ADVANCES IN WROUGHT MAGNESIUM ALLOYS FOR LIGHTWEIGHT APPLICATIONS

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AMAP Colloquium, 2. November 2017, Aachen

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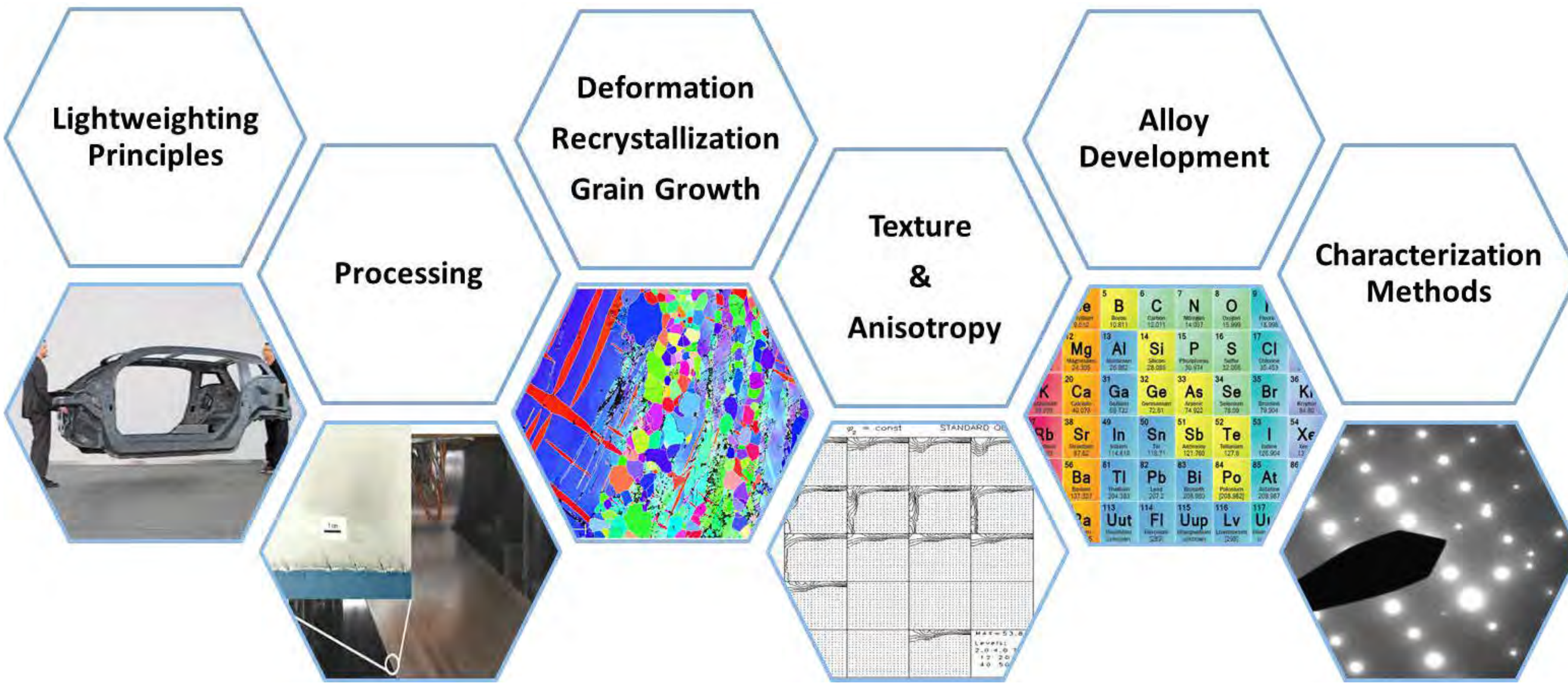
Lecture content

Today‘s Talk will discuss the Materials Science and Engineering of Mg and its alloys and their potential use in Lightweight Applications



The big tension between economy and ecology

The automobile…

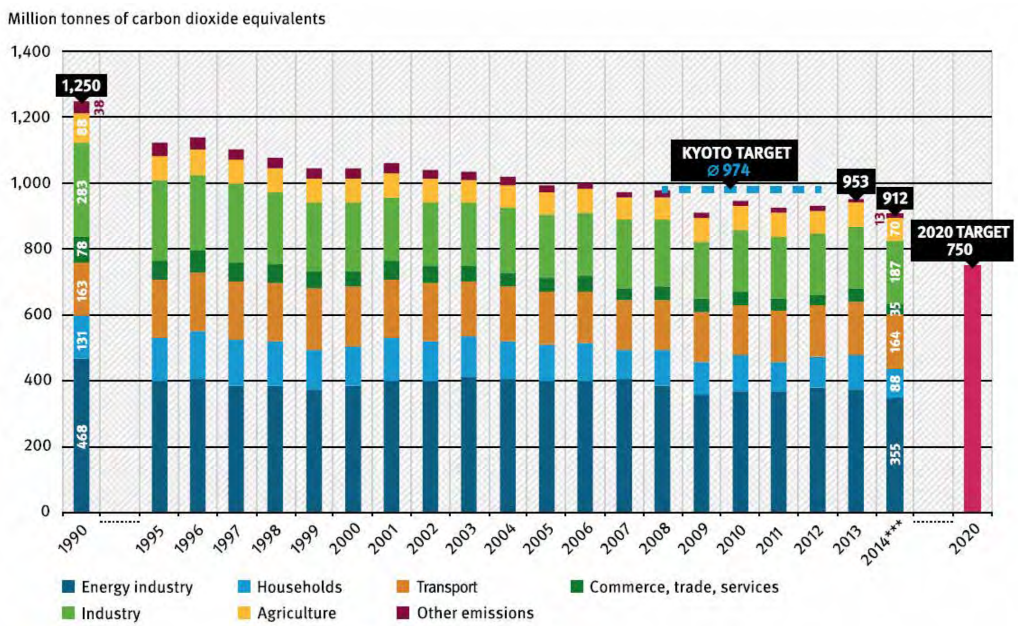
+ The automotive industry is the largest industry sector in Germany.

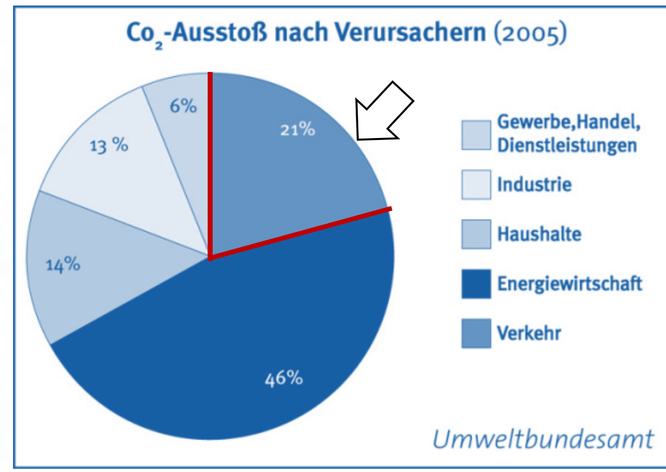
+ It is considered as means of mass transportation worldwide.

– **Huge contributor to environmental pollution, and thus widely criticized**

Environmental pollution in numbers

Graph showing the amount of yearly emission of greenhouse gases in Germany





Source: Umweltbundesamt

Current situation in the EU: CO_2 – average emission is 130 gCO_2/km per vehicle

Target values for reduced CO_2 fuel emission till 2020

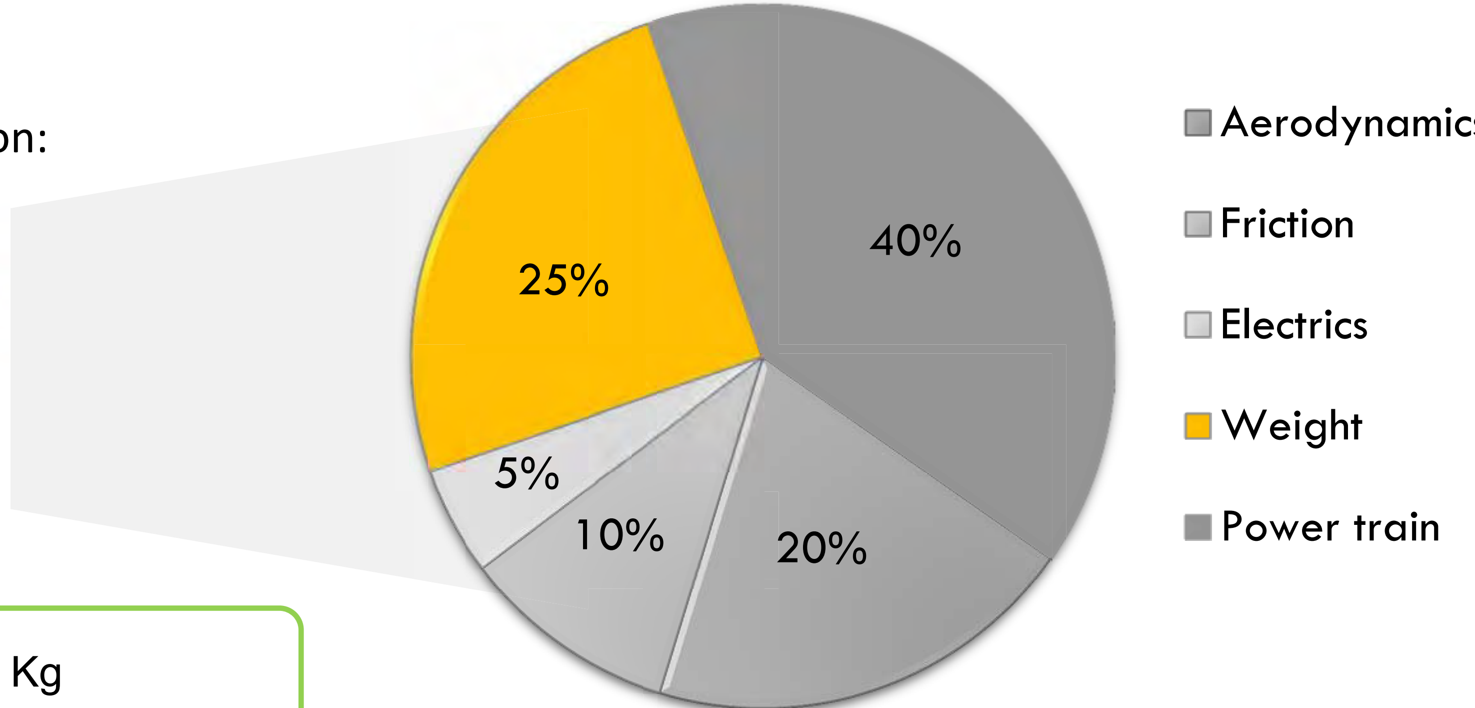

95 g/km


113 g/km


117 g/km

Factors affecting fuel economy

100% fuel consumption:



Gewicht
- 100 Kg

Verbrauch
- 0,35 l/100 km

CO_2-Ausstoß
- 8,5 gCO_2/100 km

25% of the total consumption depends on vehicle weight

Source: SUPERLIGHT-CAR (SLC) EU-project

Development trends in automobiles: 40 yrs VW Golf

VW Golf I, 1974

VW Golf VII, 2014

The obvious solution of manufacturing lighter cars has become almost impossible because of the strong customer demand for bigger, faster, luxurious cars!

Current challenges for automakers

New cars should…

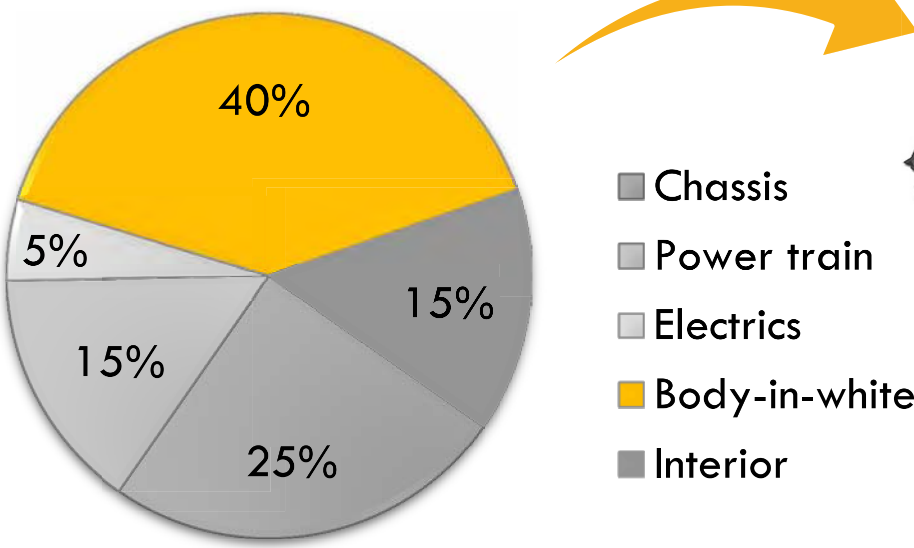
- have more comfort and HP but consume less energy
- have better technology and safety but weigh less
- be more attractive than previous models but not cost more

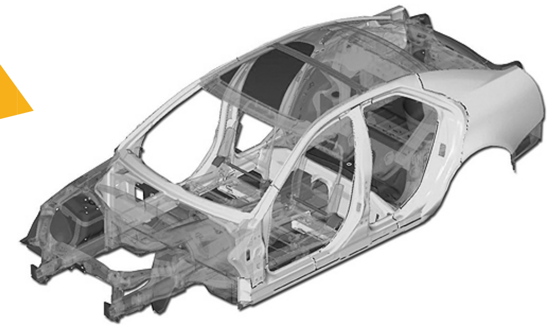
Materials scientist / engineer

We need innovative and cost attractive lightweight design concepts!

Lightweight body-in-white: Which expertise needed?

Vehicle weight distribution





Required expertise

Manufacturing
- Production of cast, sheet and extruded parts
- Forming and joining techniques

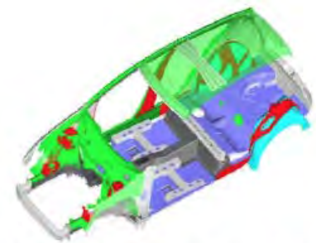
Materials
- AHSS
- Light metals (Al, Mg)
- Thermoplastics (CFRP)
- Hybrid material design

Important factors for reducing body weight
- Design (geometry, wall thickness,…)
- Car concept (power train, aerodynamic,…)
- Safety (crash behavior, passenger and pedestrian protection)
- Work environment (temperatur, climate,…)

Lightweight potential of current structural materials

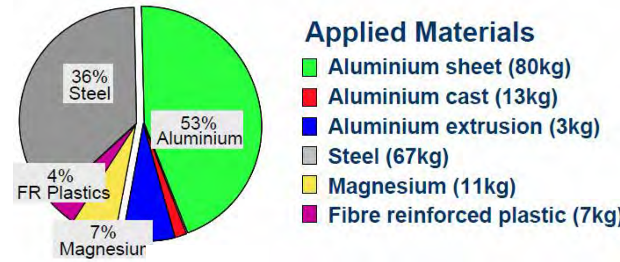
Steel intensive

Weight reduction:	40 kg (14 %)*
Additional part costs:	< 2,5 €/kg



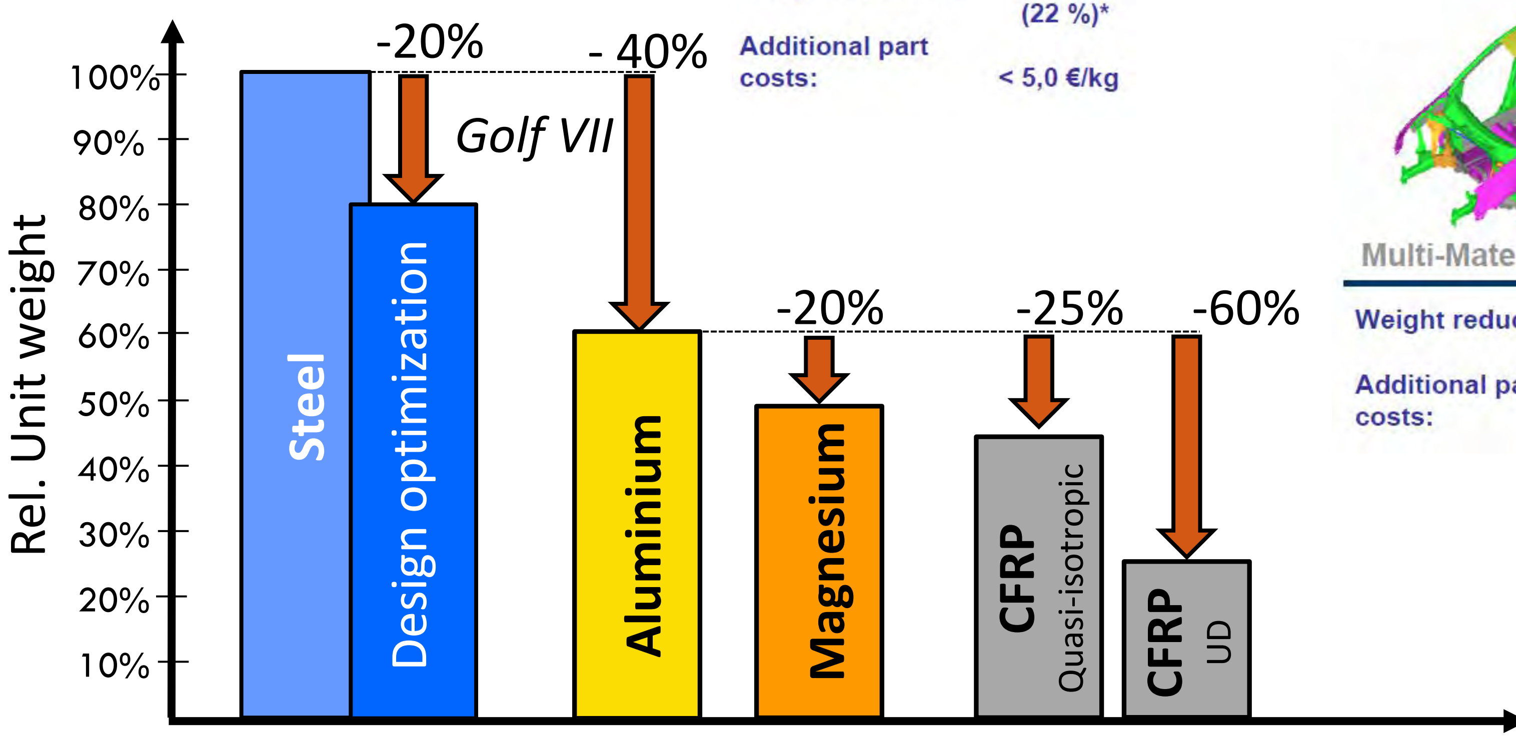
Multi-Material, economic

Weight reduction:	62 kg (22 %)*
Additional part costs:	< 5,0 €/kg



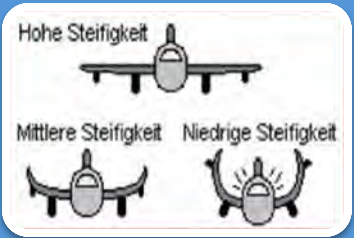
Multi-Material, advanced

Weight reduction:	114 kg (41 %)
Additional part costs:	< 10,0 €/kg



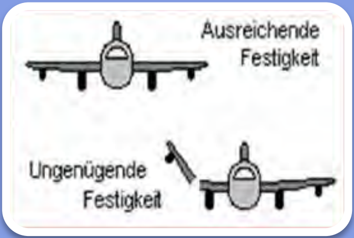
Source: SUPERLIGHT-CAR (SLC)

Essential requirements for lightweight materials



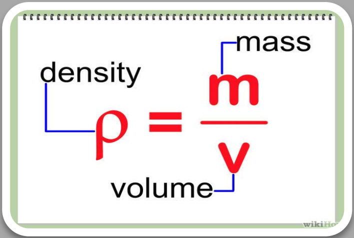
High stiffness

- Resistance of a body to elastic (non-permanent) deformation by an applied force
- Representative parameter: Young's modulus, Shear modulus

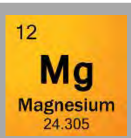


Sufficient strength

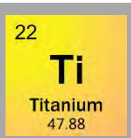
- Ability to withstand an applied force without plastic deformation (yielding) or failure
- Representative parameters: Yield strength, ultimate strength



