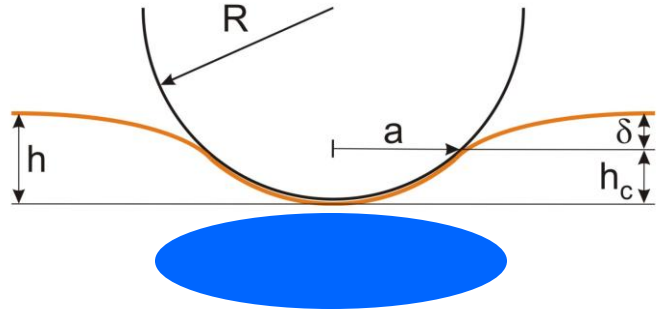
(a)

J. Olbricht et al., Int. J. Mater. Res. 99 (2008) 1150-1156.

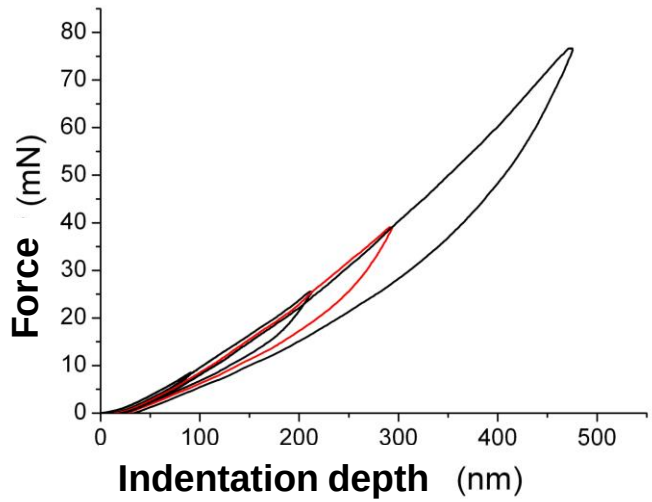
TEM in-situ straining

Nanoindentation of pseudoelastic NiTi

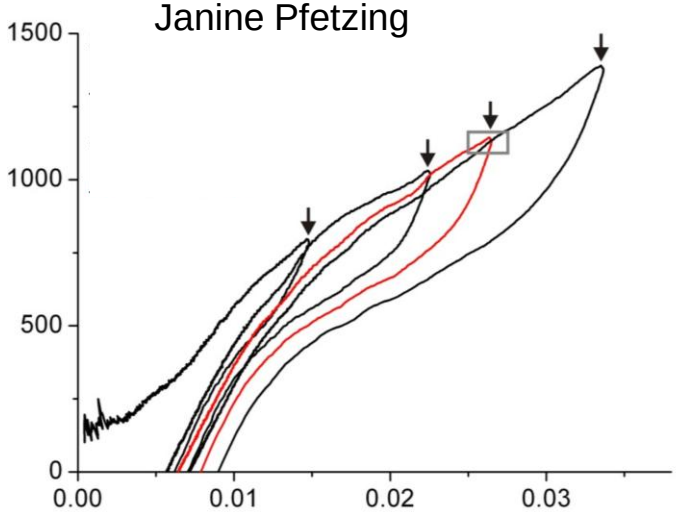




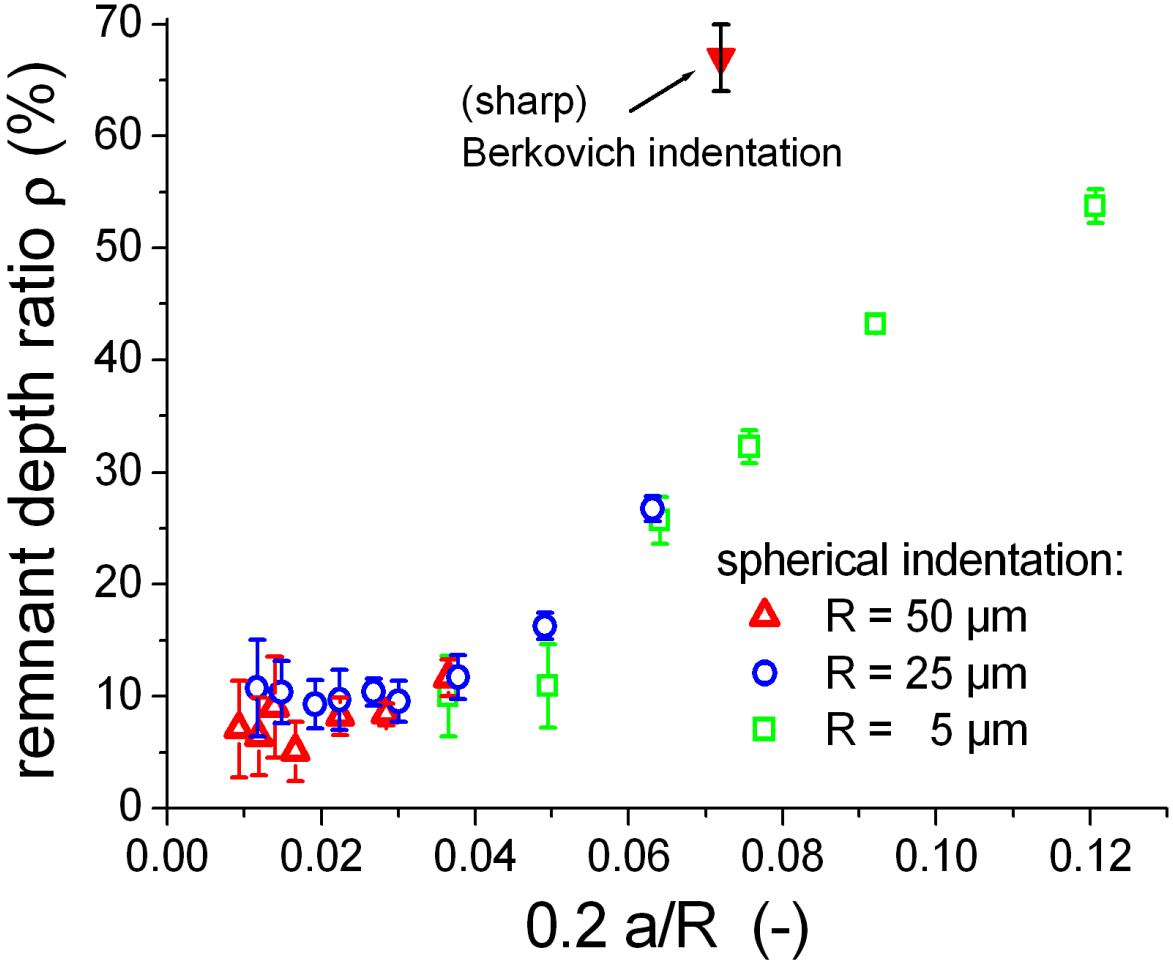
$$RDR = \frac{h_r}{h_{max}}$$



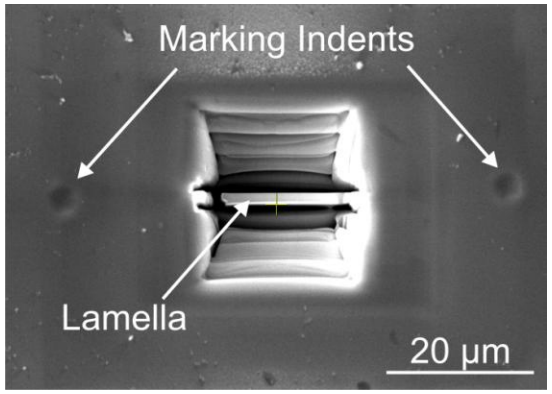
Janine Pfetzing



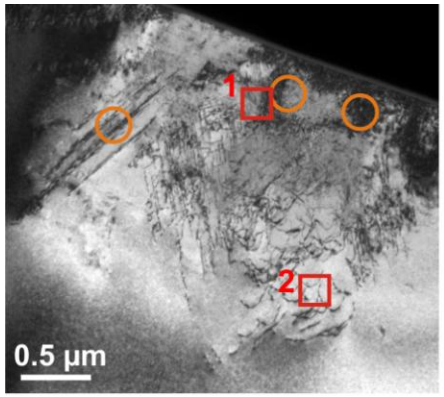