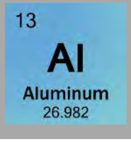
Low density



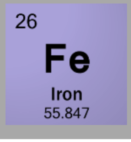
1.74 g/cm^3



4.51 g/cm^3



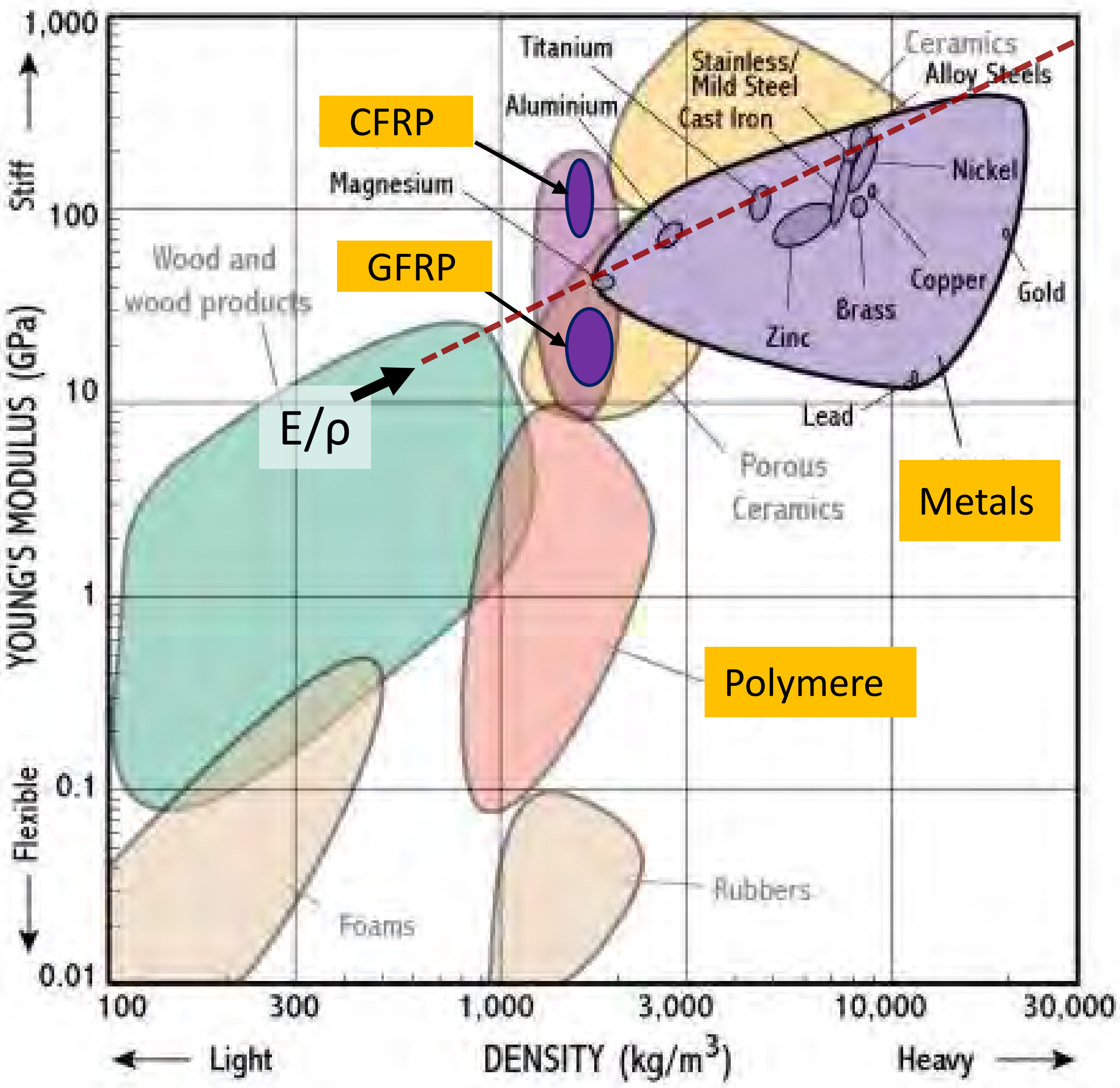
2.7 g/cm^3



7.87 g/cm^3

Bilder in Anlehnung an R&G Handbuch Faserverbundwerkstoffe

Stiffness-guided lightweight design



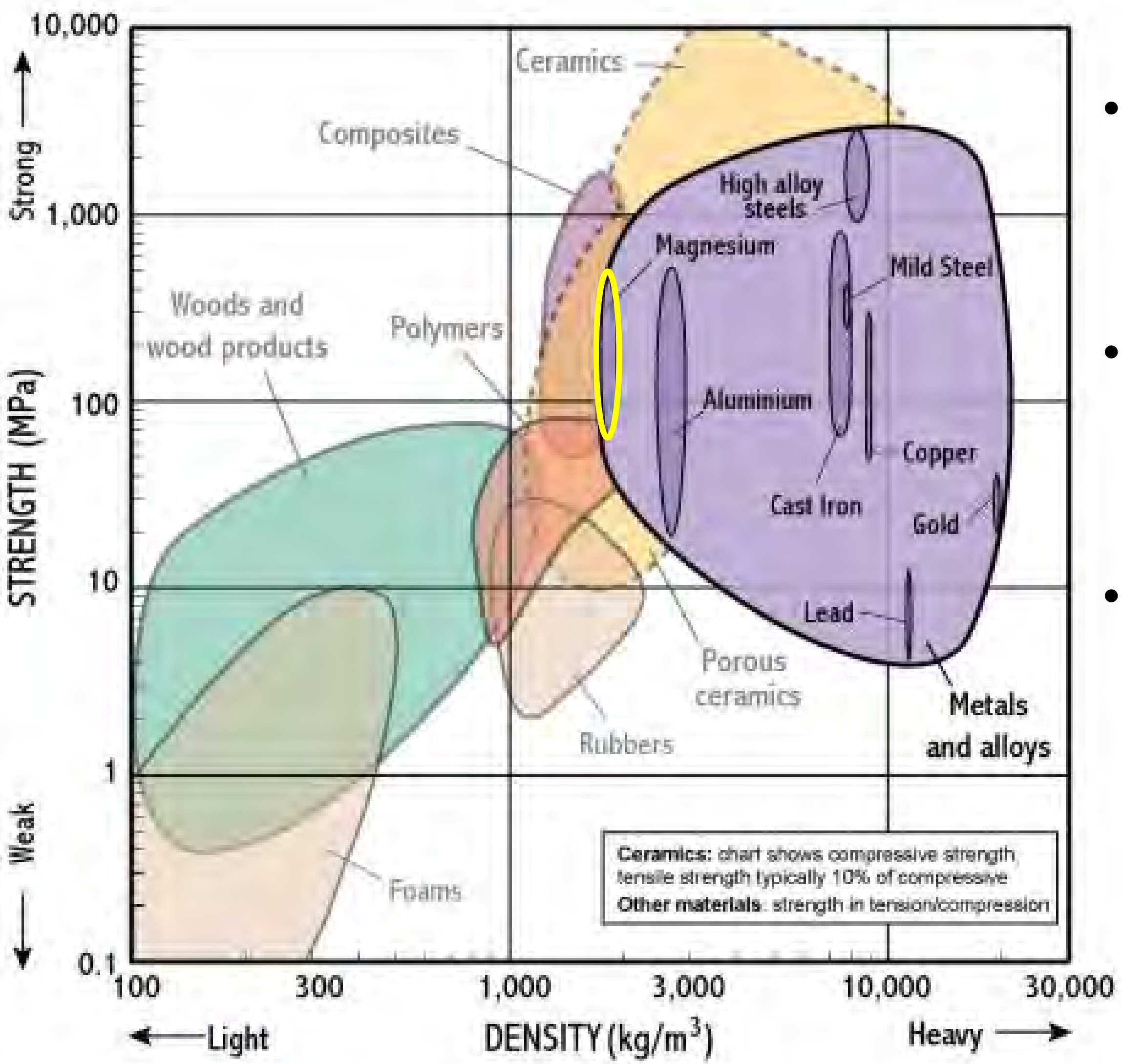
Material selection charts (Ashby plots)

Leg.	$\frac{E}{\rho}$	$\frac{\sqrt{E}}{\rho}$	$\frac{\sqrt[3]{E}}{\rho}$
Steel	25	1,8	0,8
Al	26	3,0	1,5
Ti	25	2,4	1,1
Mg	26	3,9	2,0
CFRP	85	7,3	3,2

Among structural metals Mg has the biggest potential for a stifness-guided lightweight design.

http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/default.html

Strength-guided lightweight design



- With respect to specific strength Mg alloys are also highly competitive
- Broad strength spectrum (σy ≈ 70 und 500 MPa) due to alloying
- Great enhancement potential by means of microstructure design

http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/default.html

Historical use of Mg in aerospace

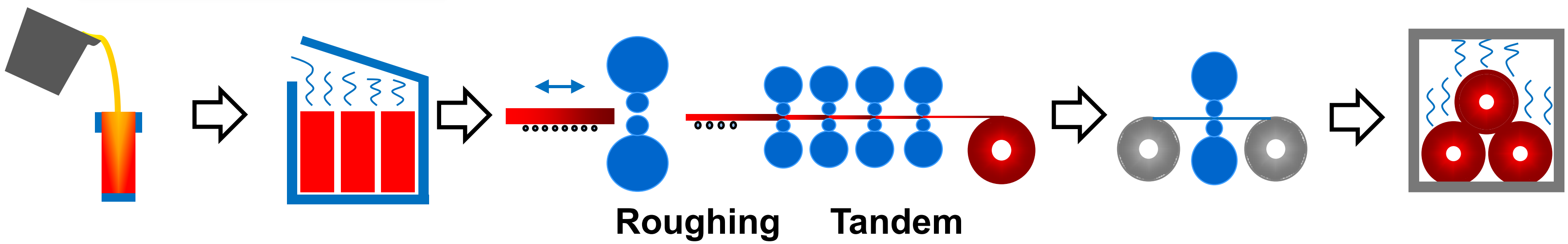
Mg alloys were frequently used in the WWII era in experimental aircrafts because aluminum was in short supply. The foto shows an example of a fighter-interceptor aircraft (XP-56) with 100% Mg-alloy airframe and skin

"The XP-56 "Black Bullet" was conceived at a time where almost any concept could find official backing.
This environment led to some interesting designs and one of the strangest was Northrop's XP-56 Black Bullet"

Source: U.S.A.A.F. Resource Center (http://www.warbirdsresourcegroup.org)

Process chain for Mg sheet production

Conventional route



Casting (720 - 760°C)

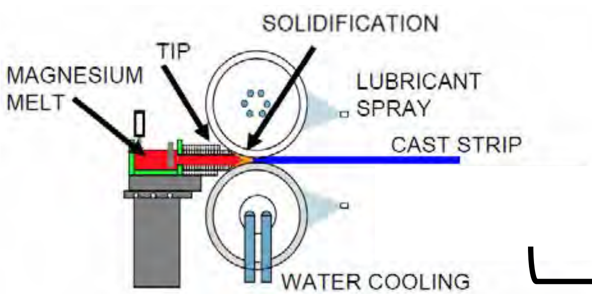
Homogenization (450 - 520°C/ 12 – 24 h)

Hot rolling (400 – 450°C)

Cold rolling

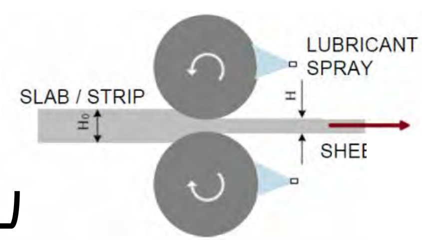
RX-annealing (400°C / 1h)

Today‘s better alternative: Twin roll casting (TRC)



TRC
(Solidification + Hot rolling)

No need for hot rolling



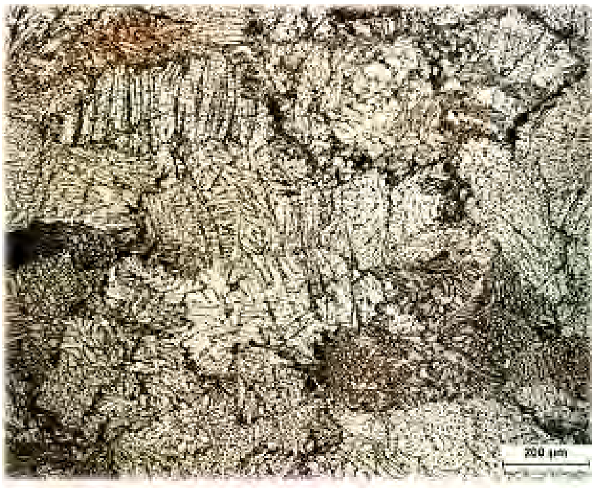
Cold rolling

TRC facility at HZG (sheet width 650 mm)

Economic solution for saving resources and reducing costs for mass production

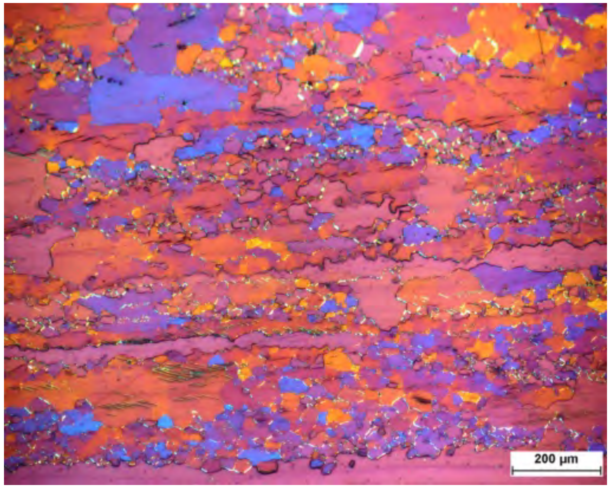
Microstructural changes during sheet production

- As-cast (α-Mg + β-Mg12Al17)



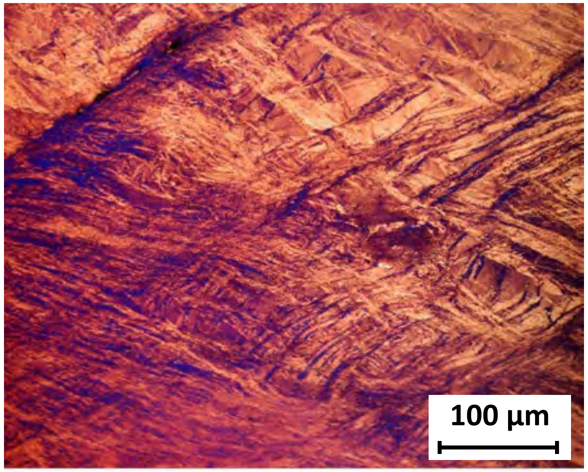
$T, \varepsilon, \dot{\varepsilon}$

- Hot rolled (partial RX)



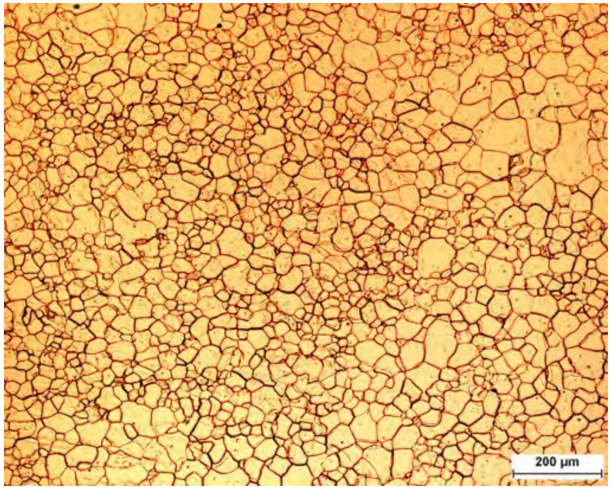
$\varepsilon, \dot{\varepsilon}$

- Cold rolled (shear bands)

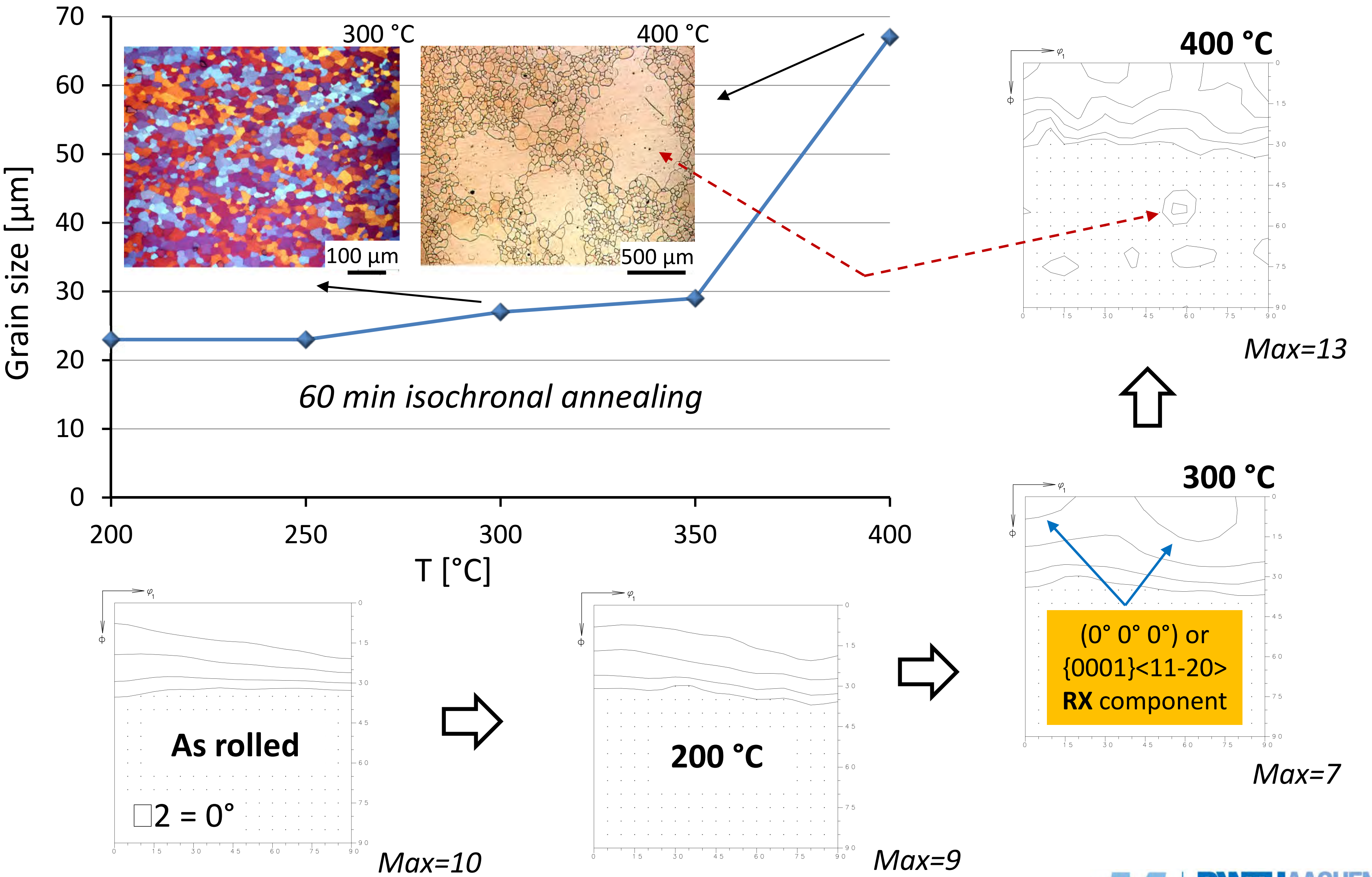


T, t

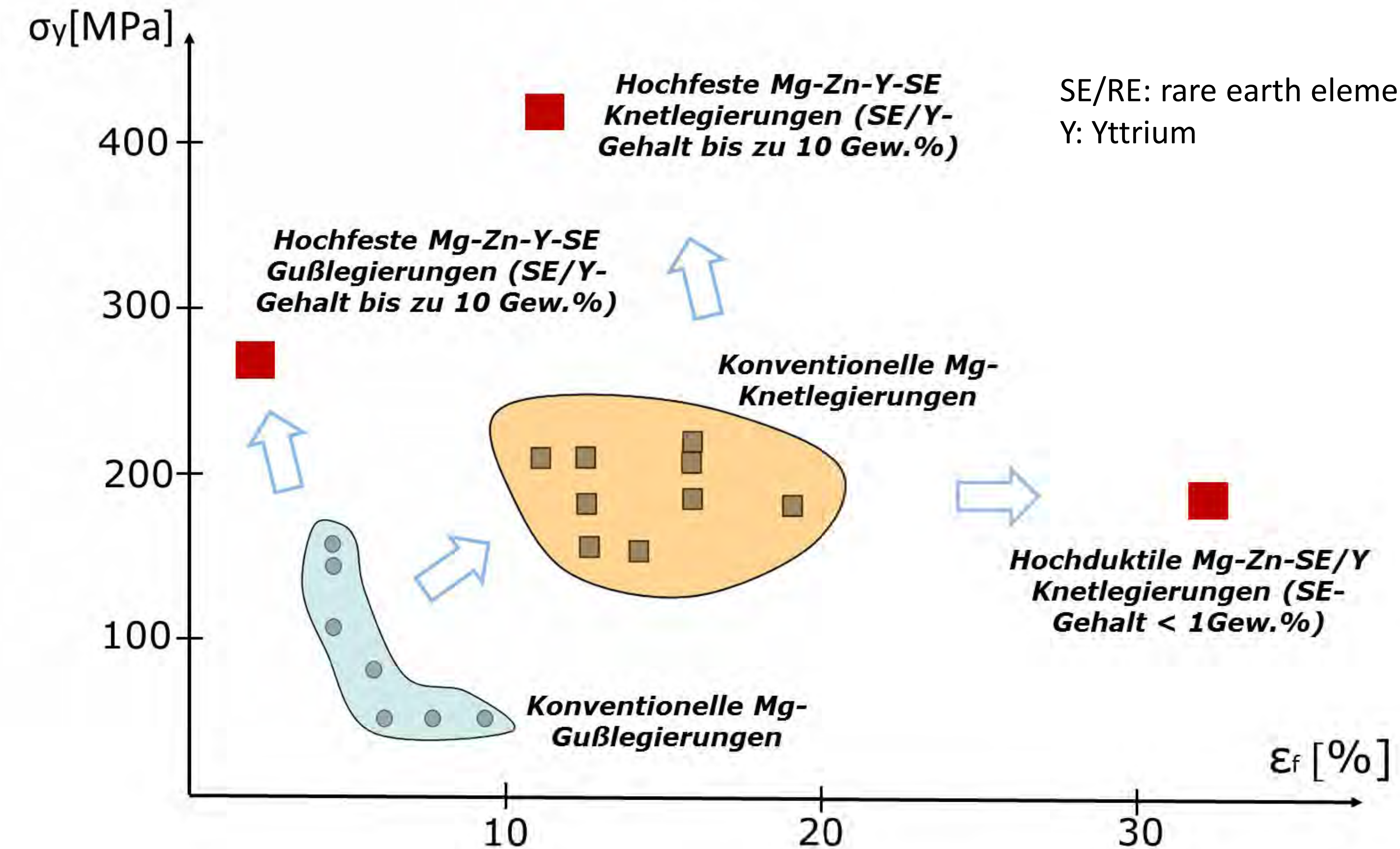
- As-annealed (fully RX)



Retention of the deformation texture during annealing



Cast vs. wrought alloys



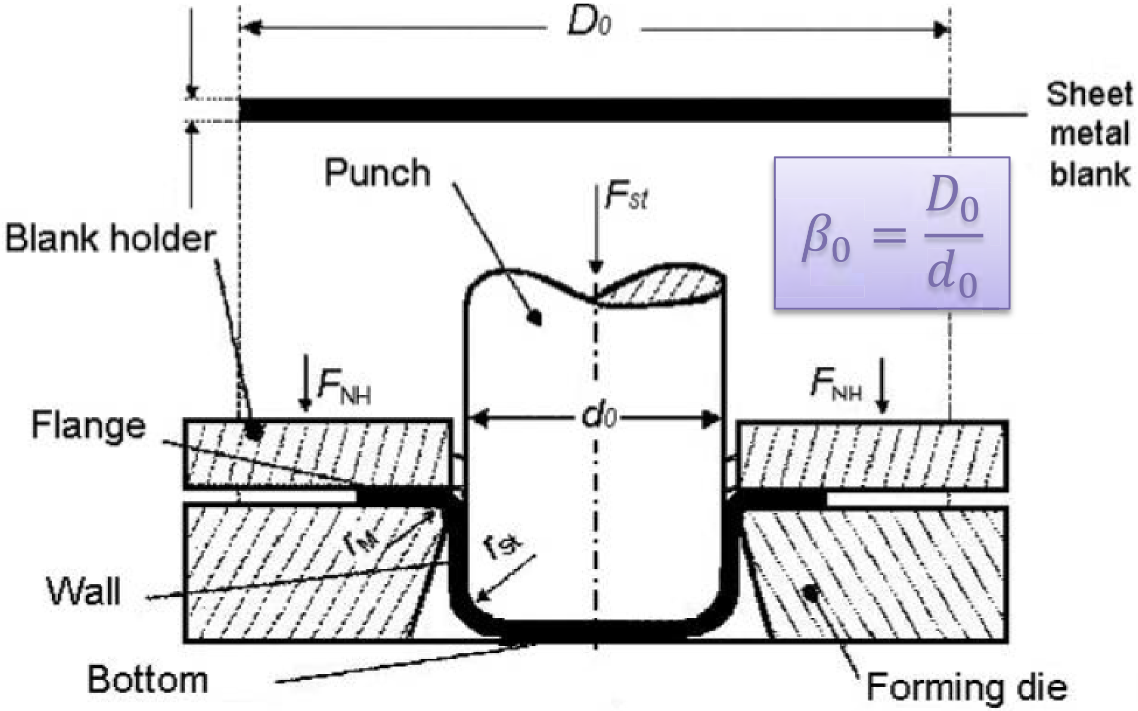
SE/RE: rare earth elements

Y: Yttrium

In Anlehnung an: F.W. Bach et al. Materialwissenschaft & Werkstofftechnik 35 (2004)

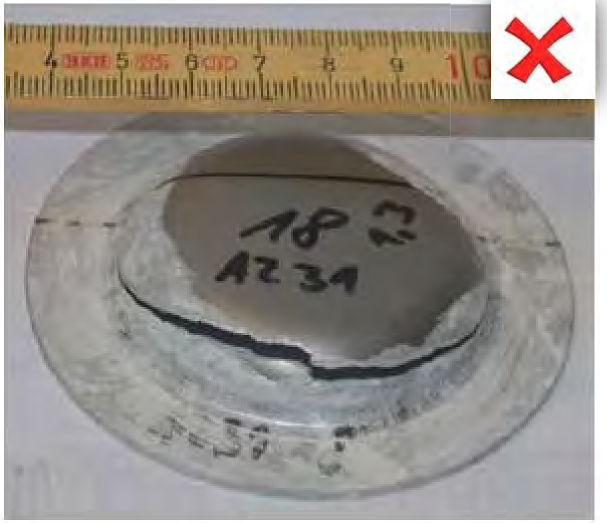
Formability of conventional Mg sheet

Deep drawing



$$\beta_0 = \frac{D_0}{d_0}$$

AZ31 (150°C)



AZ31, (200°C)

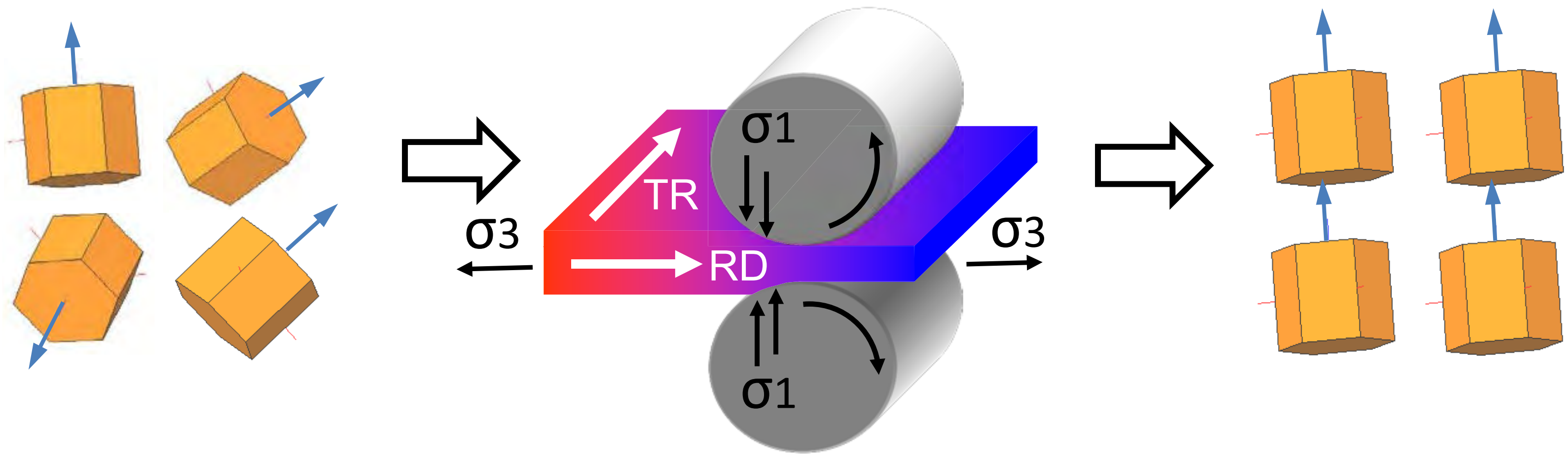
Mg sheet has limited formability below 200°C

Source: S. Yi et al. Acta Materialia 58, 2010

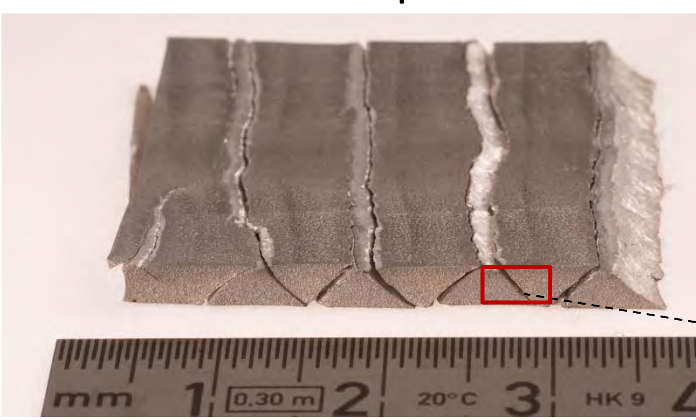
Texture formation during rolling of Mg

Initial texture (random)

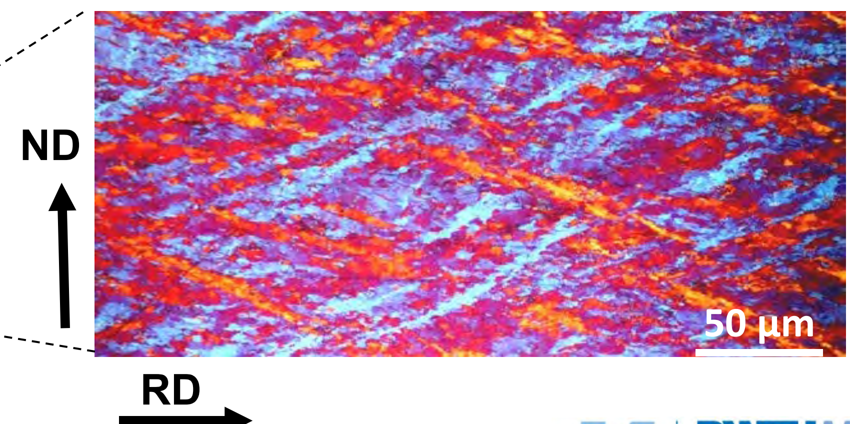
Deformation texture (well-defined)



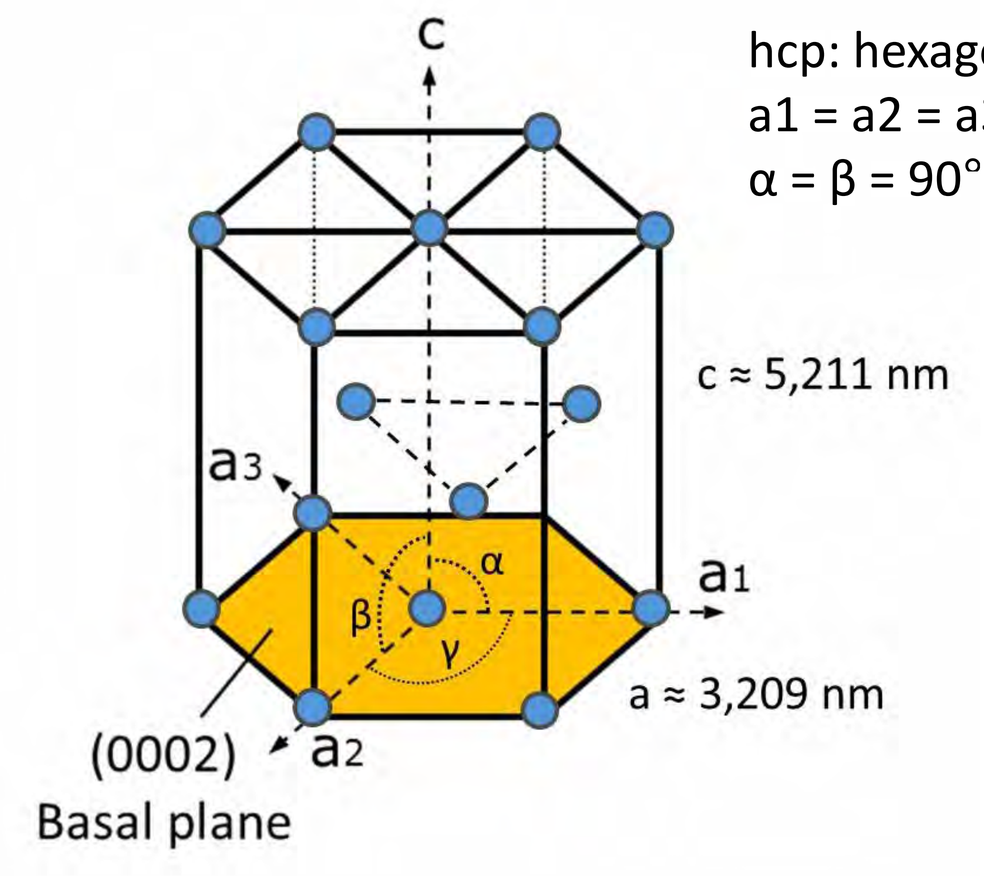
Typical shear-type failure at ambient temperature



Severe shear banding (strain localization)



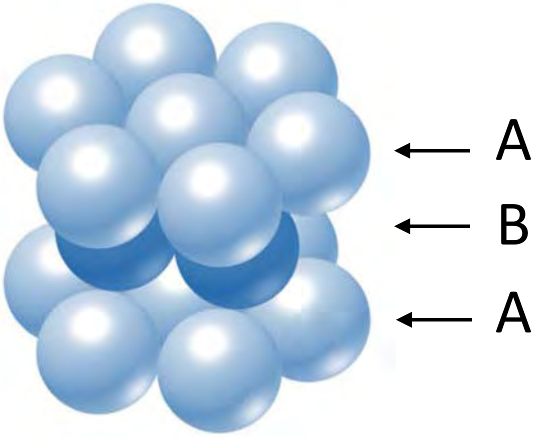
HCP crystal structure



hcp: hexagonal close-packed structure

a1 = a2 = a3 ≠ c

α = β = 90°, γ = 120°



$$\left(\frac{c}{a}\right)_{th} = \sqrt{\frac{8}{3}} = 1{,}633$$

c/a-ratio of different hexagonal metals

Metall	Cd	Zn	Mg	Zr	Ti
c/a	1,886	1,856	**1,623**	1,593	1,587

c/a ratio ⇄ hexagonal rolling textures

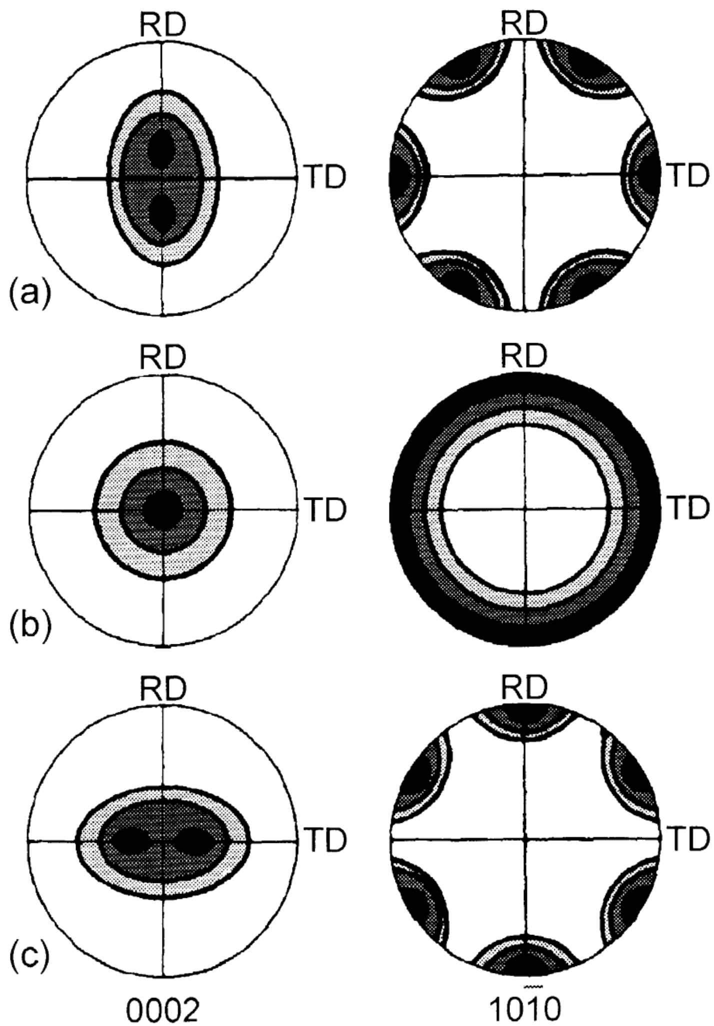
Schematic [Tenckhof 1988]

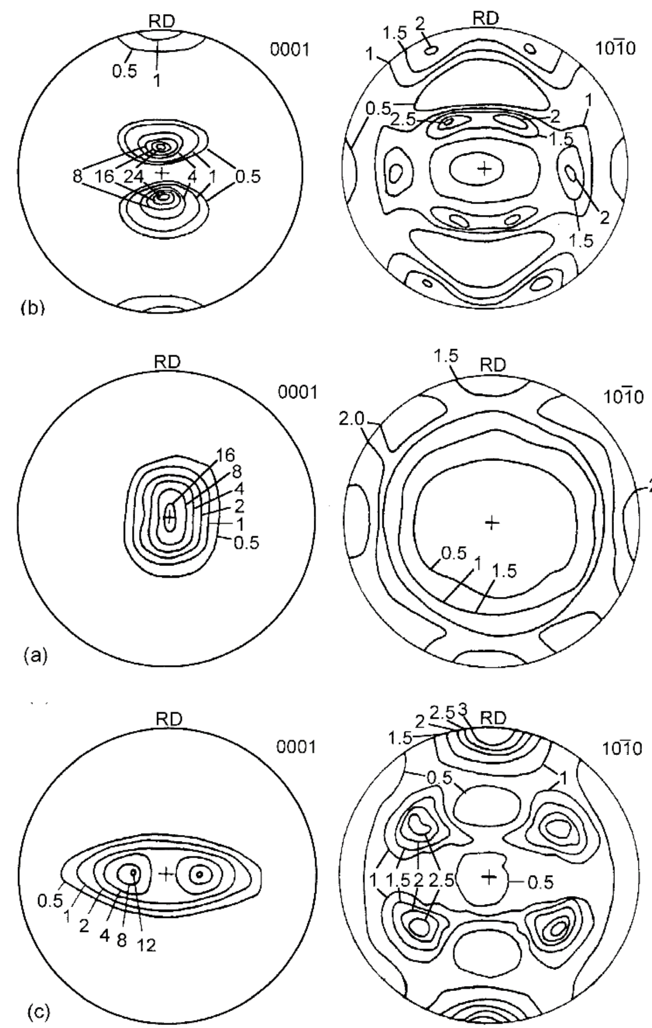
Experimental [Grewen 1973]

c/a > 1.633:
RD split in 0001
e.g. Cd, Zn

c/a = 1.633
e.g. Mg, Co

c/a < 1.633:
RD split in 0001
e.g. Ti, Zr, Be

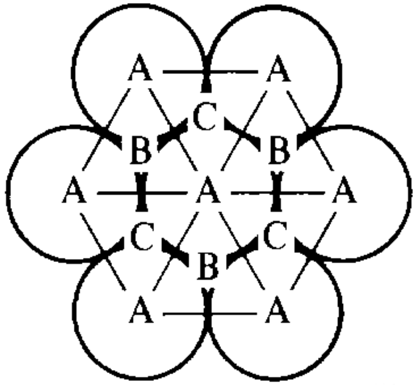


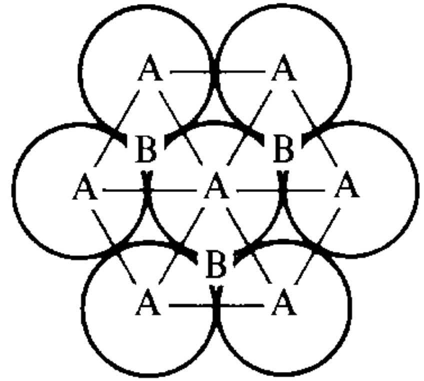


Comparison of the FCC and HCP crystal structures

...ABCABCA...

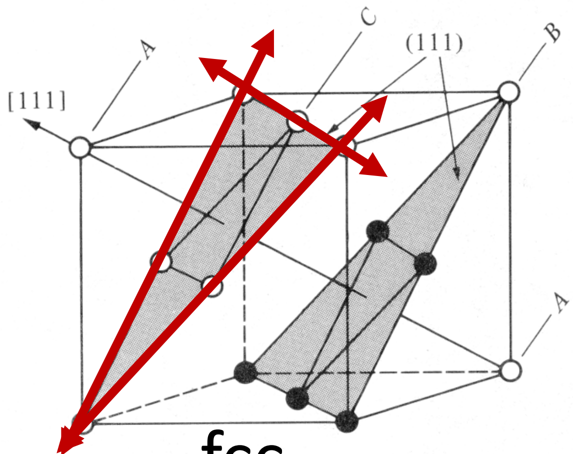
Sequence of (111)-
close-packed planes



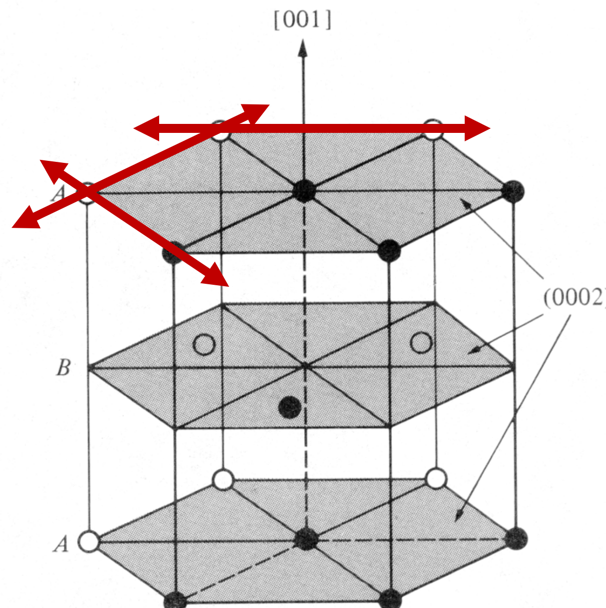


...ABABA...

Sequence of (0002)-
close-packed planes



fcc



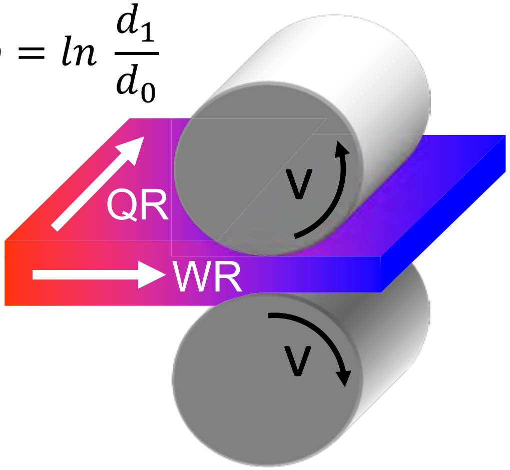
hcp

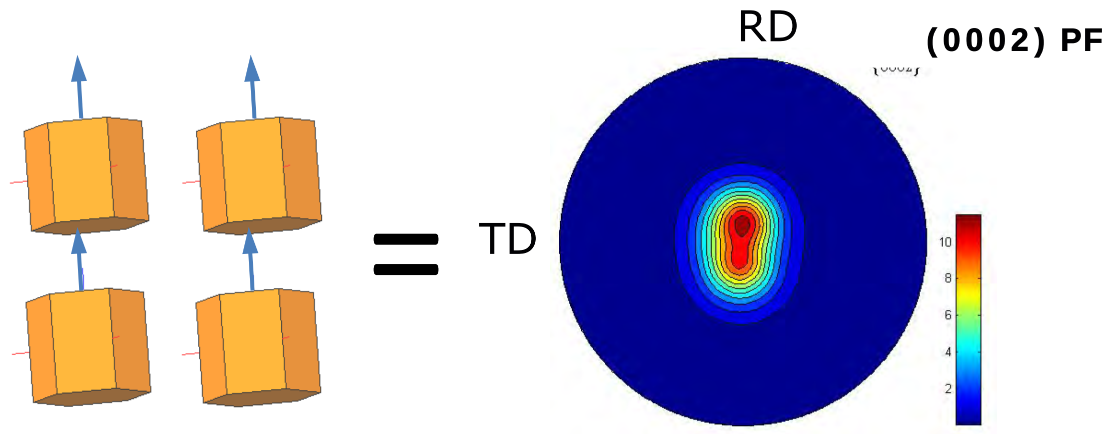
G. Gottstein, Physikalische Grundlagen der Materialkunde, Springer

Problem with strain accommodation during rolling

Basal texture (= basal plane parallel to the sheet surface)

$$\varphi = ln\,\frac{d_1}{d_0}$$

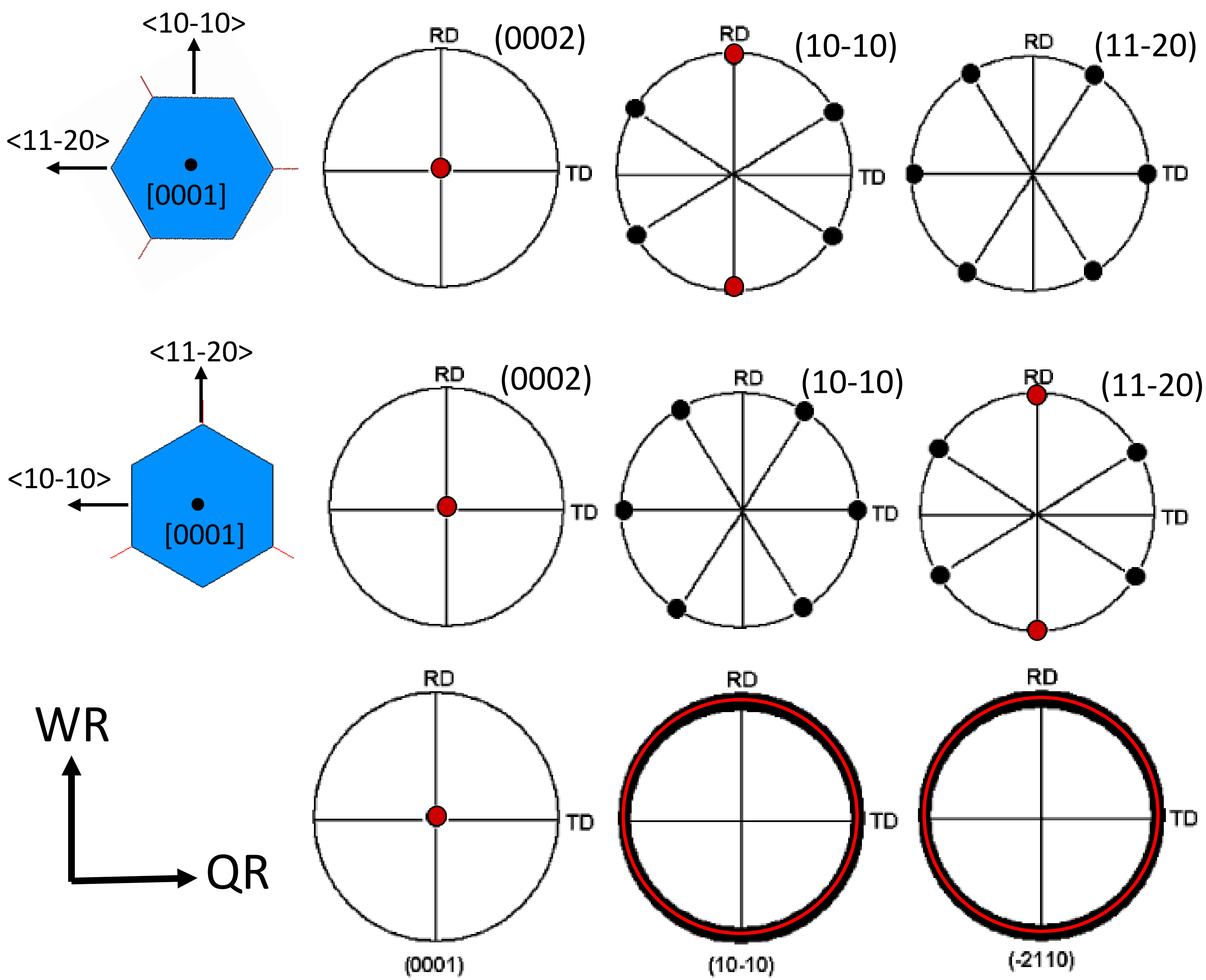




Imax=12 MRD

Basal textures are obviously not desired because c-axis compression does not work at room temperature

Representation of basal textures in pole figures

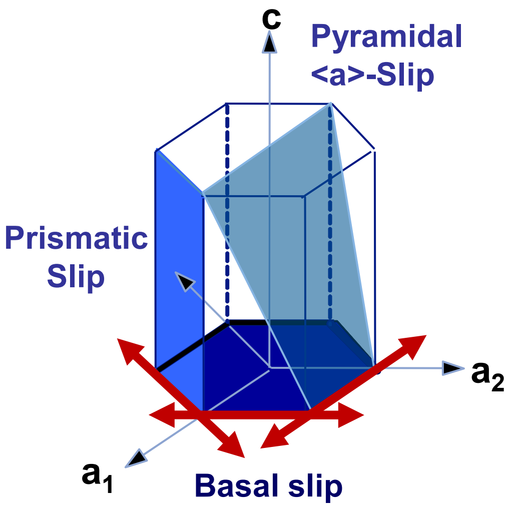


(0001)<10-10>
Basal texture

(0001)<11-20>
Basal texture

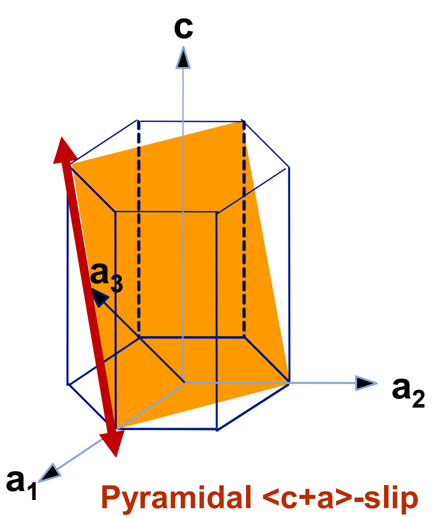
Basal fiber texture

Deformation mechanisms in Mg



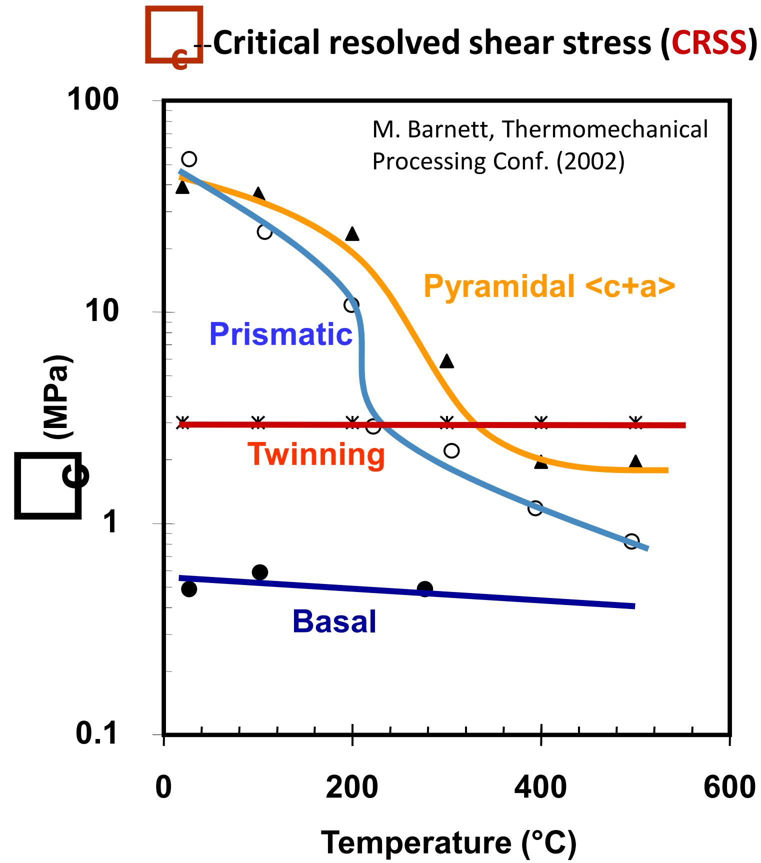
Basal: 3 slip systems
1 Slip plane: {0001}
3 Slip directions: <11-20>
2 independent