Nanoindentation and irreversible deformation

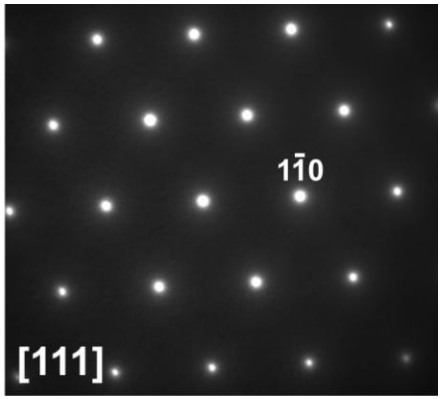


Nanoindentation and irreversible deformation



Pfetzing et al., ESOMAT 2009, submitted

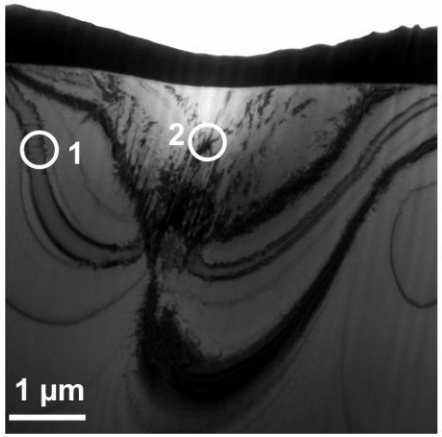


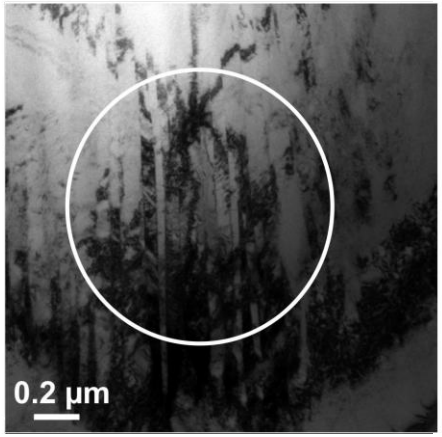


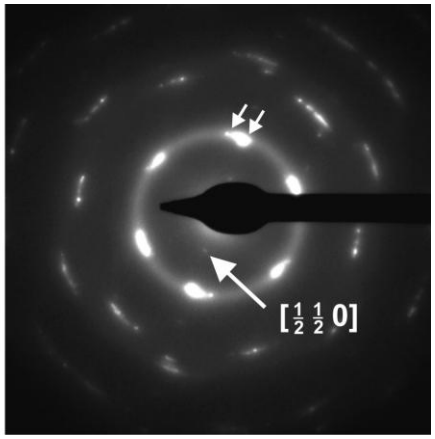
Small maximum loads (RDR ~10%)

$$RDR = \frac{h_r}{h_{max}}$$

Moderately large maximum loads (RDR ~30%)