Prismatic: 3 slip systems
3 slip planes: {10-10}
1 slip direction: <11-20>
2 independent



Pyramidal <a>: 6 slip systems
6 slip planes: {10-11}
1 slip direction: <11-20>
4 independent

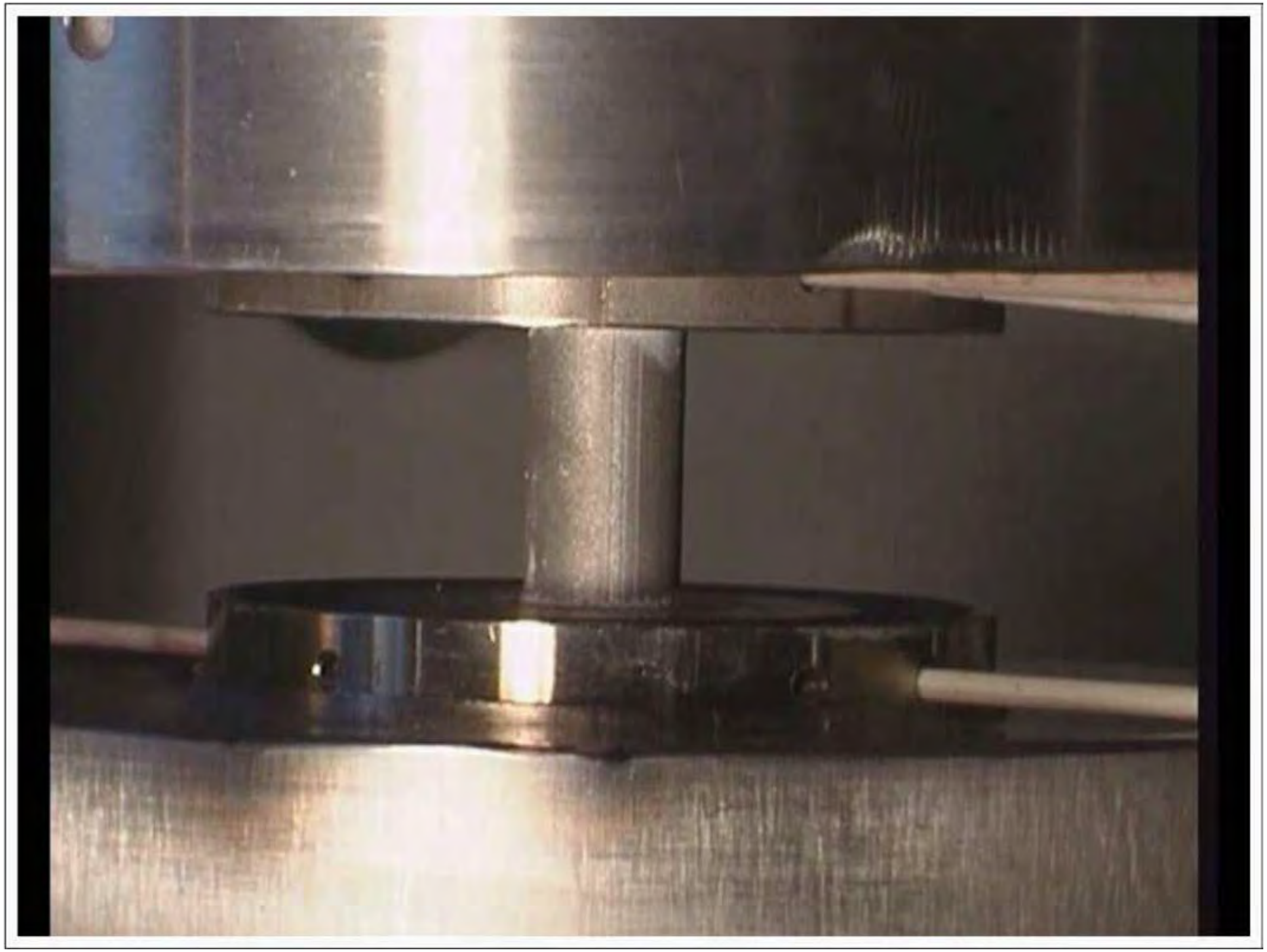
Pyramidal <c+a>: 6 slip systems
6 slip planes: {11-22}
1 slip direction: <11-23>
5 independent *fulfills the von Mises-criterium for a homogeneous deformation)*



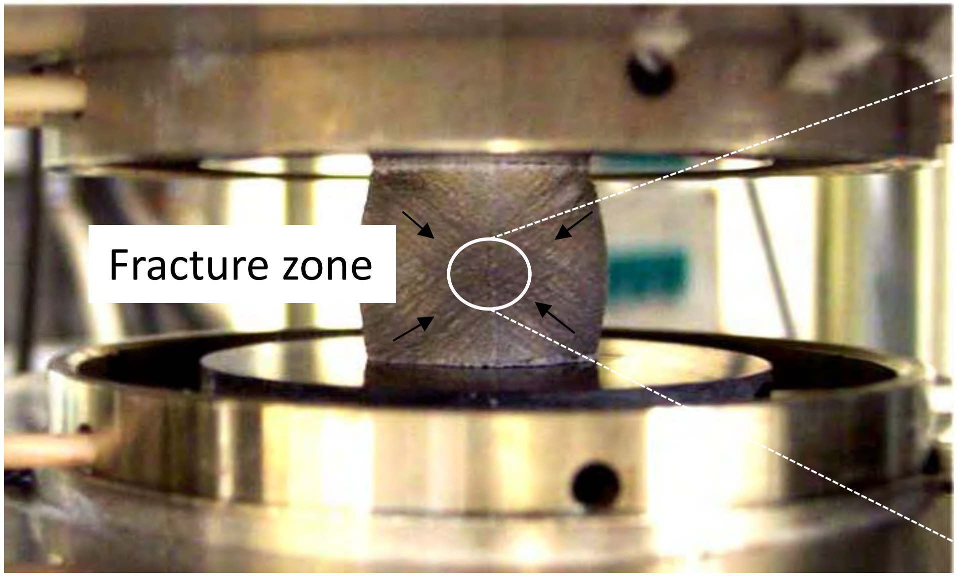
<c+a>-slip: allows deformation in both <a> and <c> directions but requires thermal activation

Deformation behavior at the transition temperature

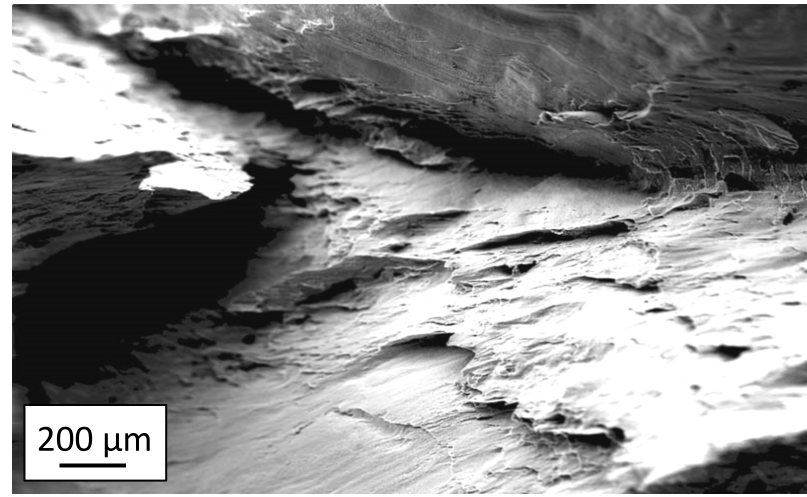
200°C is considered the brittle-ductile transition temperature in Mg



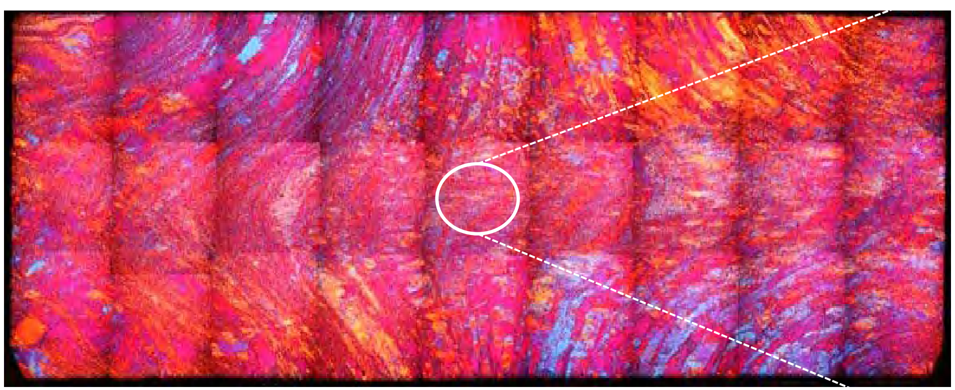
Deformation microstructure at 200°C



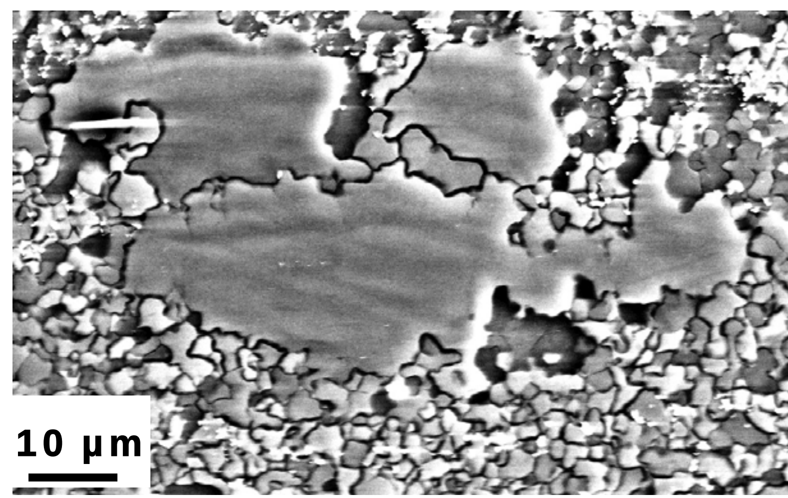
Fracture zone of localized shear



Optical microscopy panorama image in the bulk

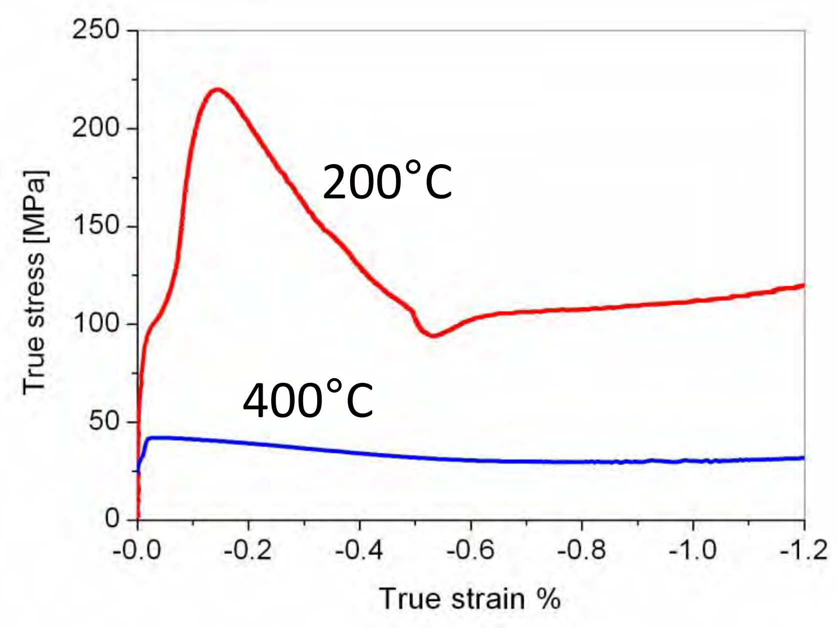


Bulk microstructure (dynamic RX)



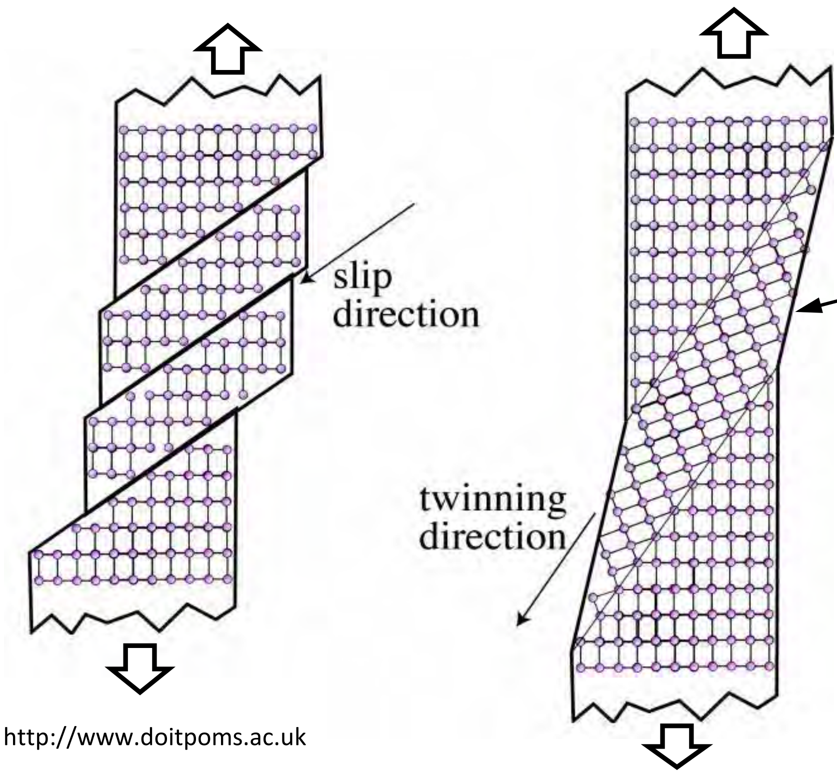
DRX restores the material‘s ductility

Deformation behavior at 400°C



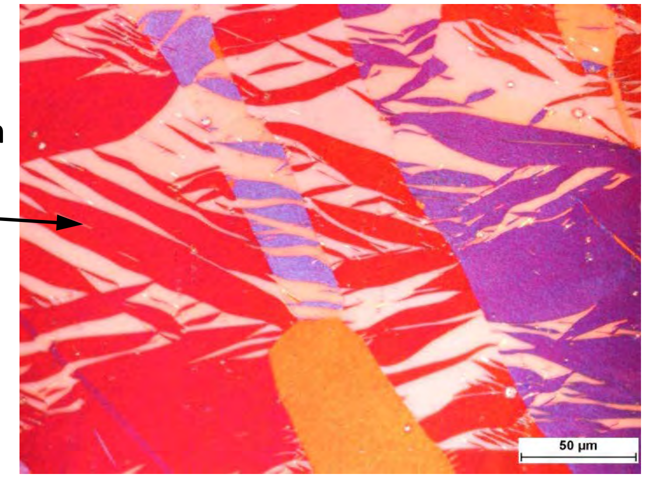
- Deformation at 400°C proceeds at much lower stresses
- Work hardening and softening are less conspicuous
- Onset of DRX is accelerated due to thermal activation
- Very high ductility (ε = 2.2) due to homogeneous deformation(<c+a>-slip)

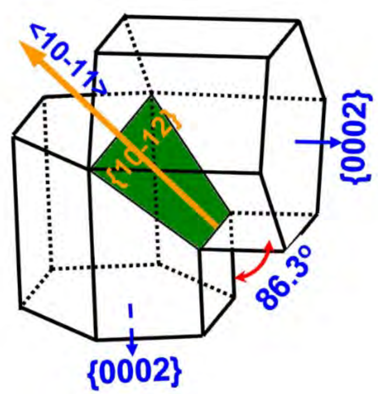
Deformation twinning in Mg



http://www.doitpoms.ac.uk

Deformation twins





Like Dislocation slip:

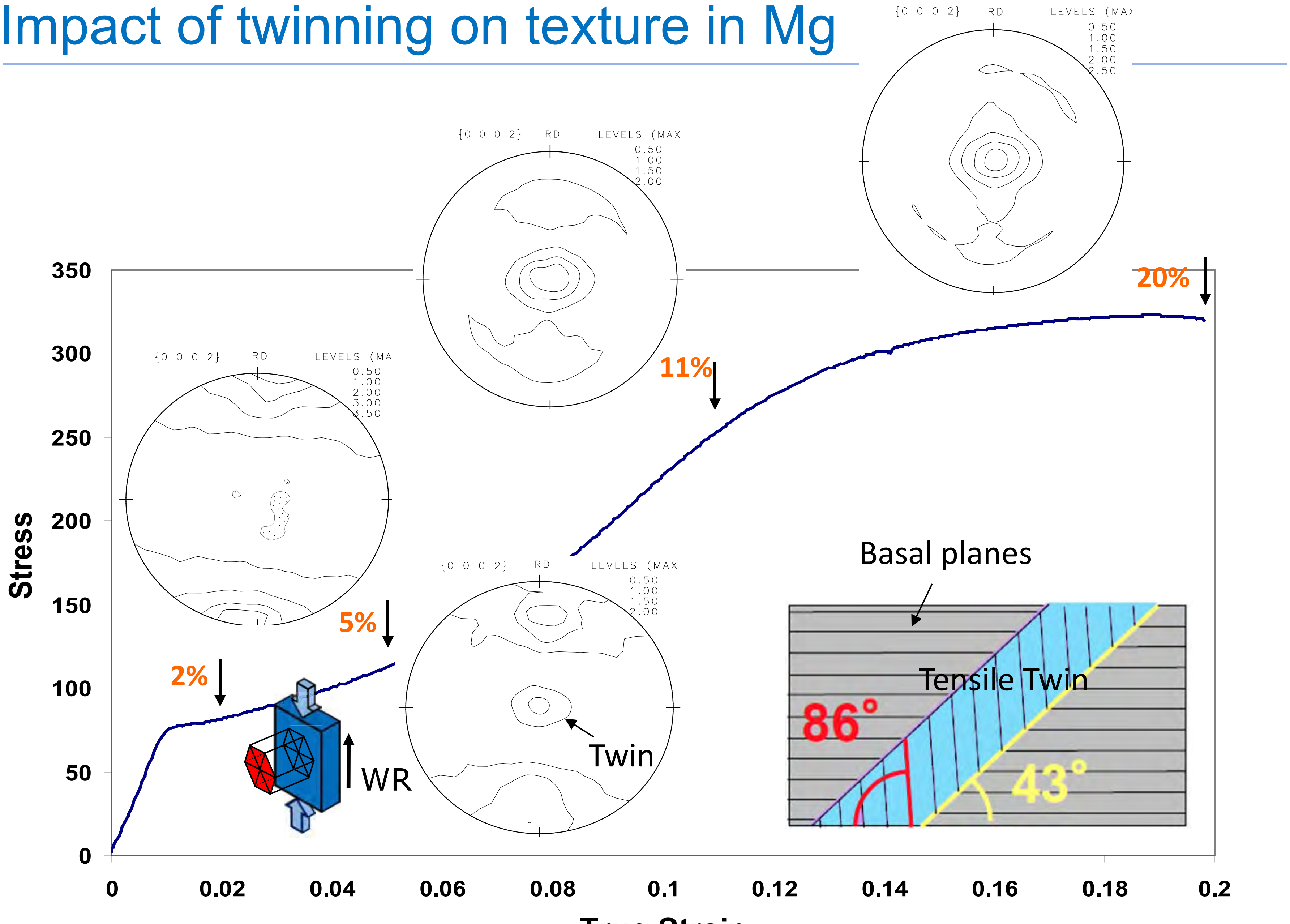
- Simple shear
- Strongly influenced by Schmid law

Unlike Dislocation slip:

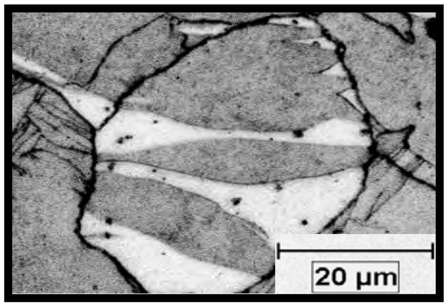
- Polarity (extension or compression)
- Limited strain accommodation

  Twin: $\gamma = V_t.\gamma_t$, **Slip:** $\gamma = \rho.b.L$
- Athermal
- Sudden lattice rotation

Impact of twinning on texture in Mg

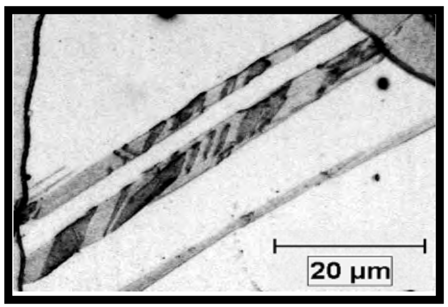


Twin types: Extension and compression twins



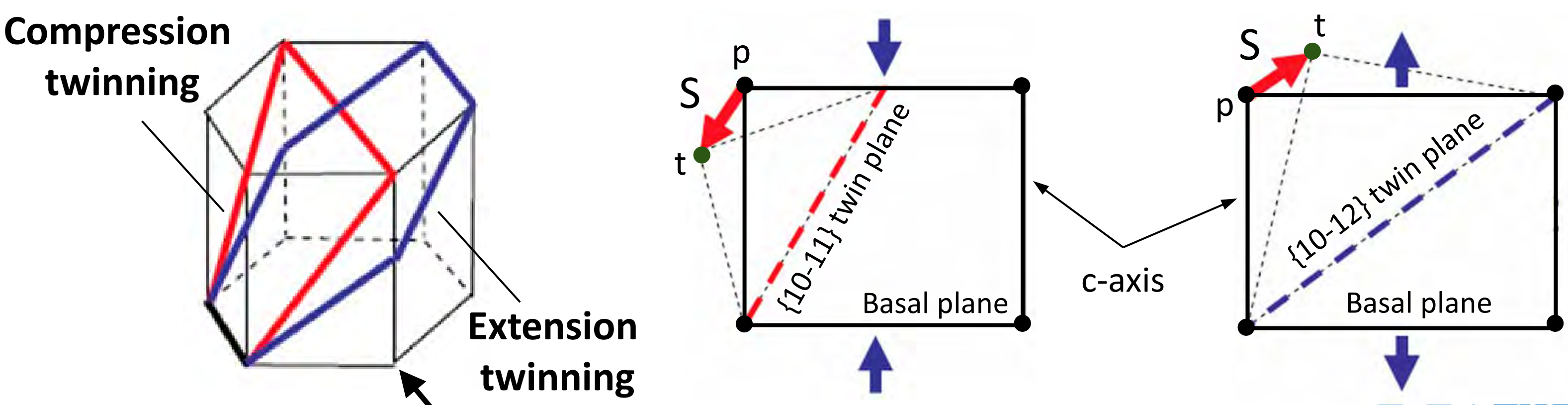
Extension {10-12} twinning (fat and very common)

- Accommodates *extension* along the c-axis
- Twinning shear 0.13
- Low CRSS: 2~4 MPa



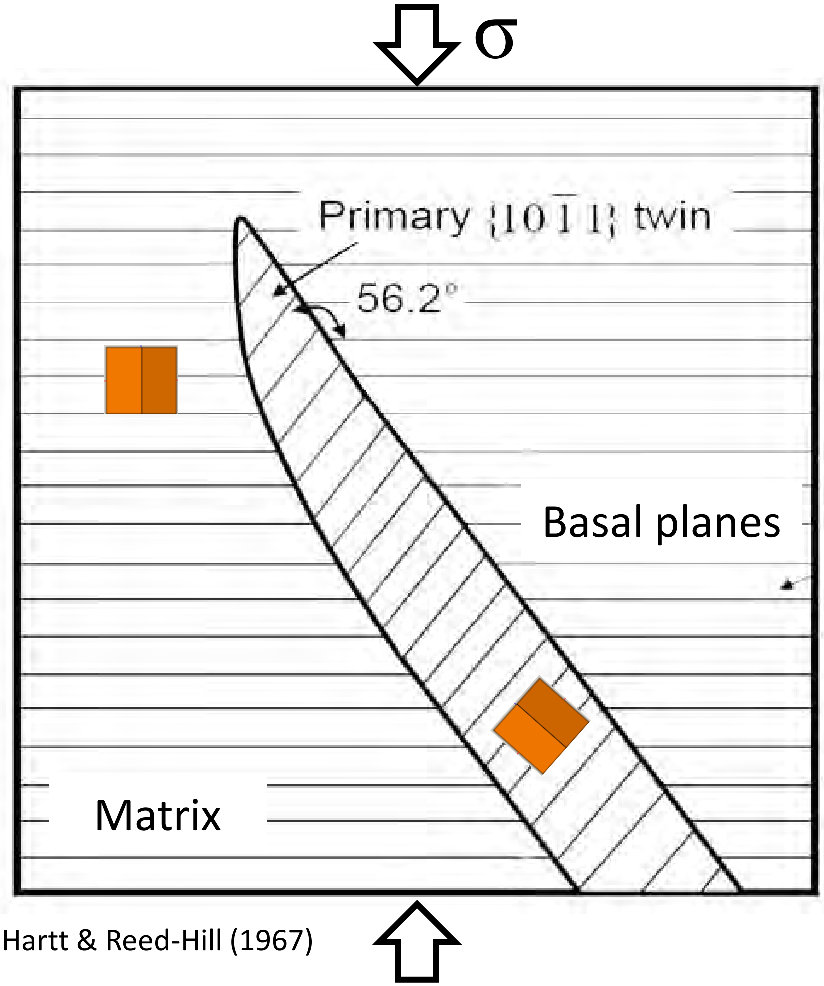
Contraction {10-11} twinning (thin and scarce)

- Accommodates *contraction* along the c-axis
- Twinning shear 0.137
- High CRSS: 76~153 MPa



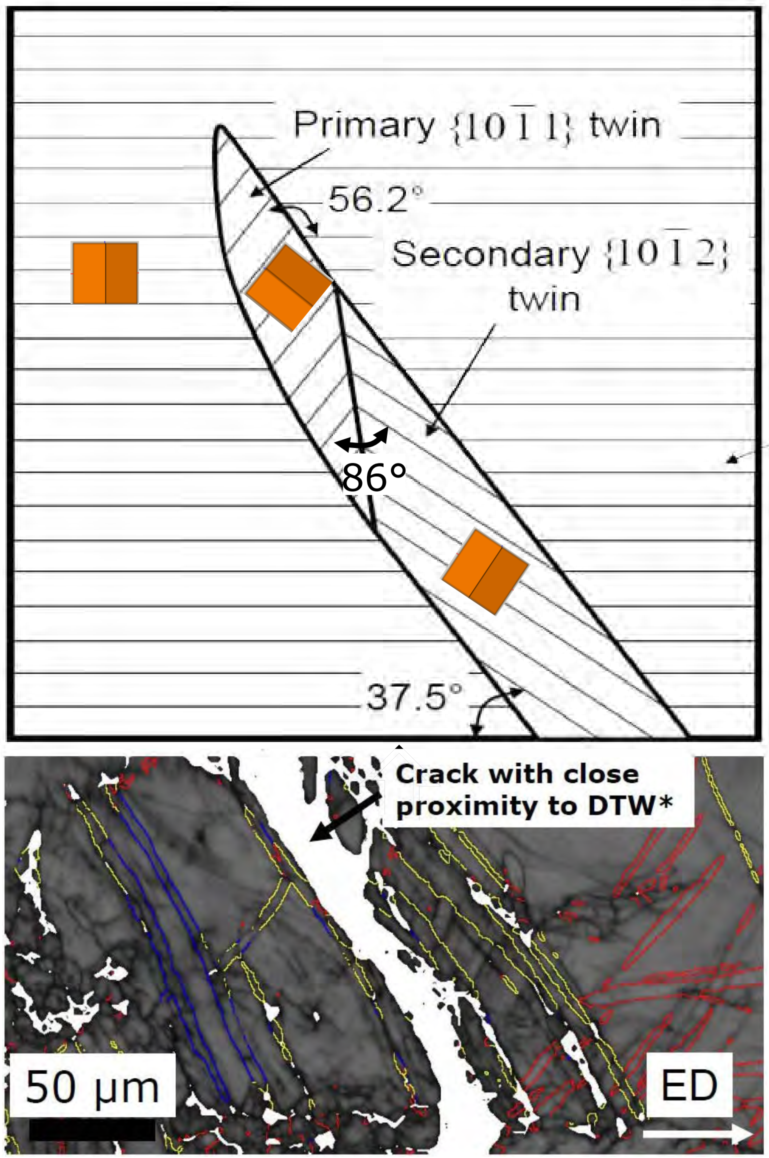
Source: Wonsiewicz & Backofen (1967)

Twin types: {10-11}-{10-12}-double twinning

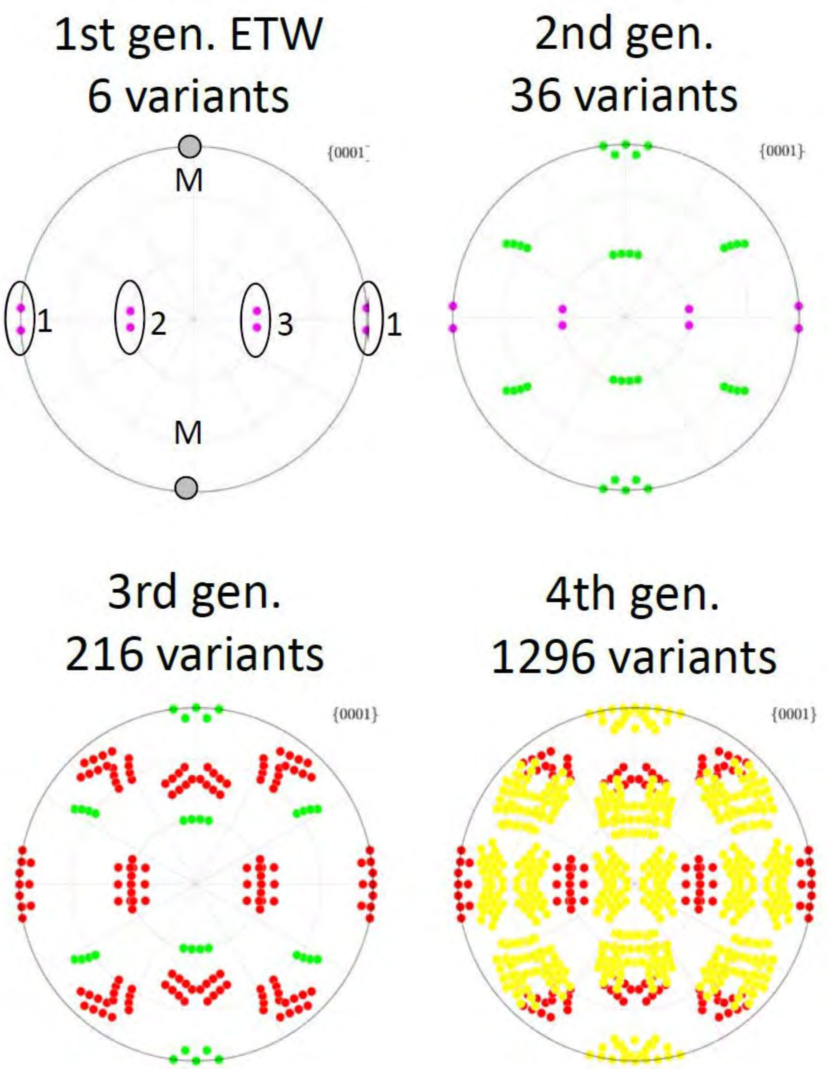


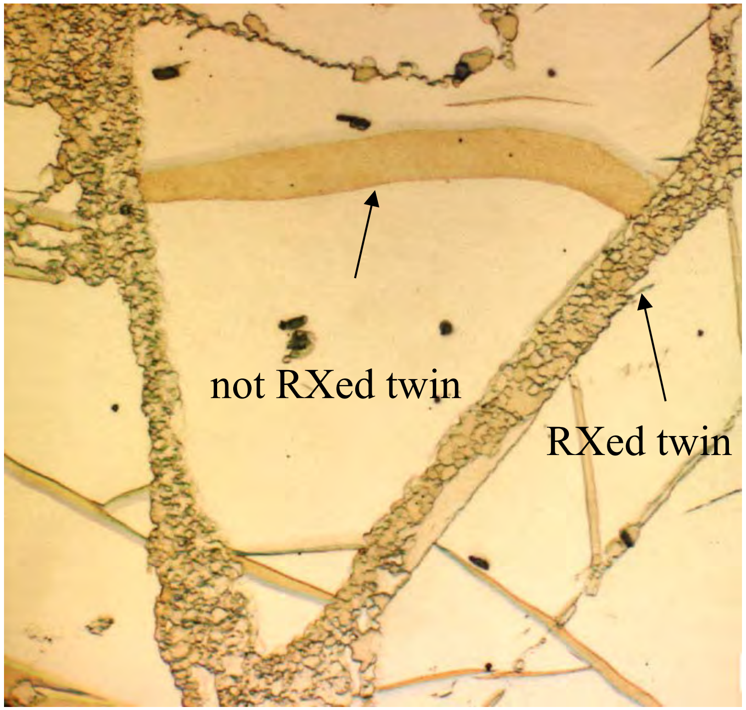
Hartt & Reed-Hill (1967)

$$L \sim 1/\sqrt{\rho},\ \tau = 1/2Gb\sqrt{\rho} \Rightarrow \tau \propto L$$



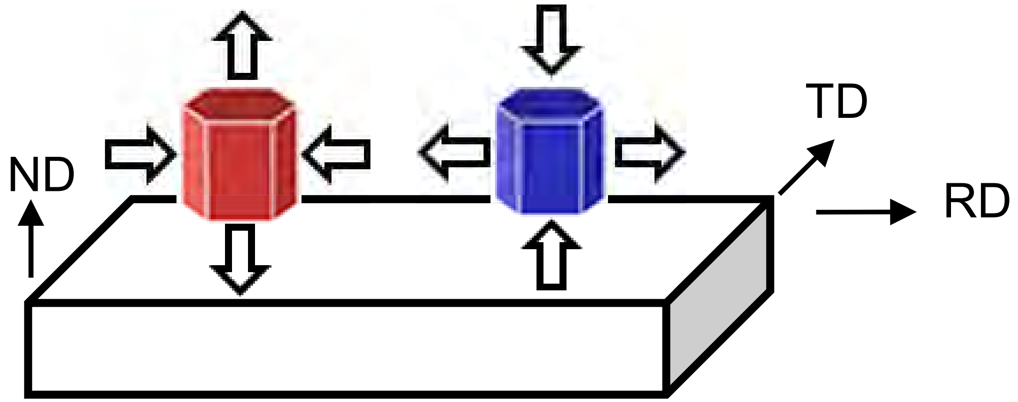
Twinning multiplicity





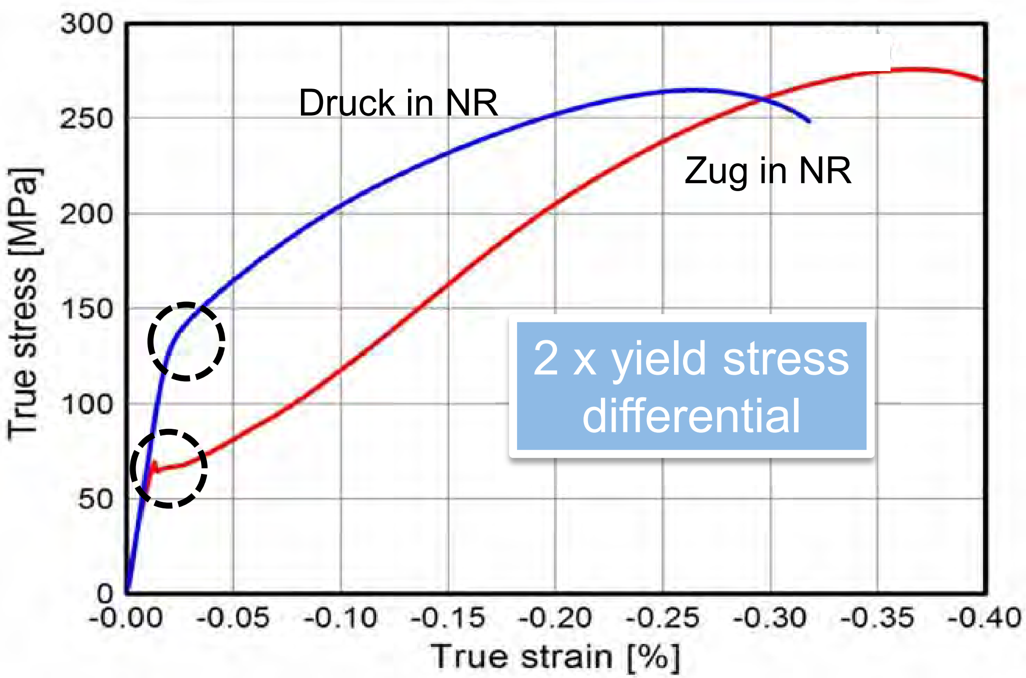
Multiple twinning has good potential for texture weakening if twins serve as nucleation sites for RX

Impact of twinning on anisotropy

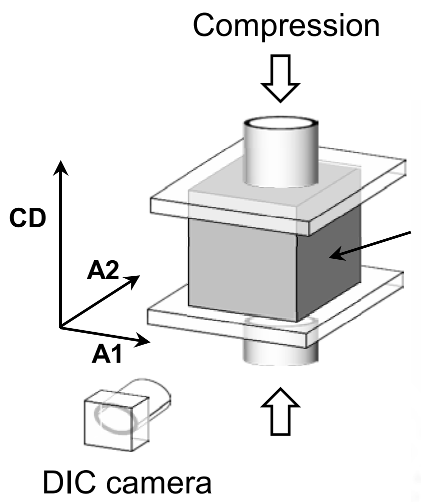


Extension twinning is easily activated during tension in ND or compression in RD → low yield stress

Activation of contraction twinning during compression in ND oder tension in RD is much harder → high yield stress

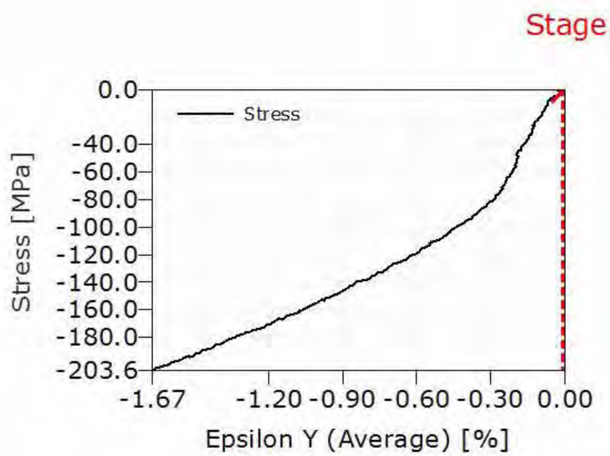


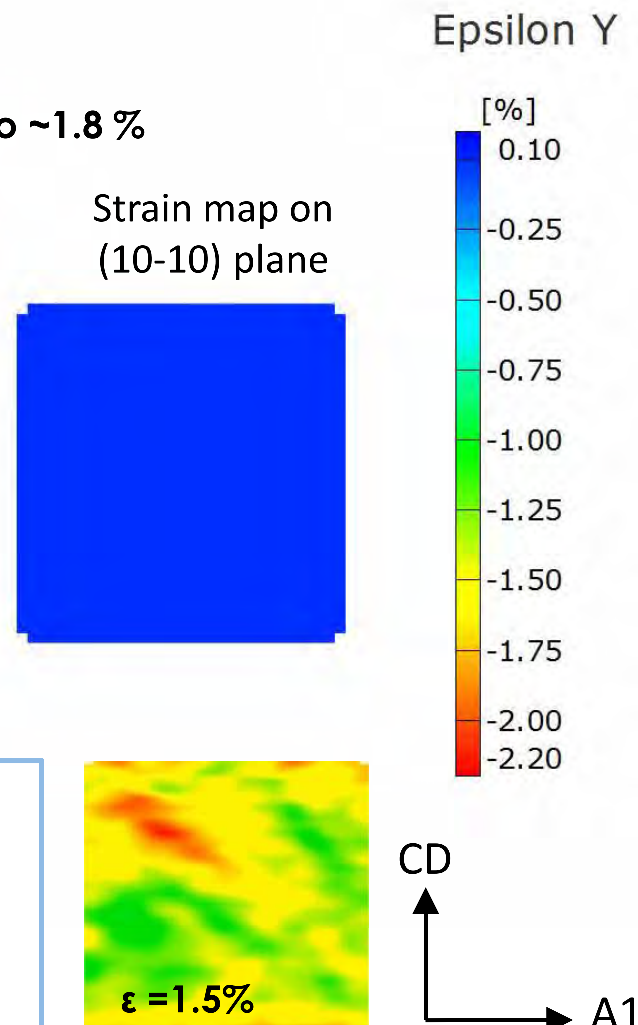
In-situ investigation of twinning - DIC

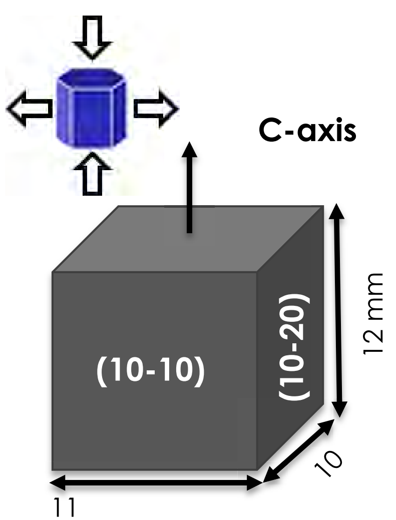


DIC: Digital Image Correlation

Compressed to ~1.8 %



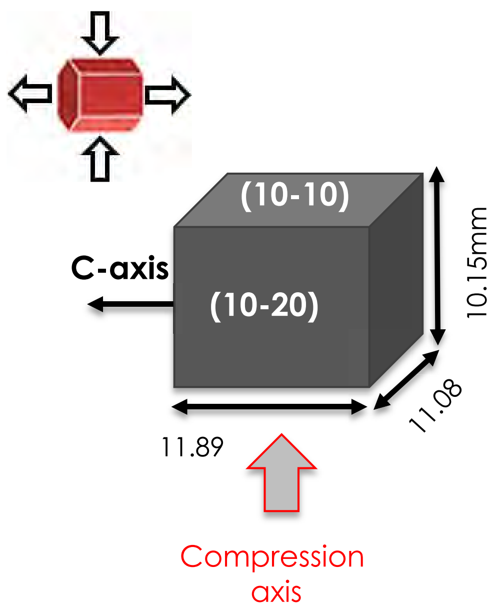




- Strain distribution almost homogeneous
- No distinct strain pattern
- Large work hardening

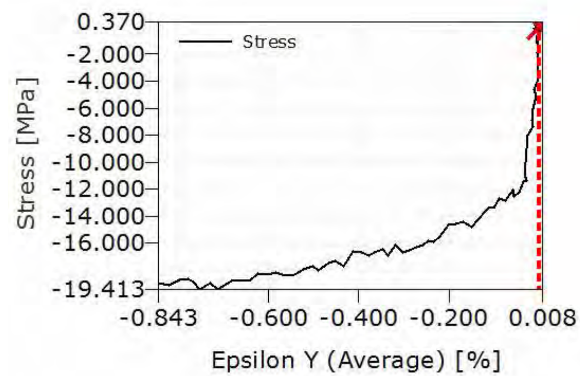
Courtesy of K. Hazeli et al., Johns Hopkins University

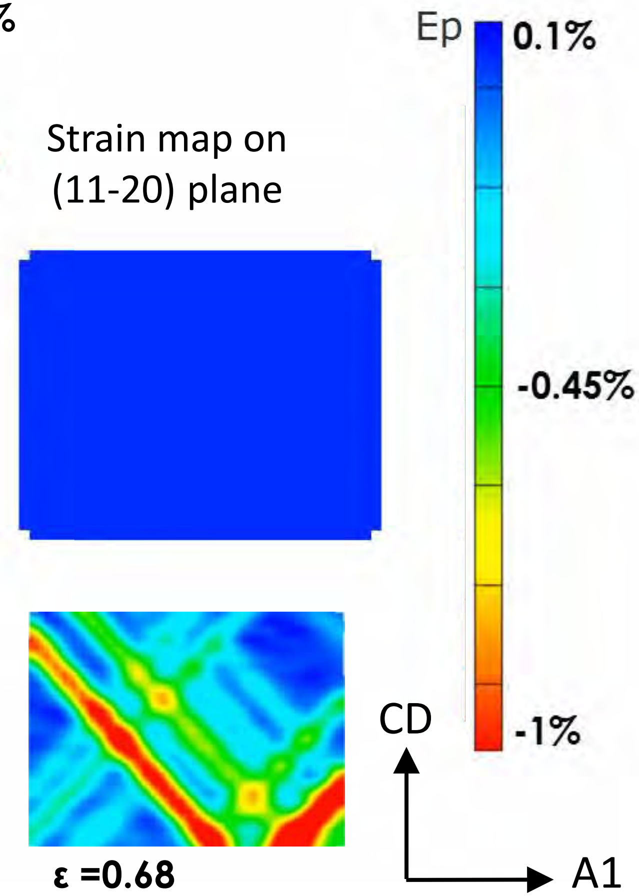
In-situ investigation of twinning - DIC



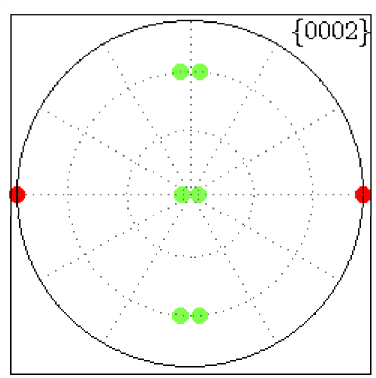
Compressed to ~1 %

Stage 0





- Strain localization within twin bands
- Distinct strain pattern
- Little work hardening