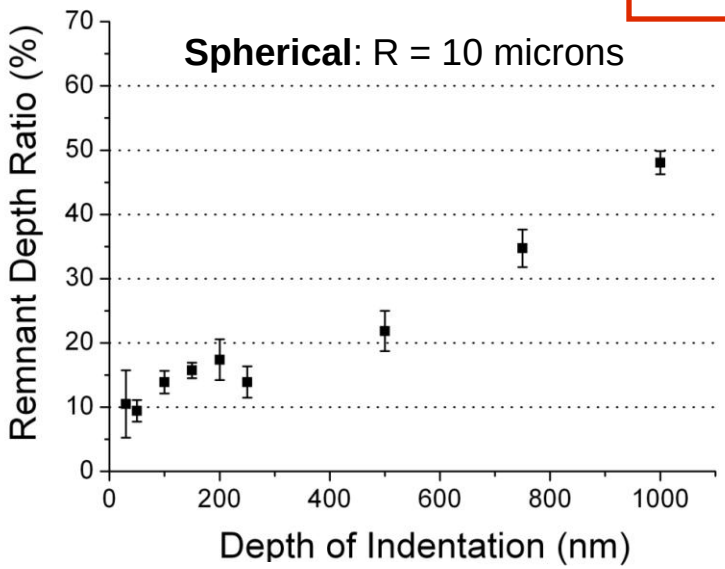


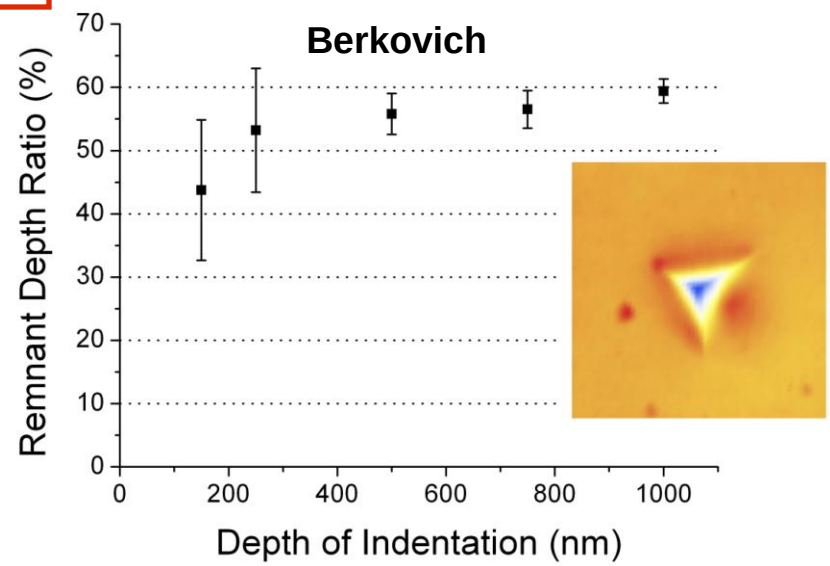




Nanoindentation and strain gradients

$$RDR = \frac{h_r}{h_{max}}$$





$$\varepsilon^{sph} = \frac{a}{5R}$$

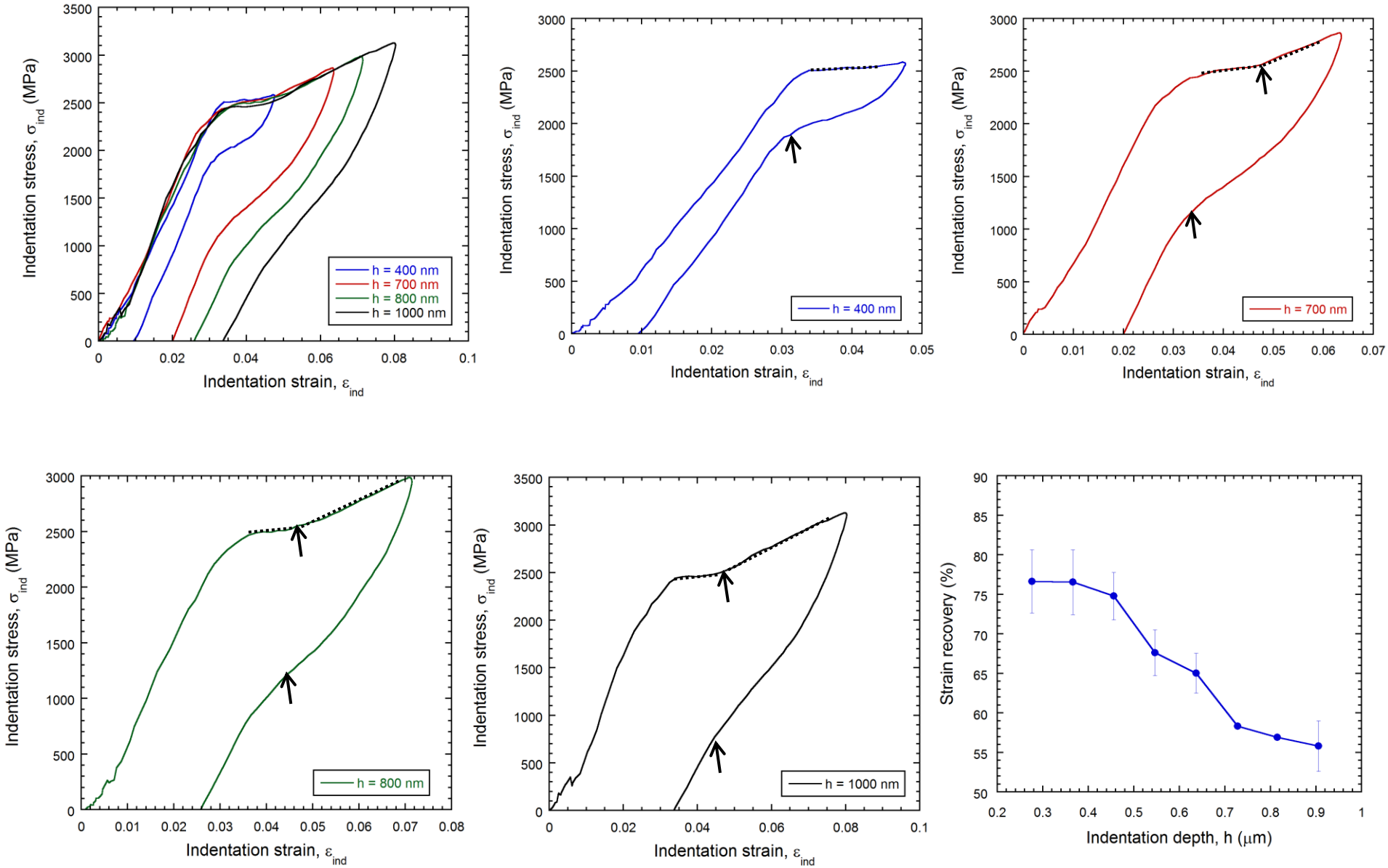
$$\rho_{GND}^{sph} = \frac{\bar{r}}{bR}$$

$$\varepsilon^{Berk} = 0.2\cot\alpha \approx 7.2\%$$

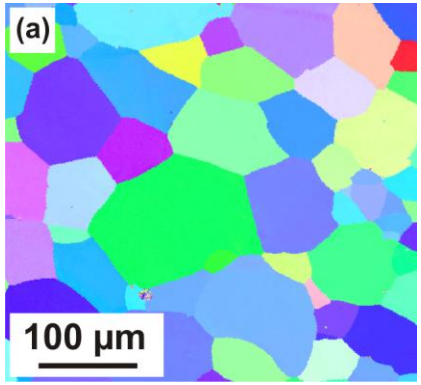
$$\rho_{GND}^{SS} = \frac{3h_c}{2ba^2} = \frac{3}{2bh_c}\tan^2\theta$$

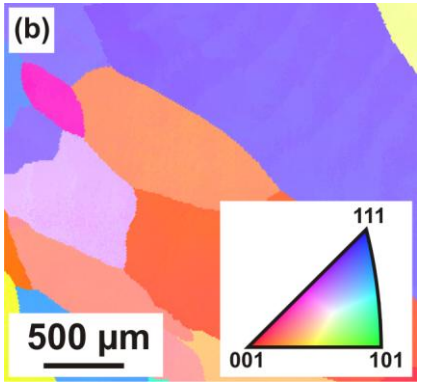
Plastic deformation occurs (almost) from the very beginning!
Even under optimized conditions: Strain gradients result in formation of GNDs.

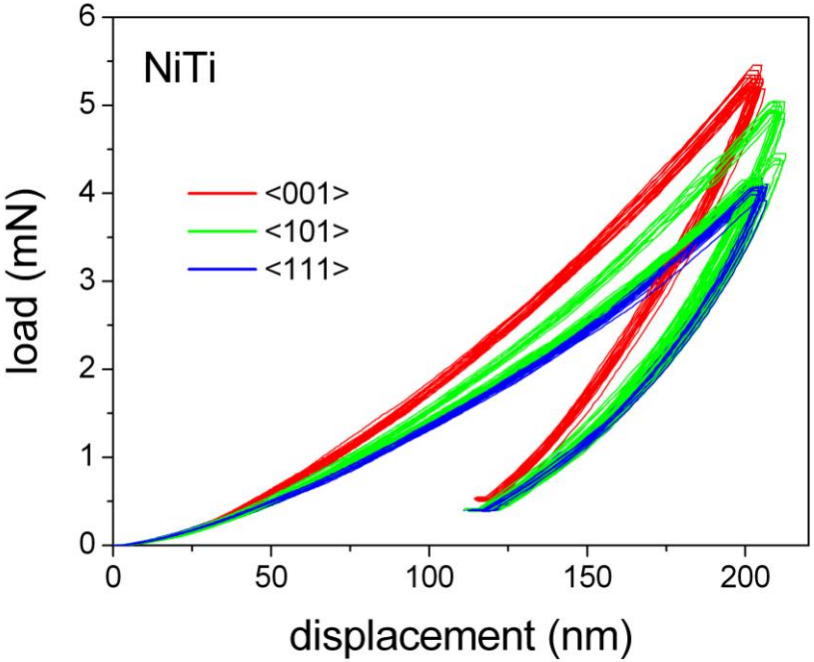
2nd regime „beyond the plateau“?