- Parent orientation
- Possible twin orientations

Courtesy of K. Hazeli et al., Johns Hopkins University

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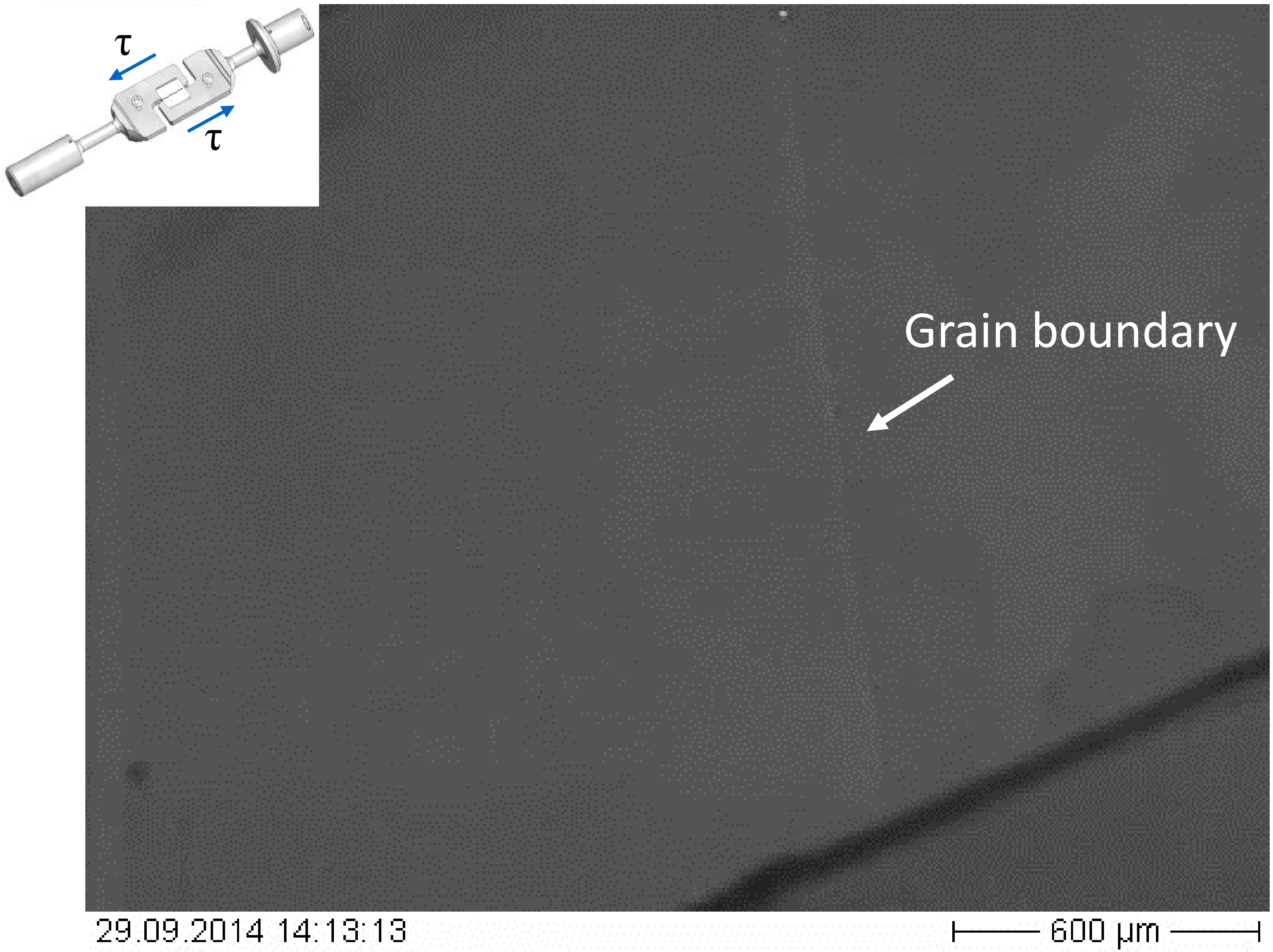
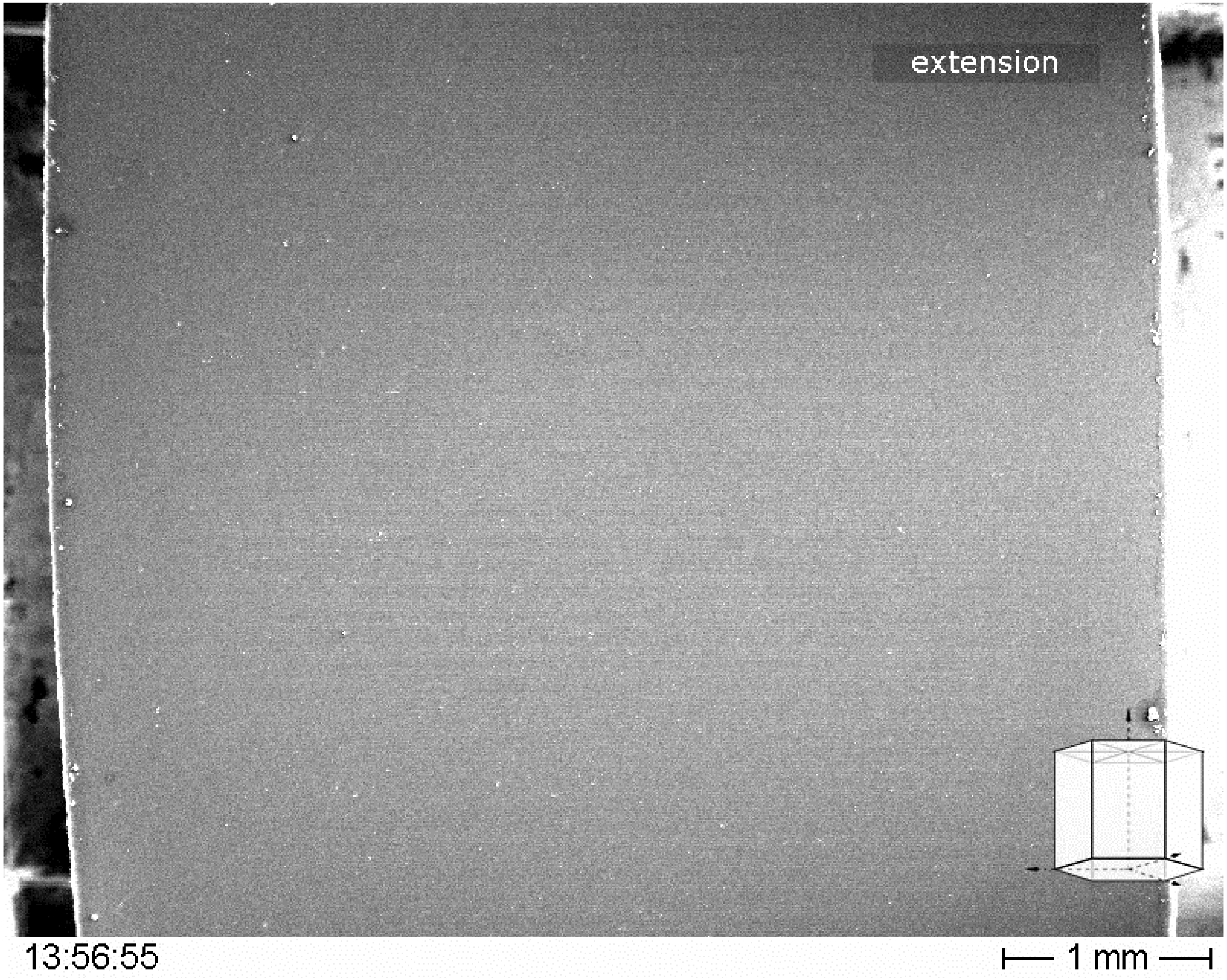
In-situ investigation of twinning in SEM



In-situ investigation of detwinning in SEM



Solution strategies

Processing problems of semi-finished Mg products:

- Limited ductility below 200°C
- Strong mechanical anisotropy

Why?

- Limited number of deformation mechanisms at RT
- Strong basal textures

What needs to be done:

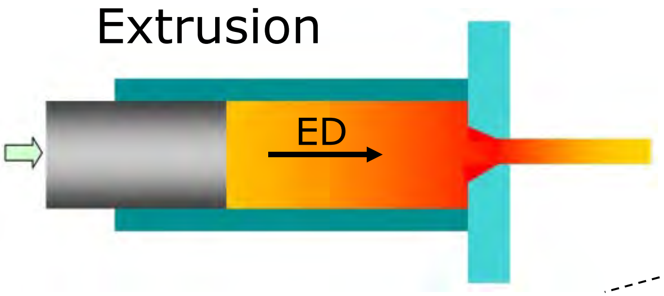
- Texture control:
  - Weakening / randomization
  - Non-basal (soft) textures
- Increase the activity of <c+a>-slip

How?

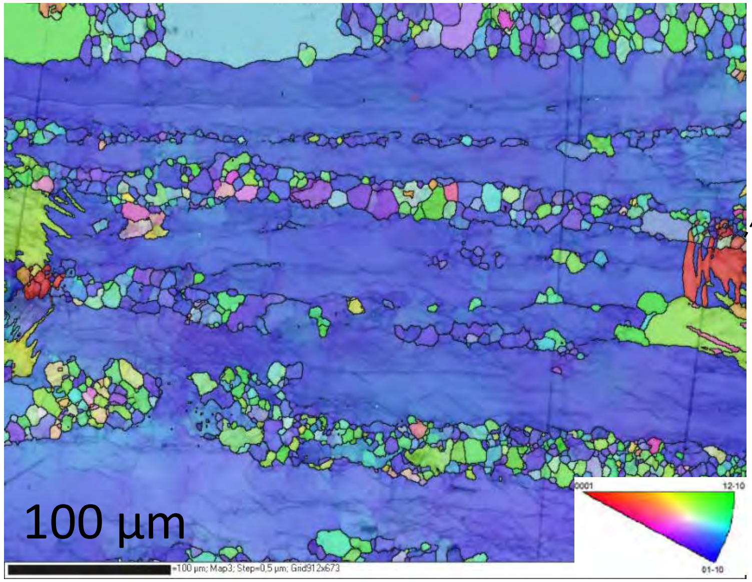
- Process design / optimization of parameters (keep the alloy chemistry)
- Alloy design (change the chemistry)

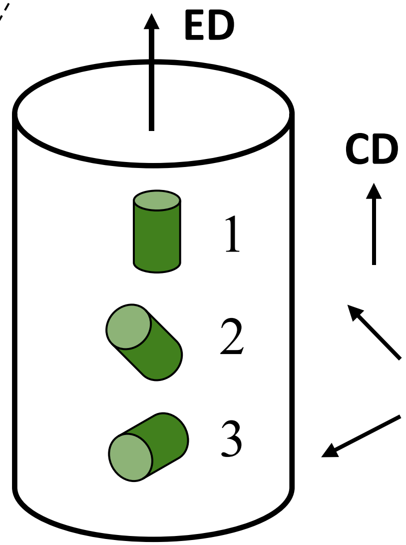
Research example: Post-processing of extruded AZ31

AZ31 Leg.	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
wt. %	**2.9**	**0.84**	**0.33**	0.02	0.004	0.001	0.001	**Rest**



T= 370°C
v= 1 mm/s
R=d_0/d_1=3.33

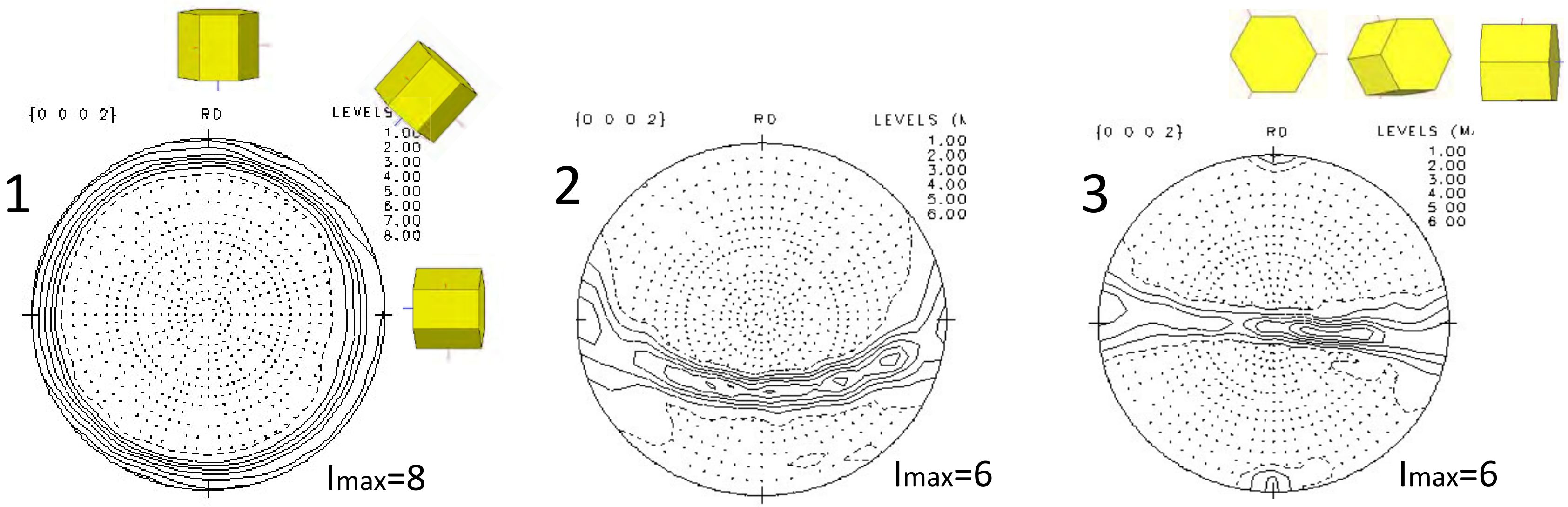




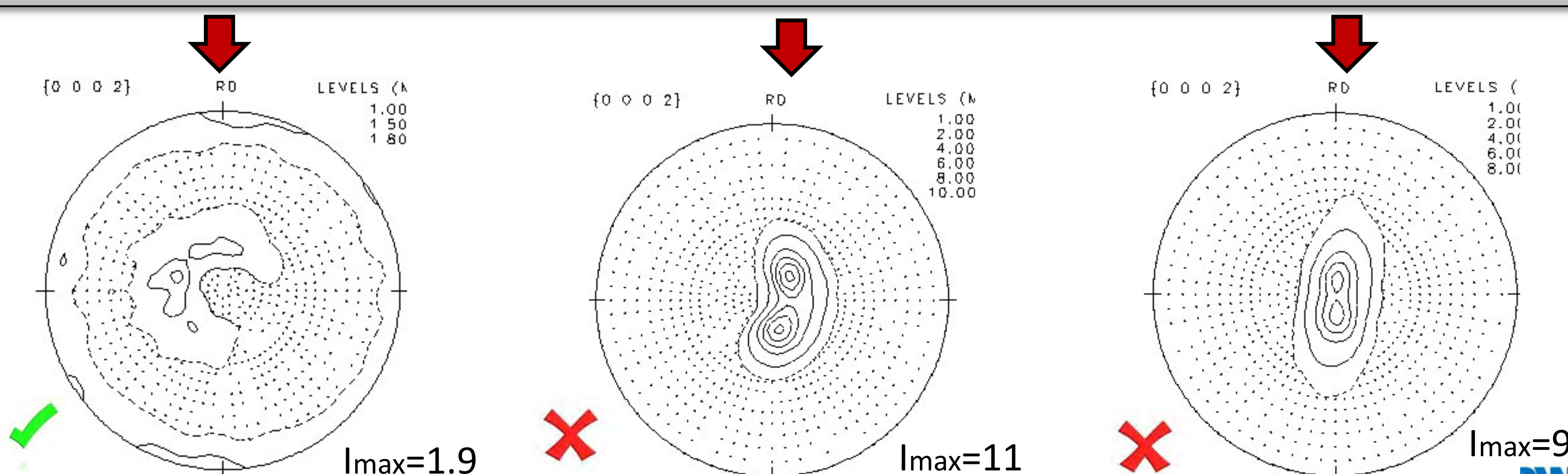
Investigation of different loading orientations:

1) CD 0° ED
2) CD 45° ED
3) CD 90° ED

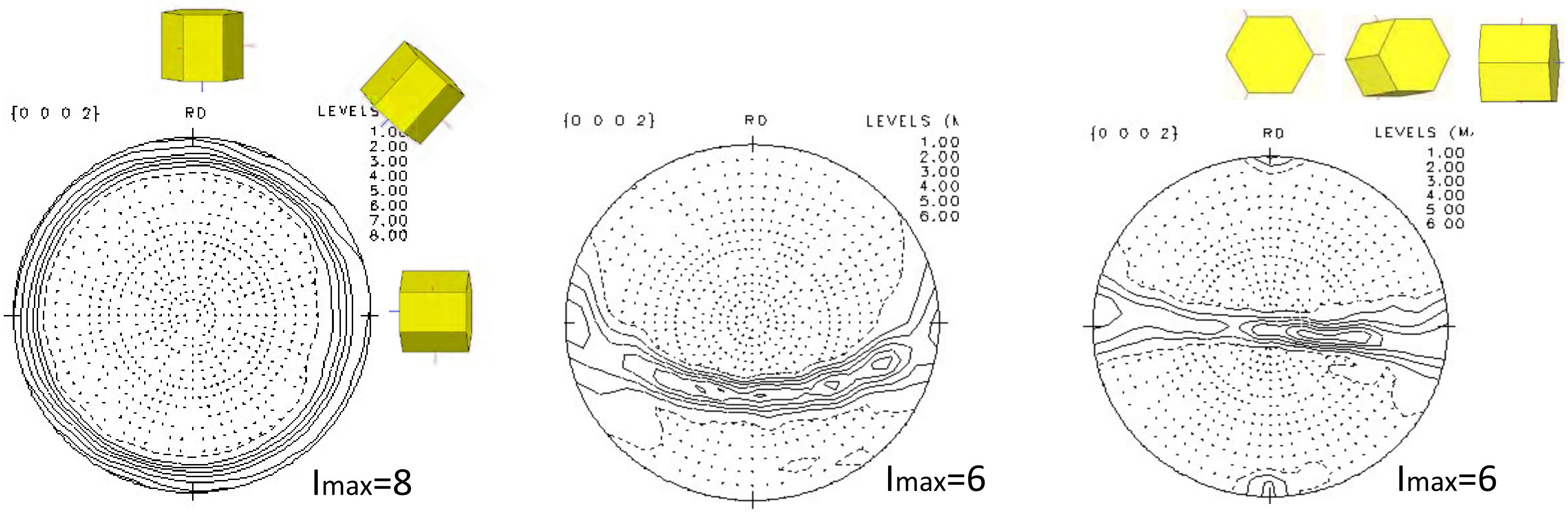
Texture evolution during compression



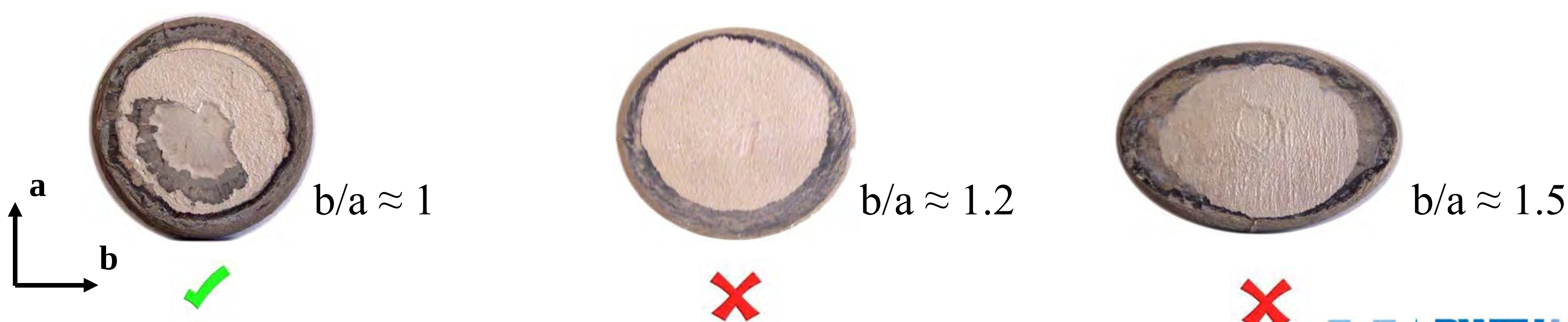
Multiple compression experiments exploring different Zener-Hollomon parameter



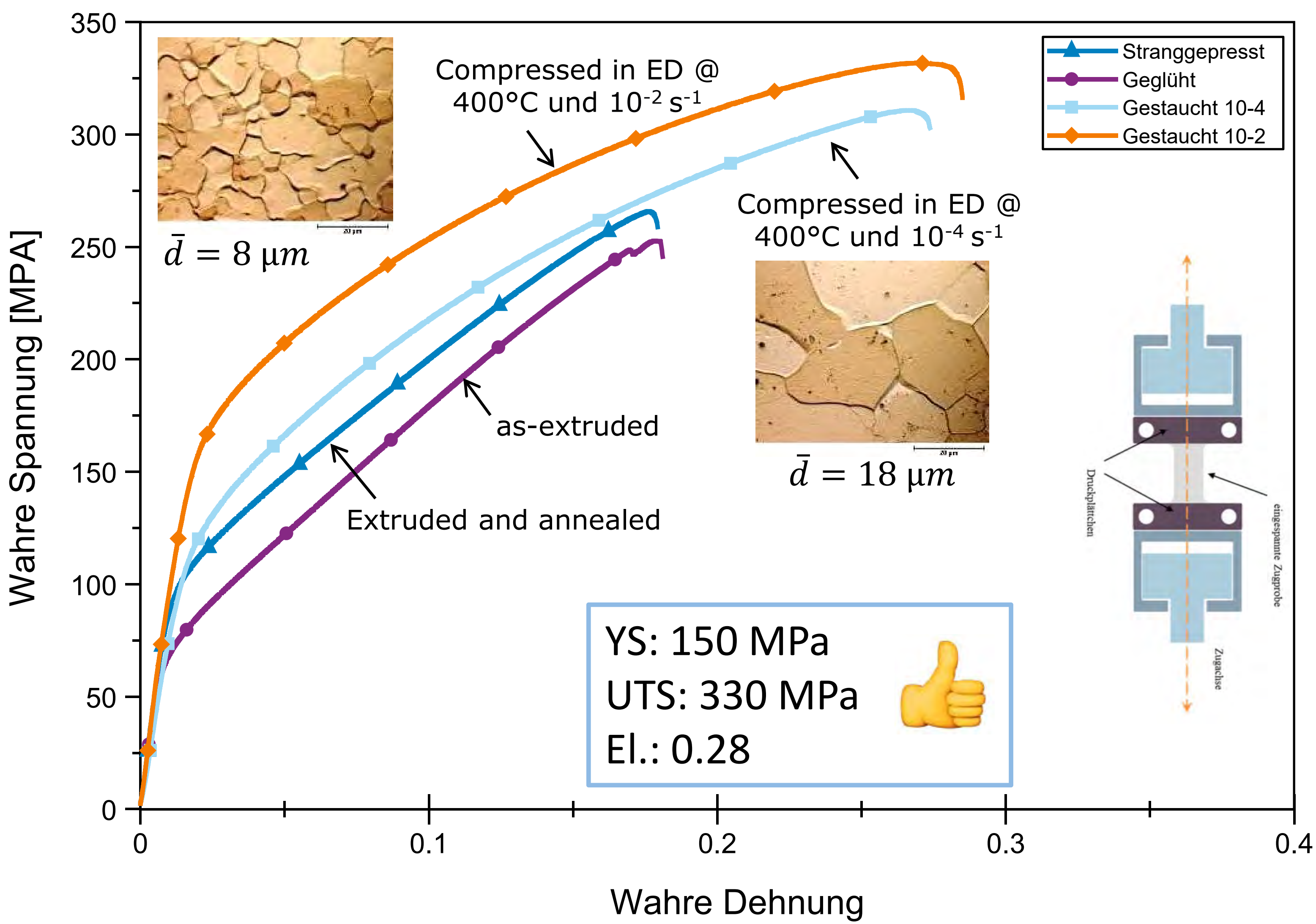
Macroscopic shape change during compression



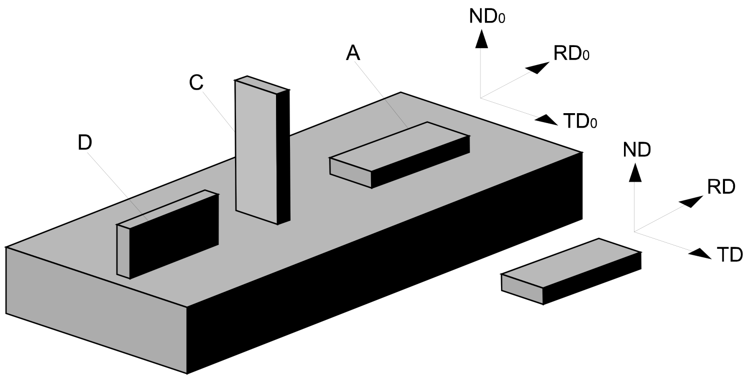
Multiple compression experiments exploring different compression parameters