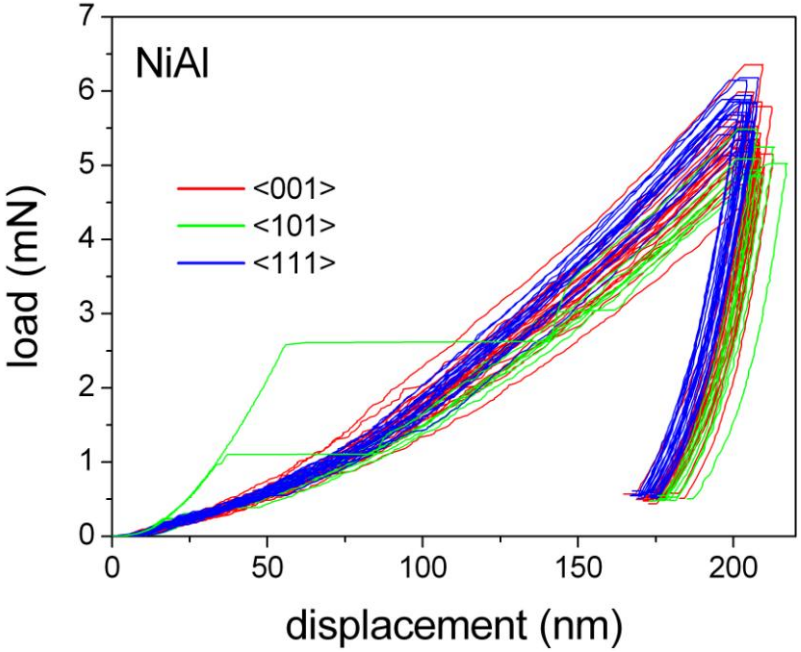


Orientation effects in NiTi / NiAl

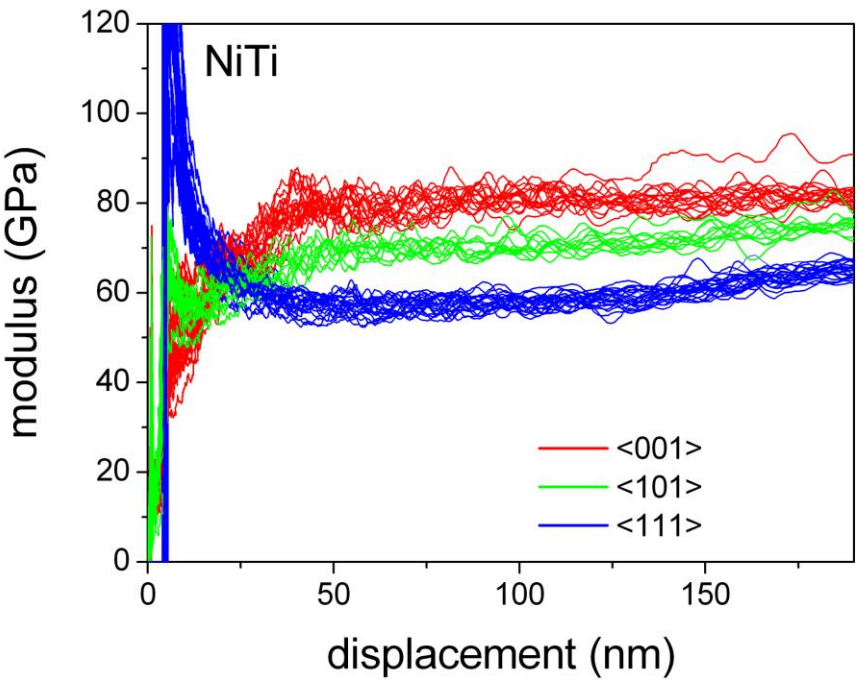


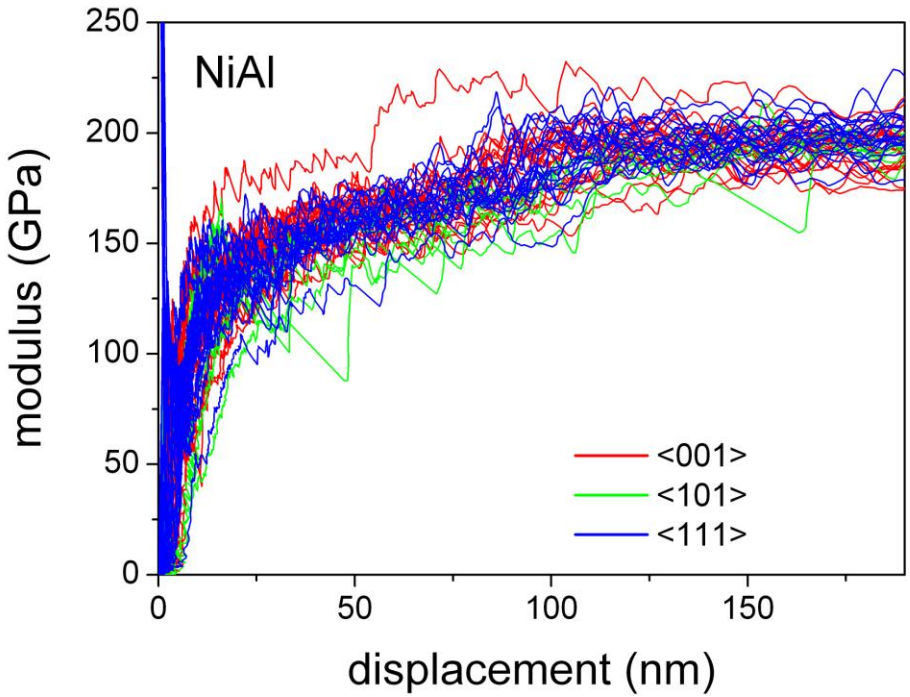




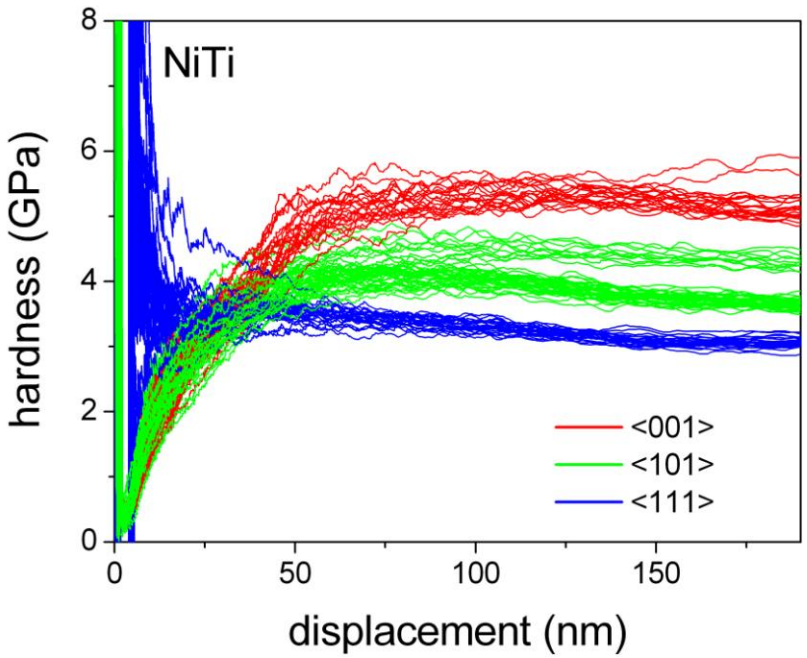


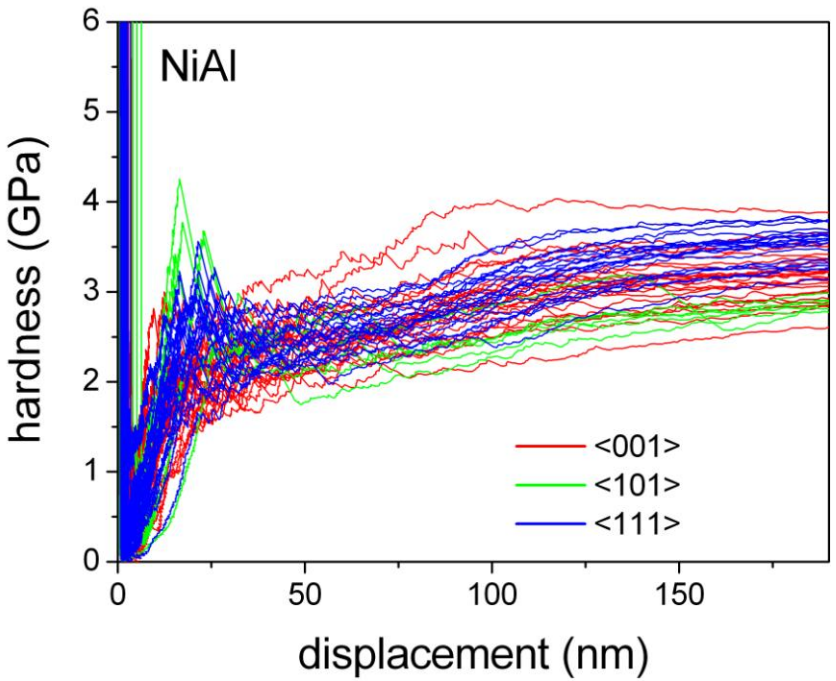
Continuous Stiffness Measurements
-
elastic moduli

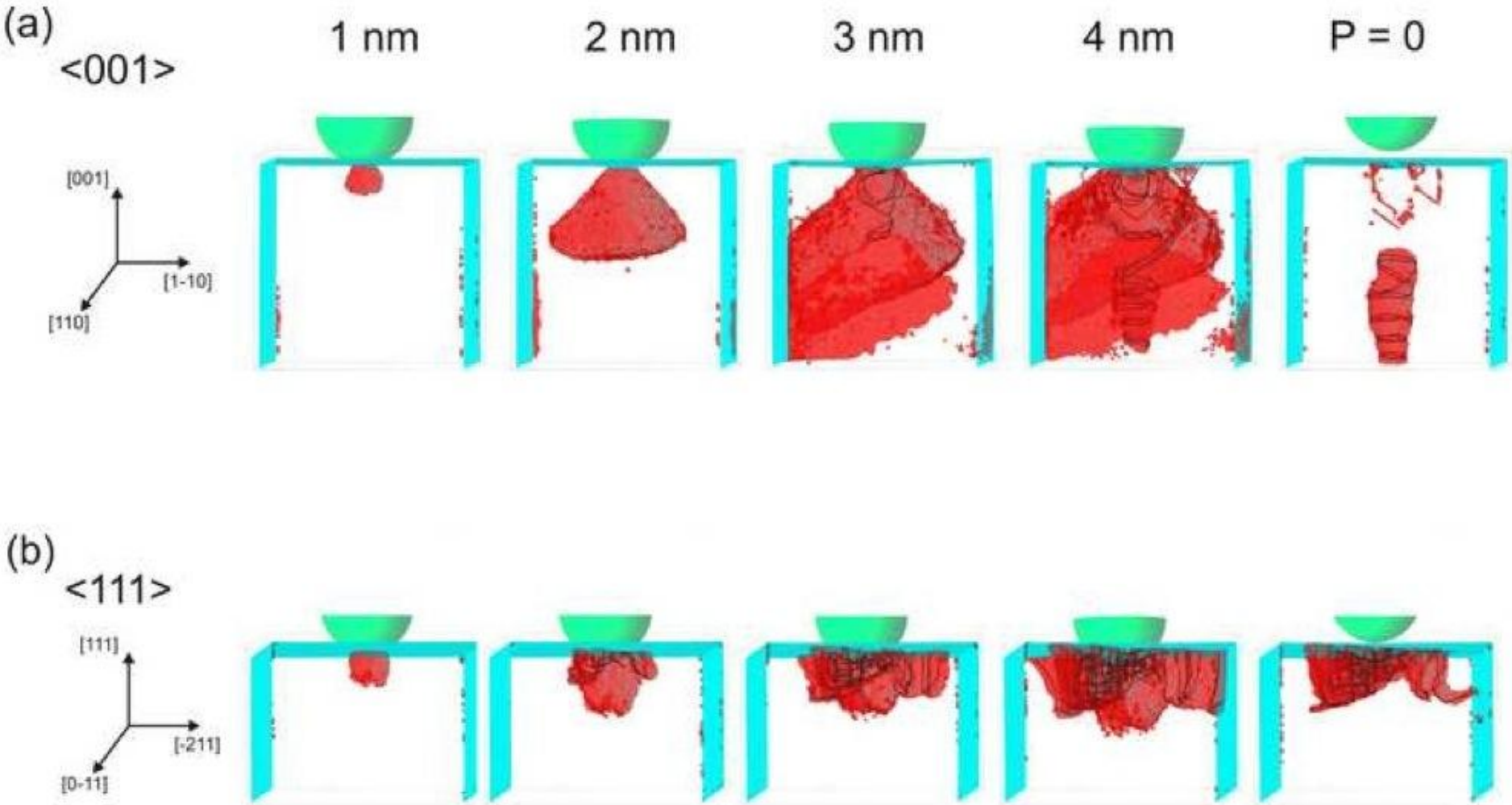




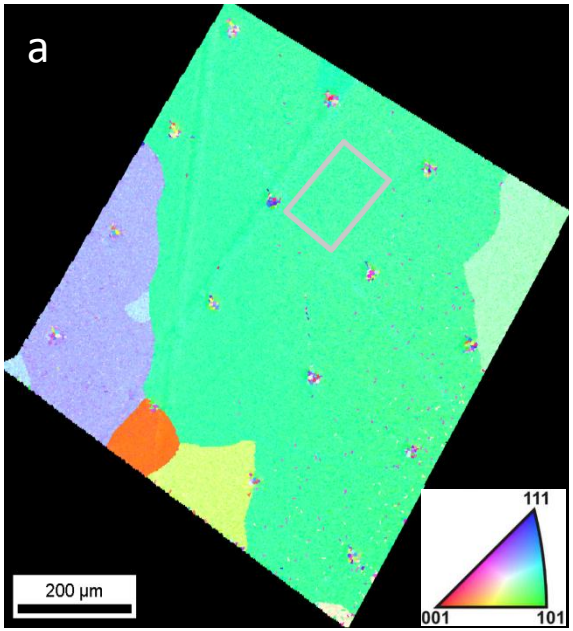
Continuous Stiffness Measurements
-
hardness