Tensile properties at RT



Research example: Post-processing of rolled AZ31



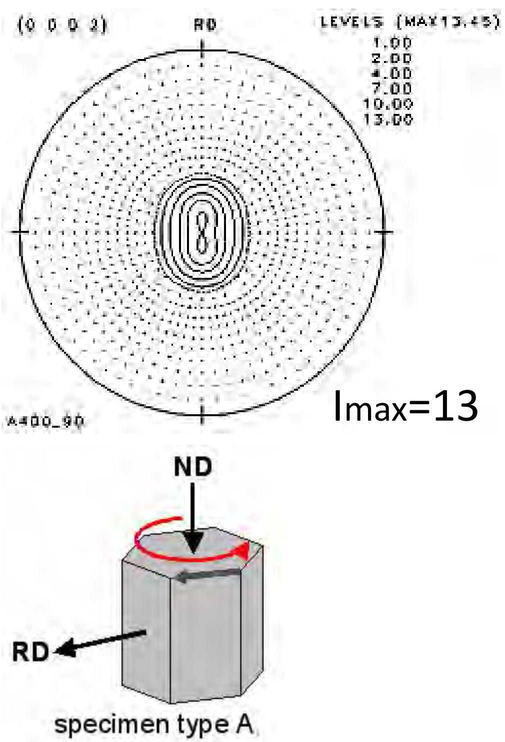
Old reference system: RD_0, ND_0, TD_0

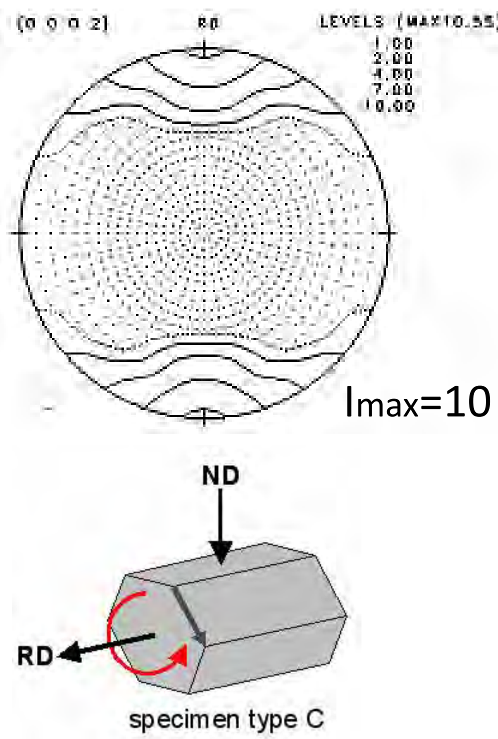
New reference system:

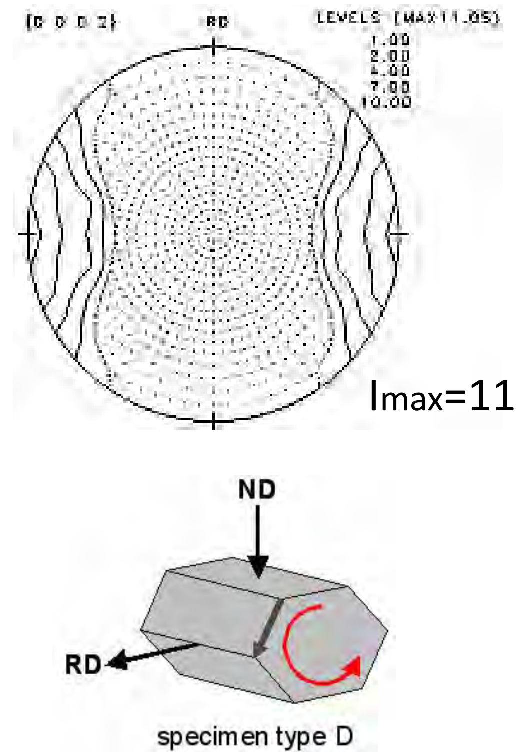
Type A: $RD//RD_0$, $ND//ND_0$, $TD//TD_0$

Type C: $RD//ND_0$, $ND//RD_0$, $TD//TD_0$

Type D: $RD//RD_0$, $ND//TD_0$, $TD//ND_0$

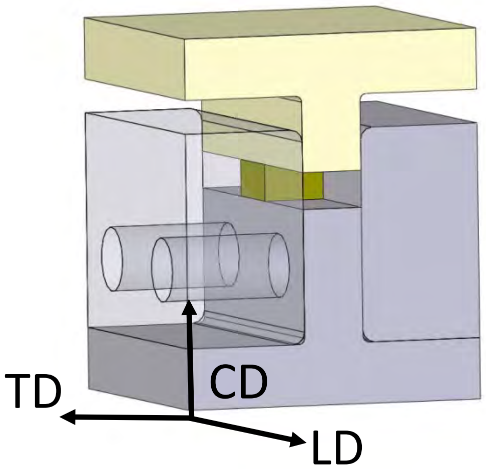




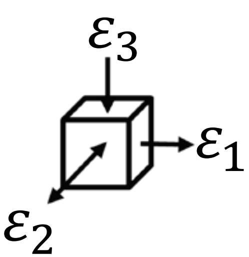


Texture evolution of types A and C

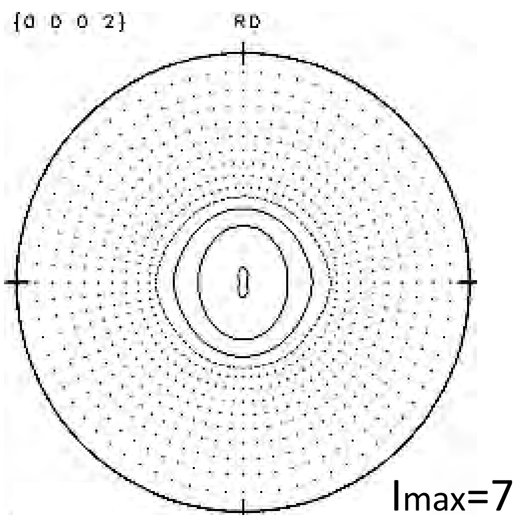
Channel-die plane-strain compression experiment



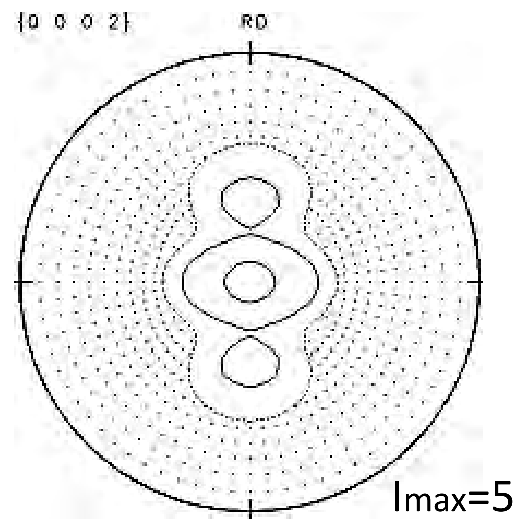
$$\begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\varepsilon_{33} \end{pmatrix}$$



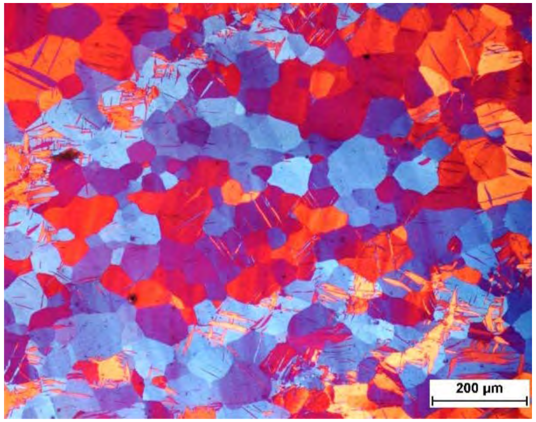
Type A, 5 %



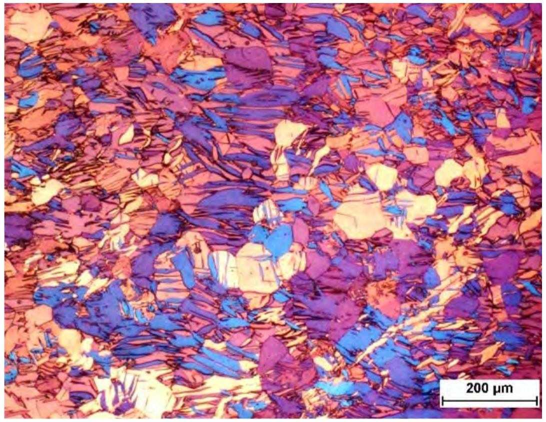
Type C, 5 %



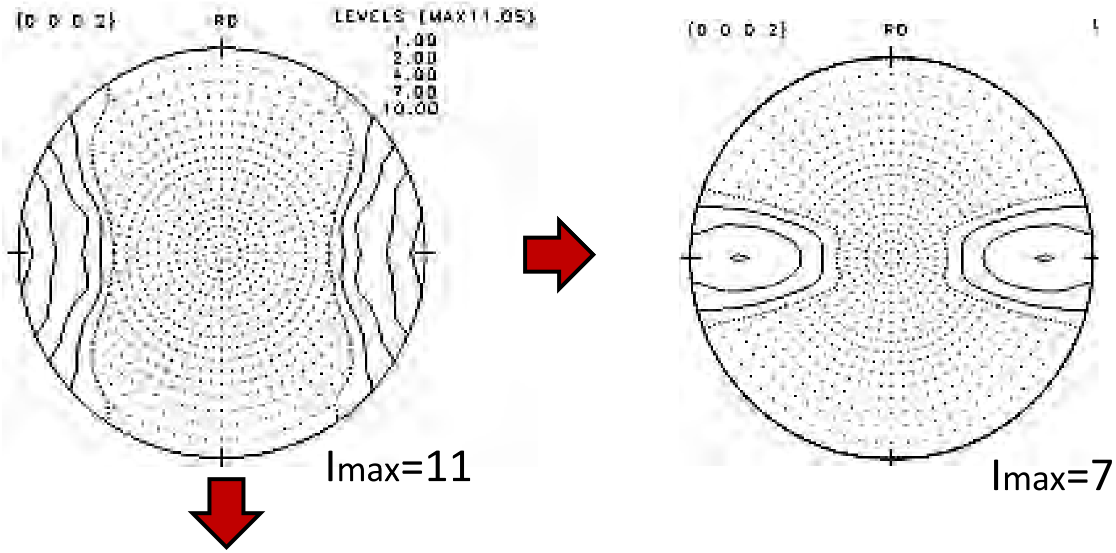
5 %-strain (no twinning)

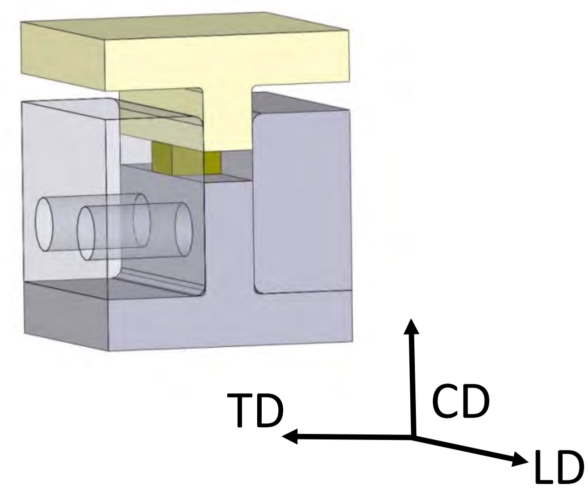


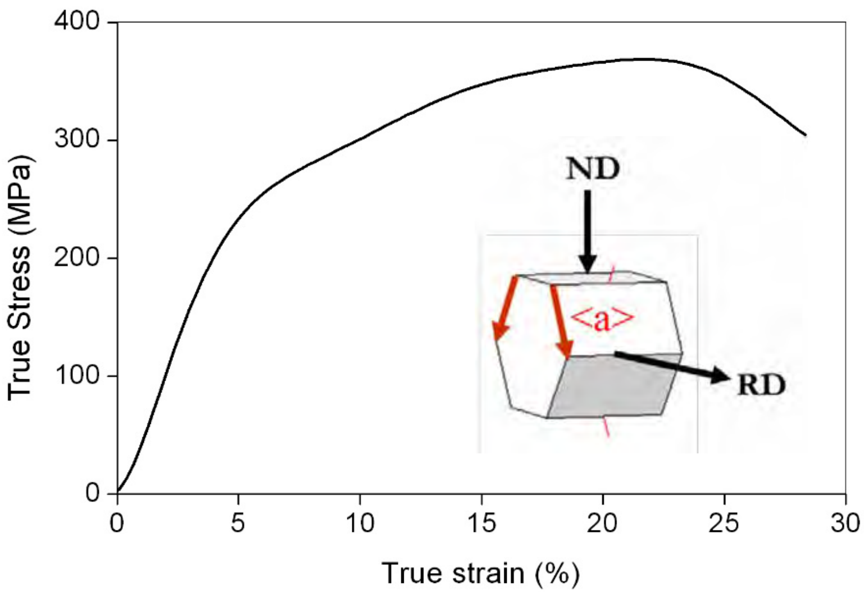
5 %-strain (profuse twinning)



Texture development of type D

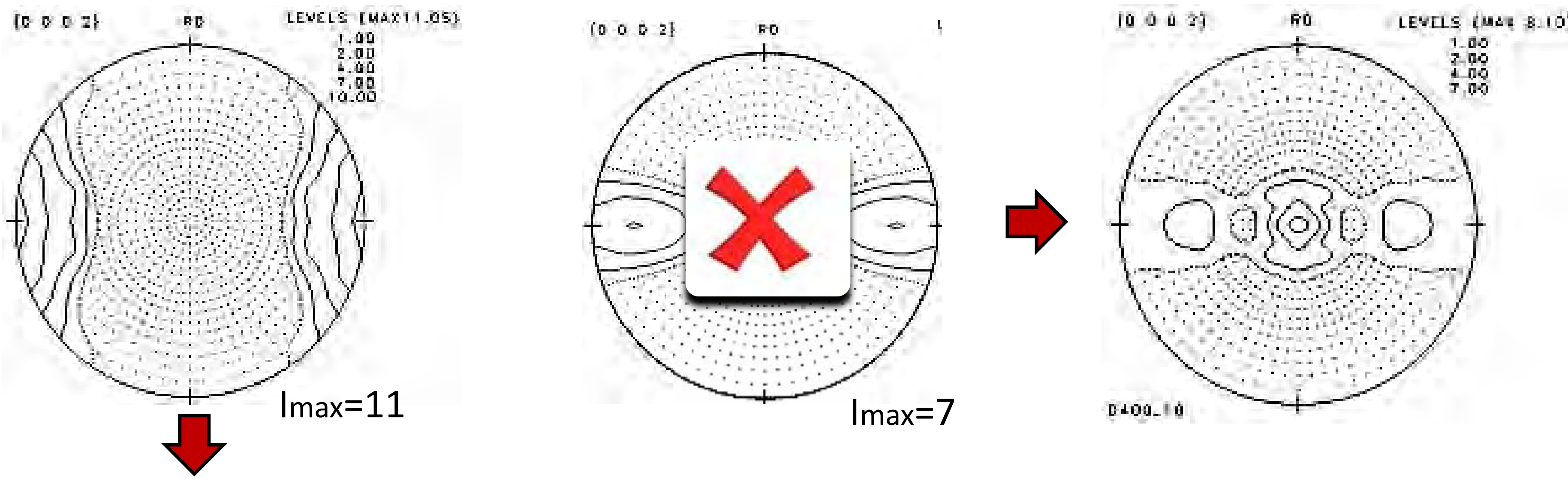


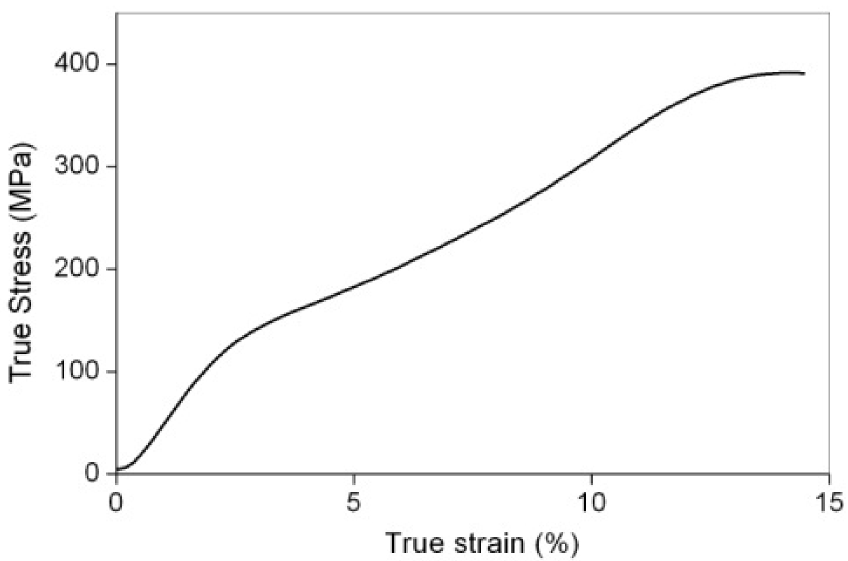




- Off-basal end-texture
- Twinning was suppressed
- Activation of prism slip
- Enhanced RT ductility

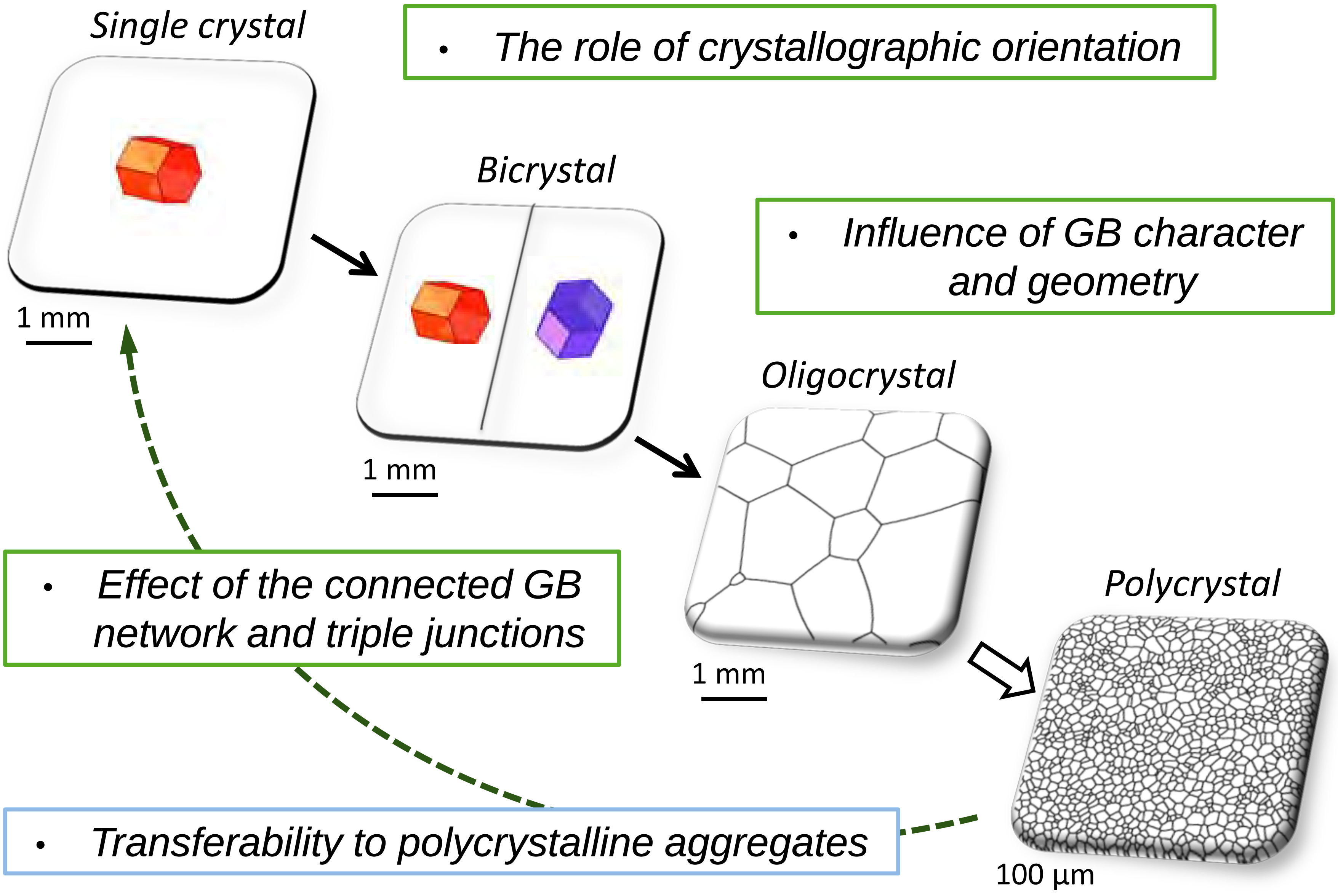
Texture development of type D ($\varepsilon_{22} \neq 0$)



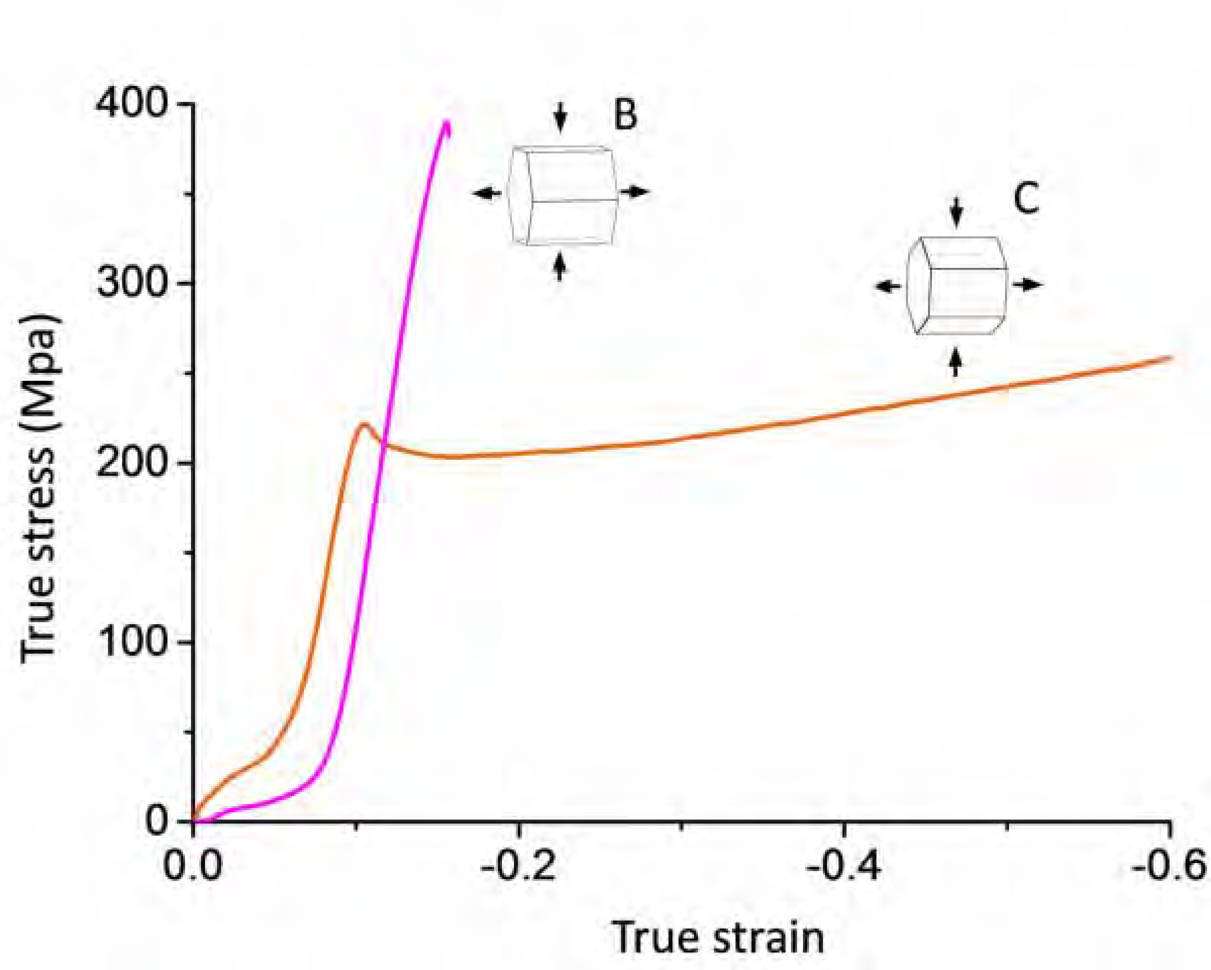


For $\varepsilon_{22} \neq 0$ (TD deformation is allowed) twinning will be active and the final texture will be basal → limited ductility

Multi-scale approach for microstructure investigations



Single crystal compression experiments



If both B and C are susceptible to extension twinning why do they deform differently?