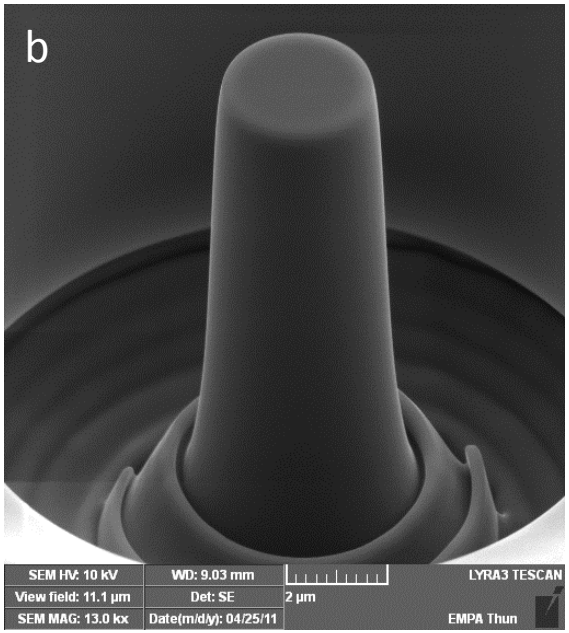





(a)
<001>
1 nm
2 nm
3 nm
4 nm
P = 0
[001]
[1-10]
[110]
(b)
<111>
[111]
[-211]
[0-11]

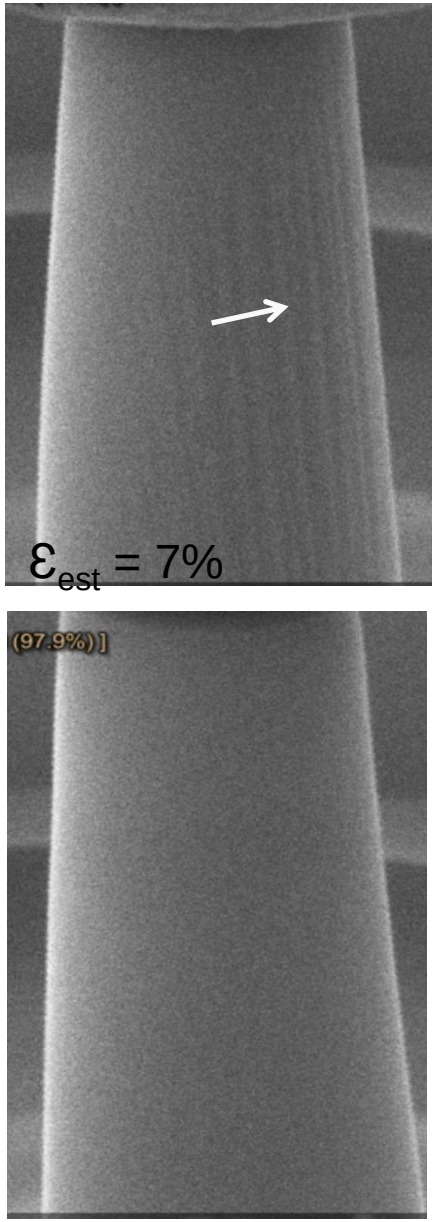
Micro-pillar Compression





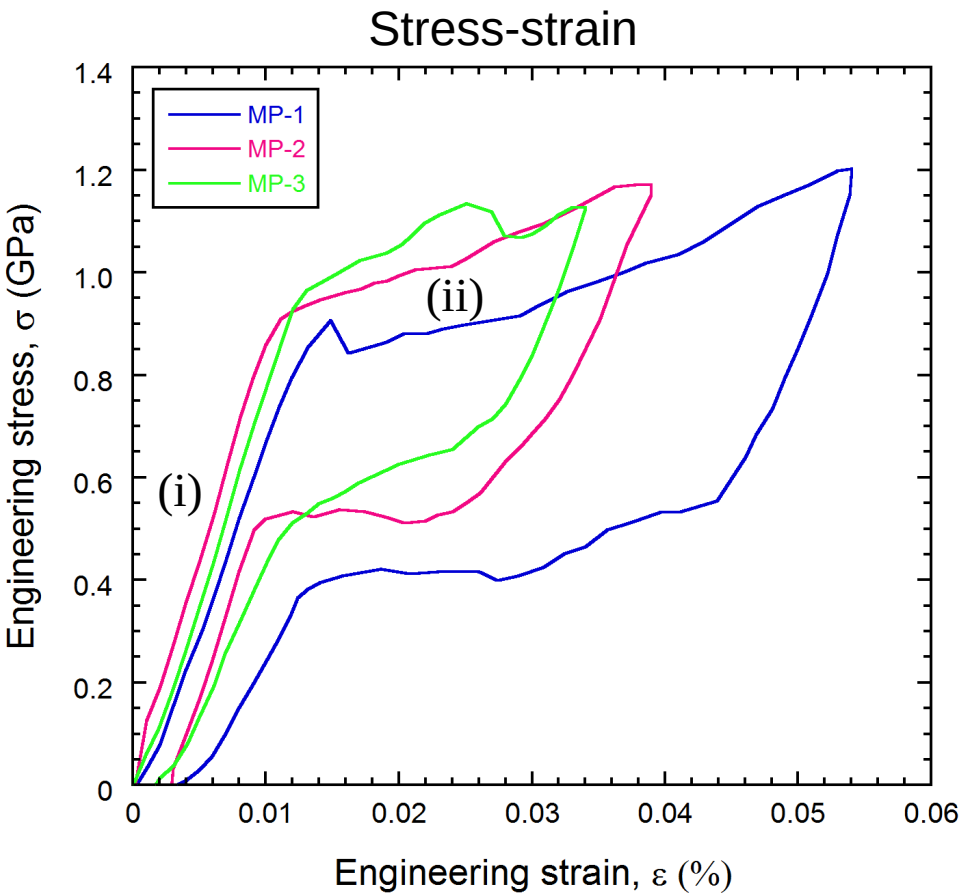
Pseudoelastic deformation

Micro-pillar compression-Pseudoelastic strain



unloading

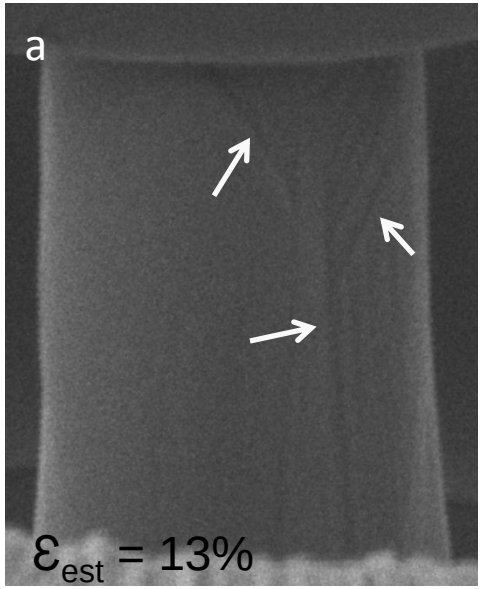
Buckling characterization

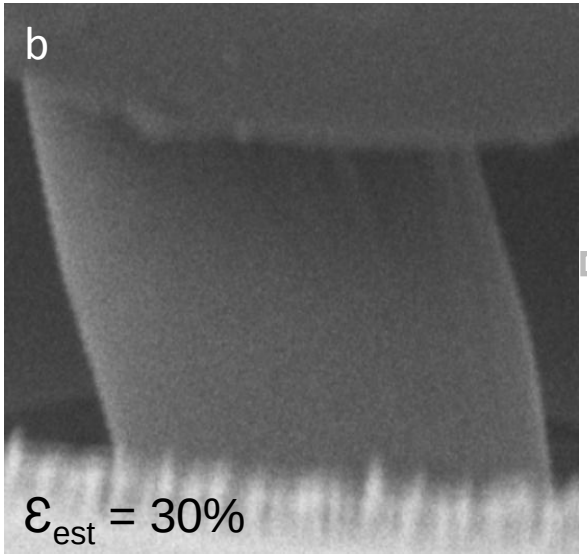


Permanent deformation

Micro-pillar compression-video

In-situ Compression





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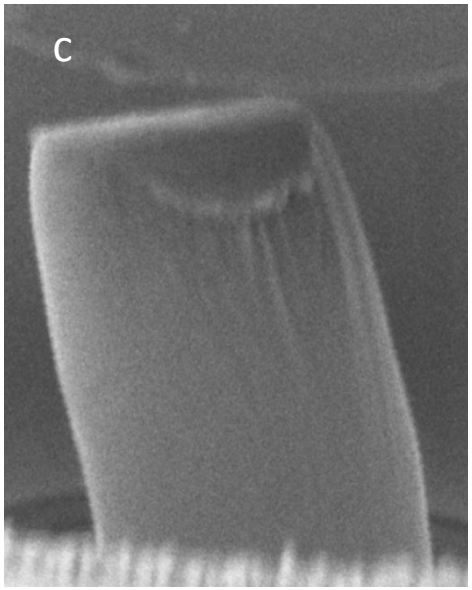
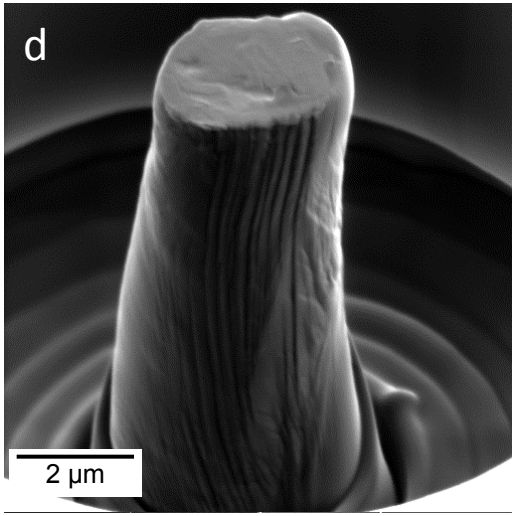
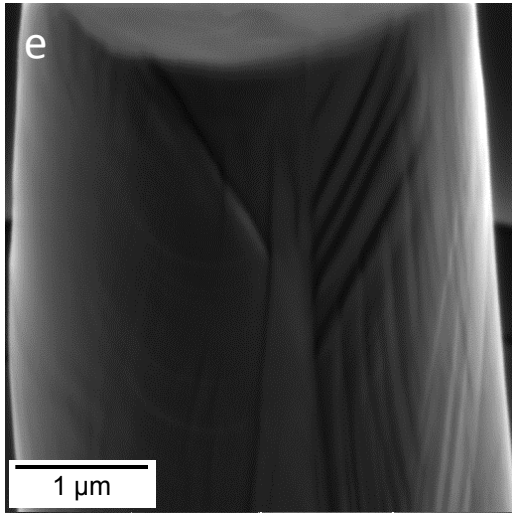


Post deformation SEM





Summary

- Research and teaching in Chemnitz
- Introduction to shape memory alloys
- Recent results on surface testing of NiTi:
    - Nanoindentation is related to irreversible deformation
    - Indenter tip geometry and testing conditions affect reversibility
    - Orientation effects are due to the martensitic transformation
    - Micro-pillar studies need in-situ observation.