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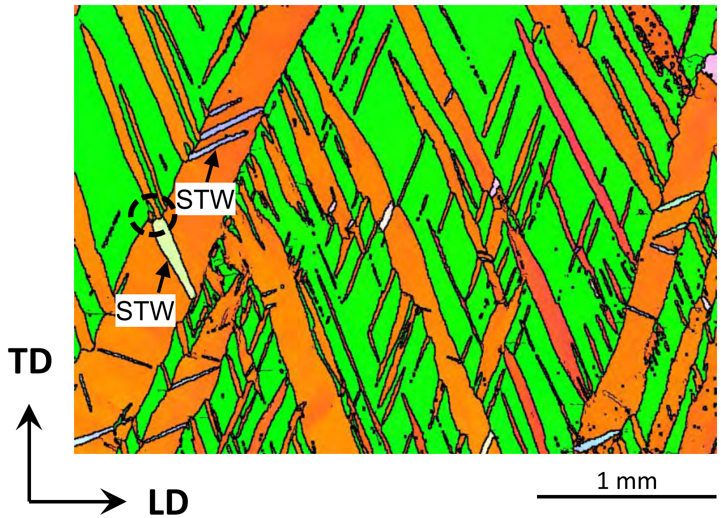
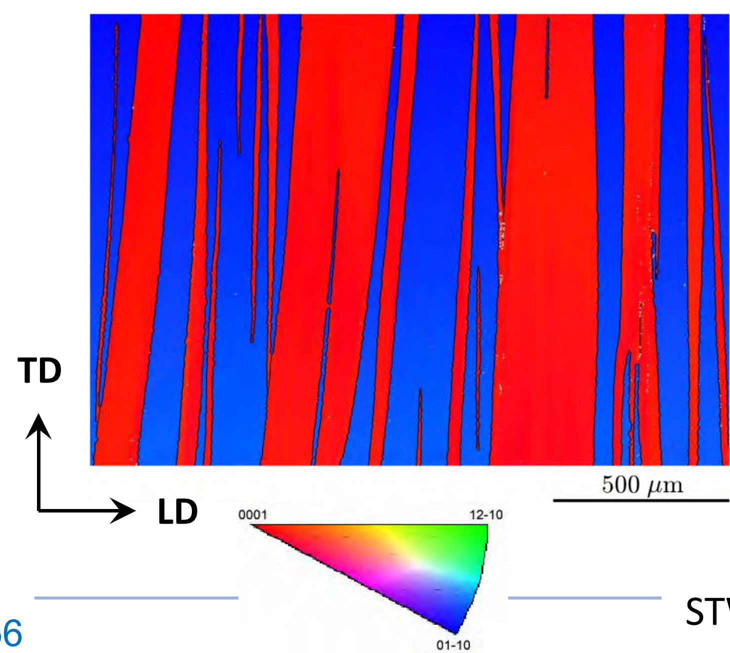
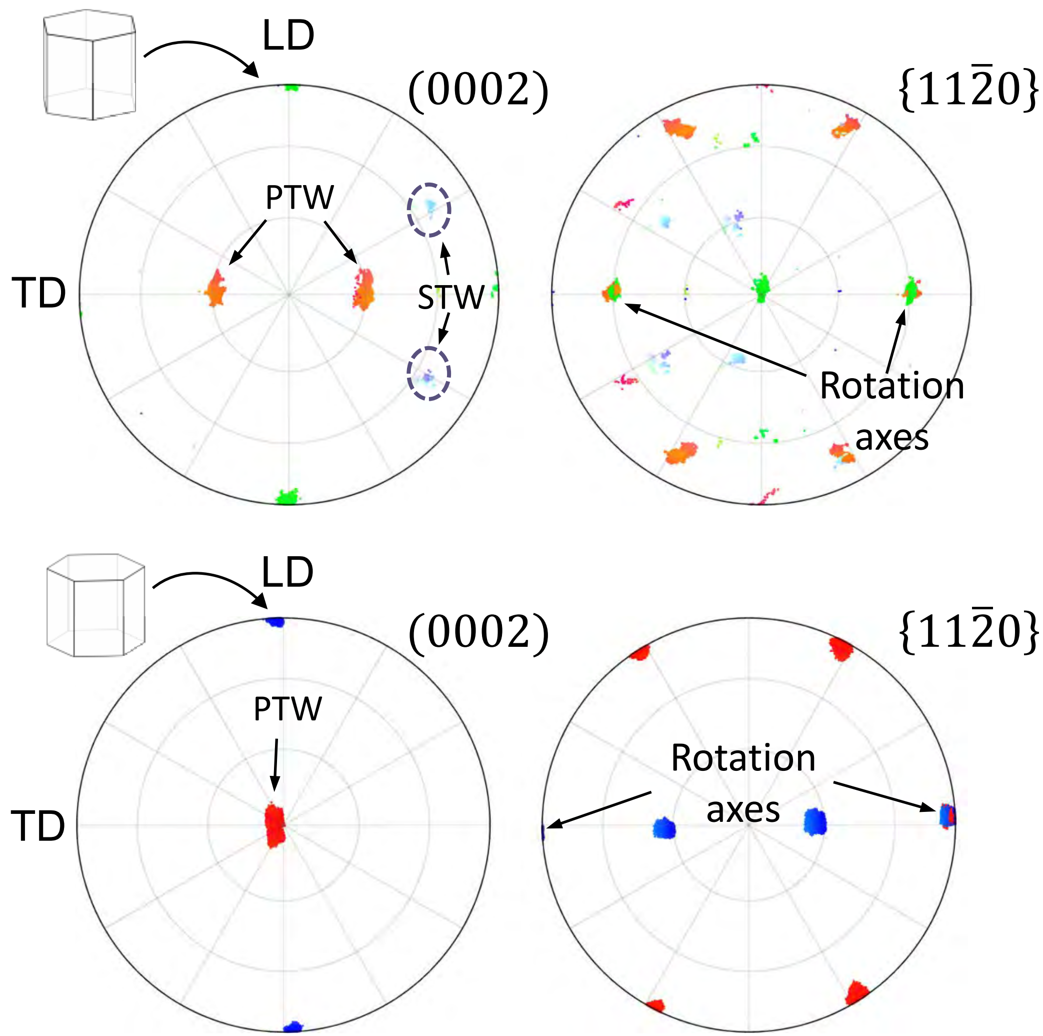
EBSD measurements of samples B and C at 3% strain

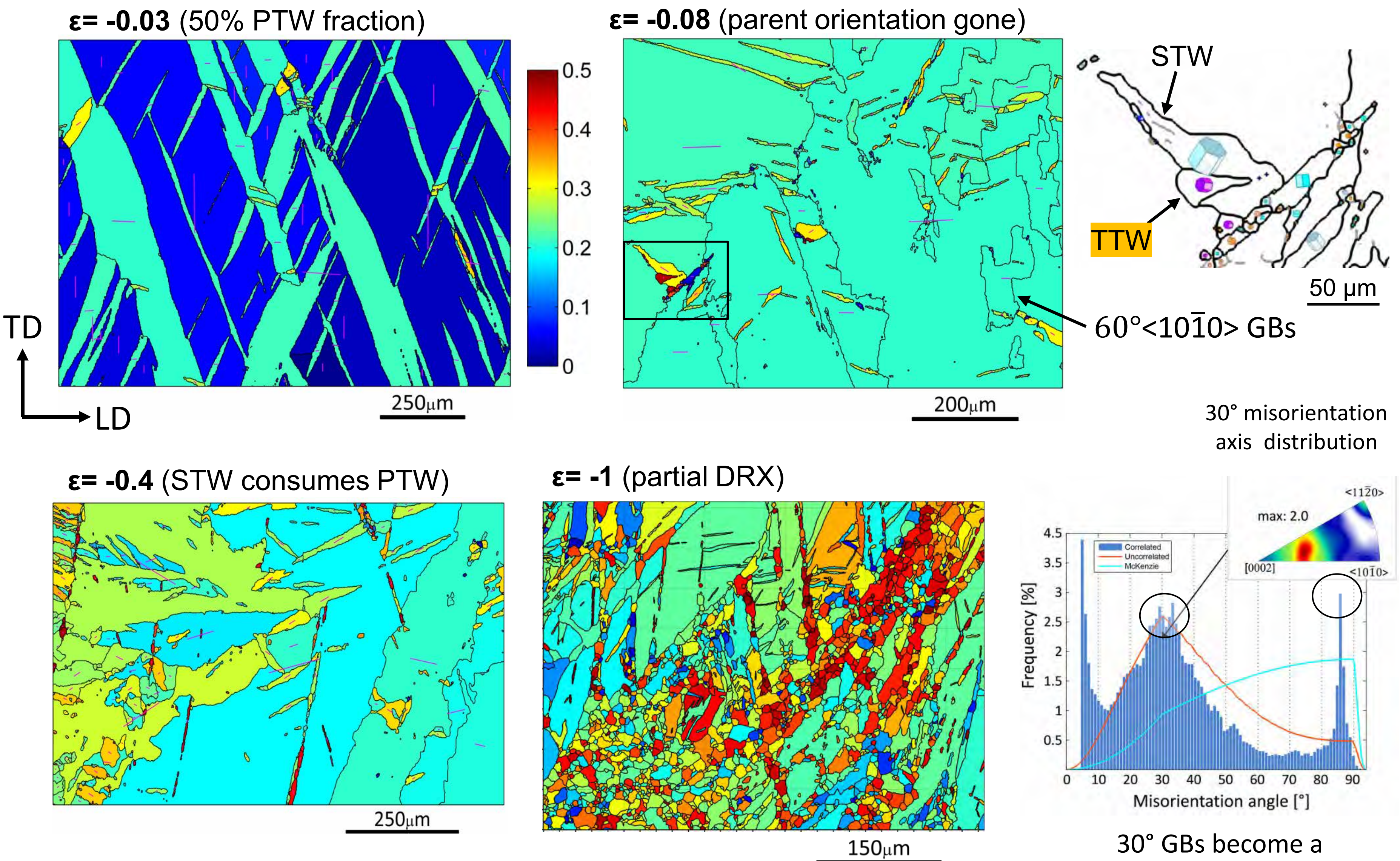






PTW: Primary twins (hard and soft orientations)
STW: Secondary twins at twin-twin intersections (soft orientations)

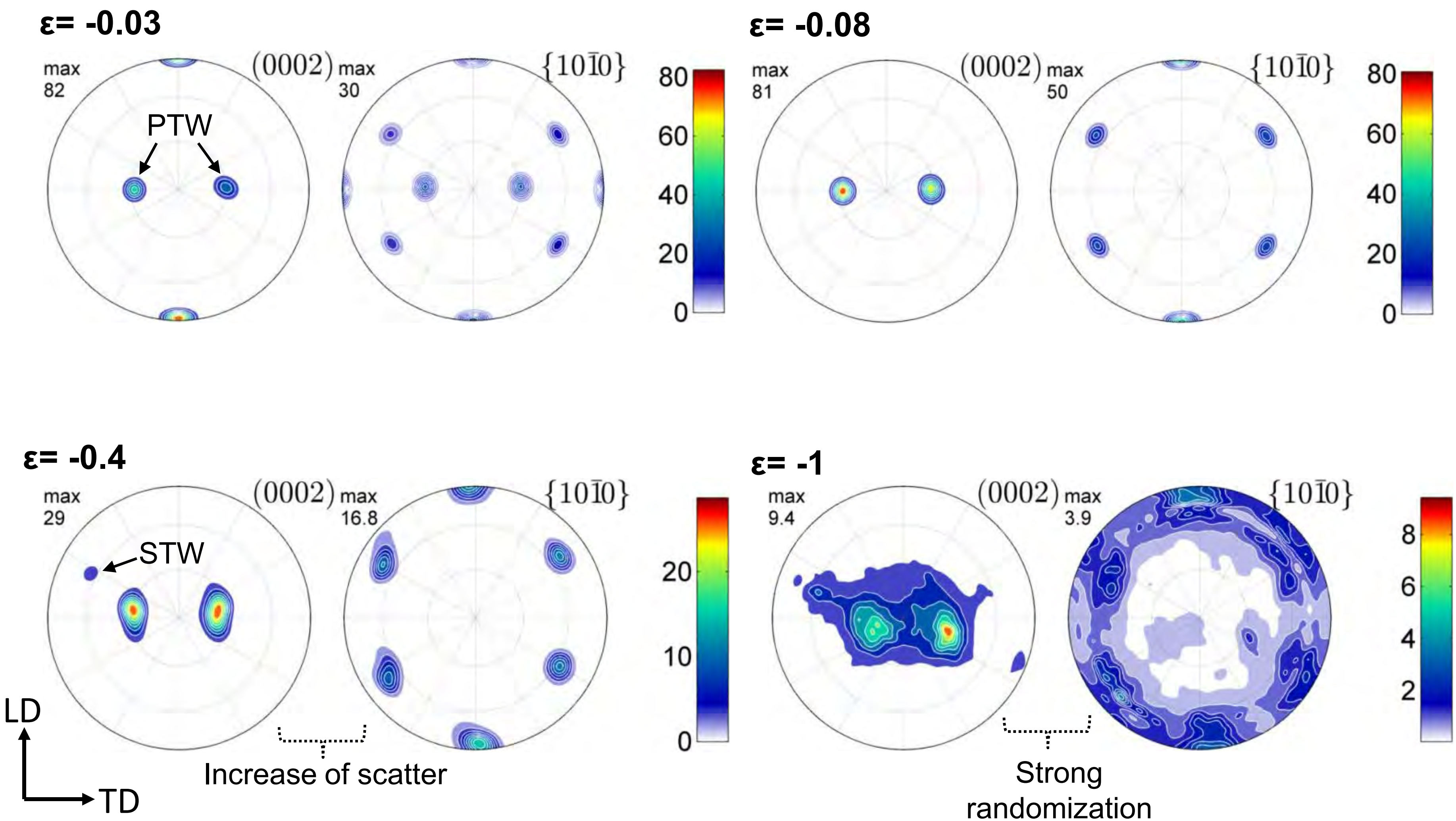
EBSDs (SF maps basal-slip) of sample C at various strains



30° GBs become a feature of the ODF

Note the increase in SF for basal slip with increasing strain

XRD texture development during deformation



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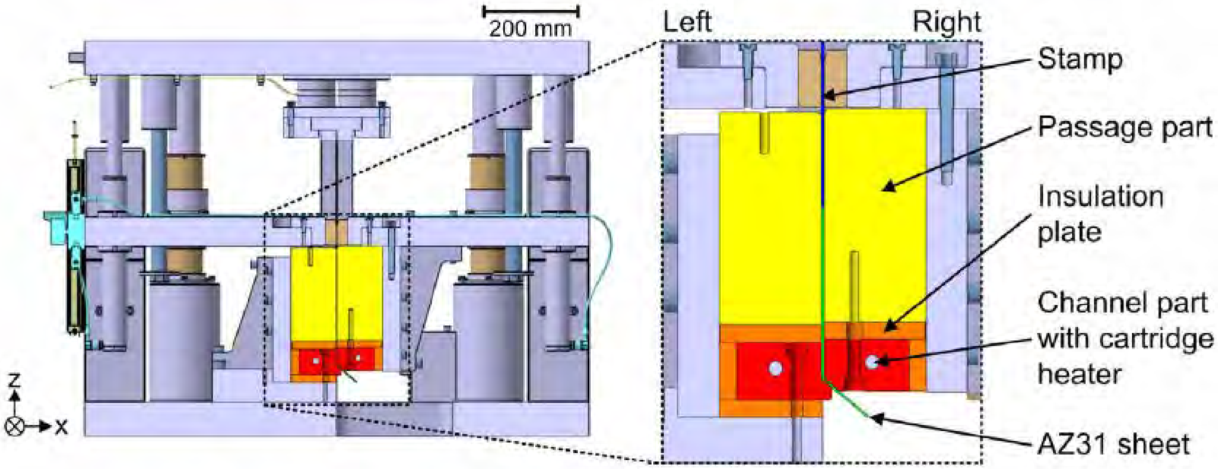
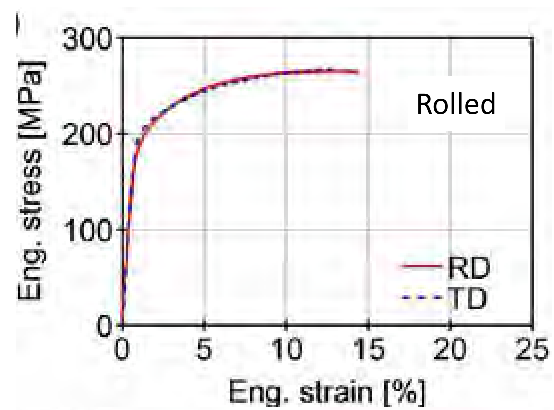
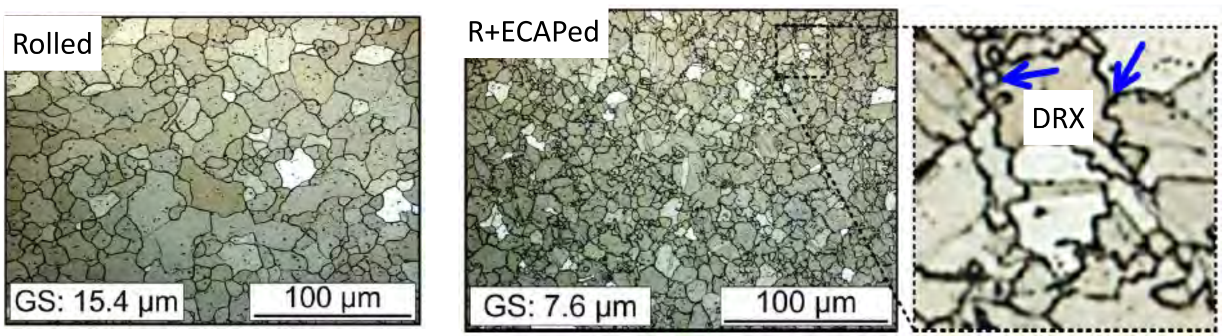
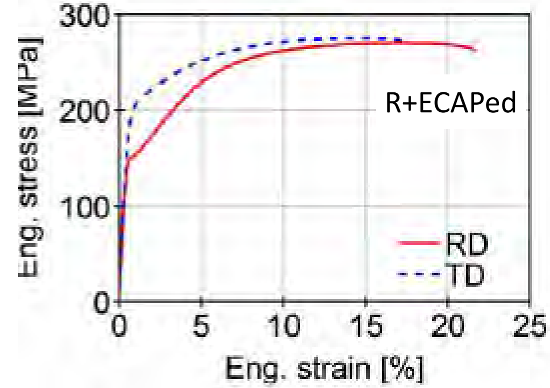
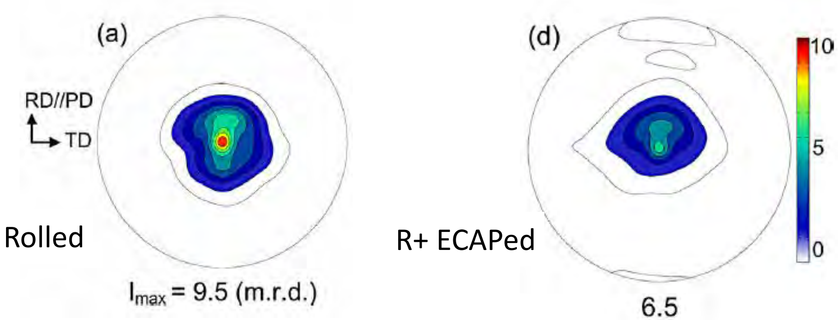
Design of new processes to weaken the texture

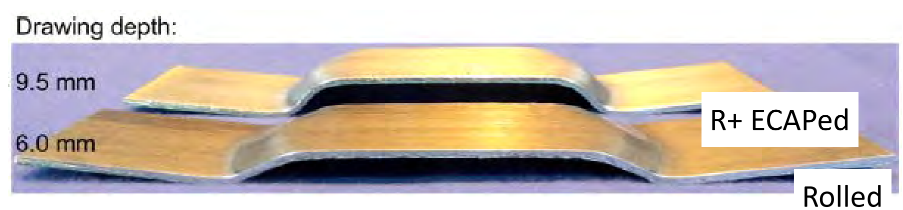






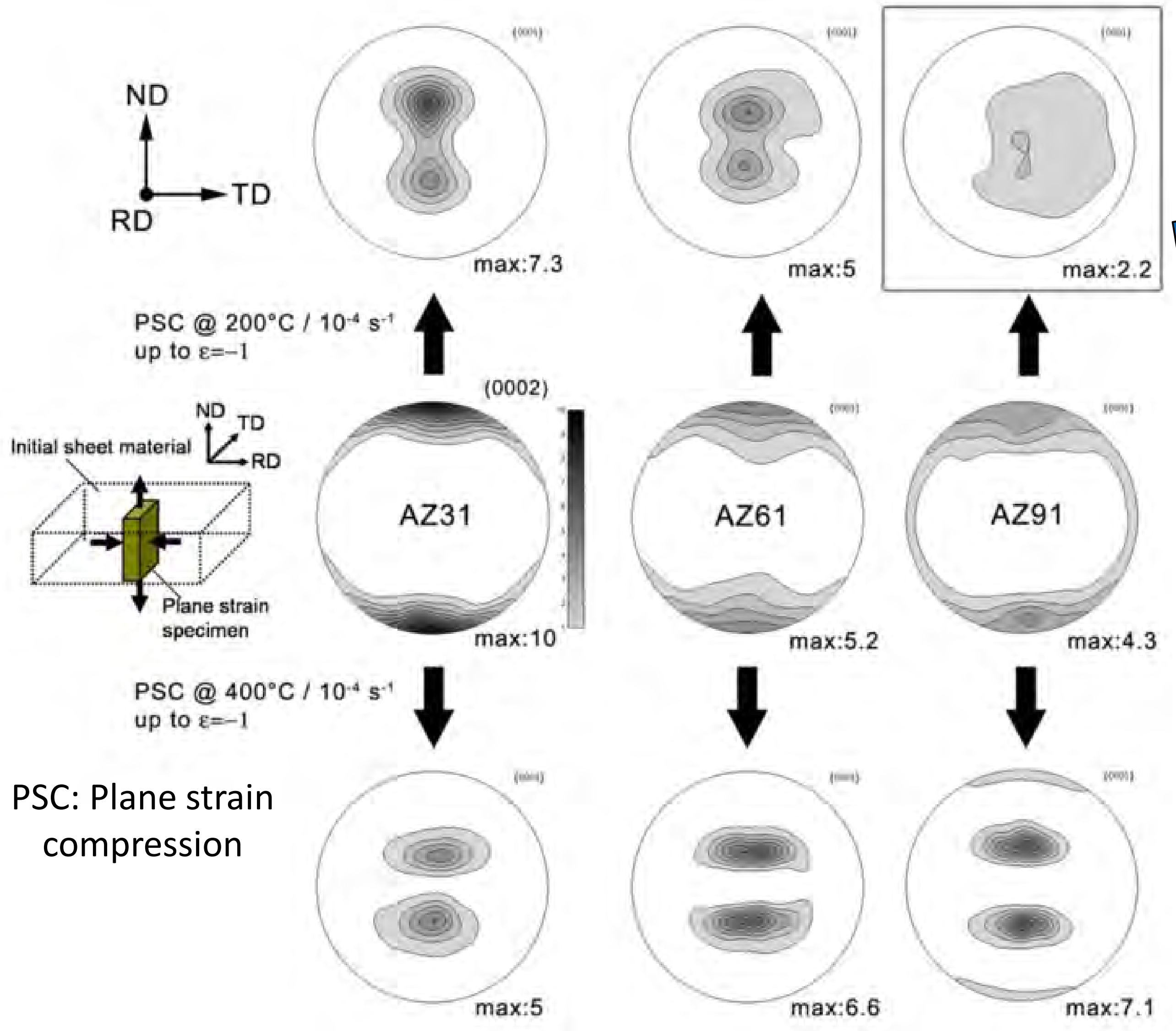






J. Suh et al., Journal of Materials Processing Technology 217 (2015) 286–293

Mg alloy design: influence of Al-content in AZ alloys



PSC textures at 200°C

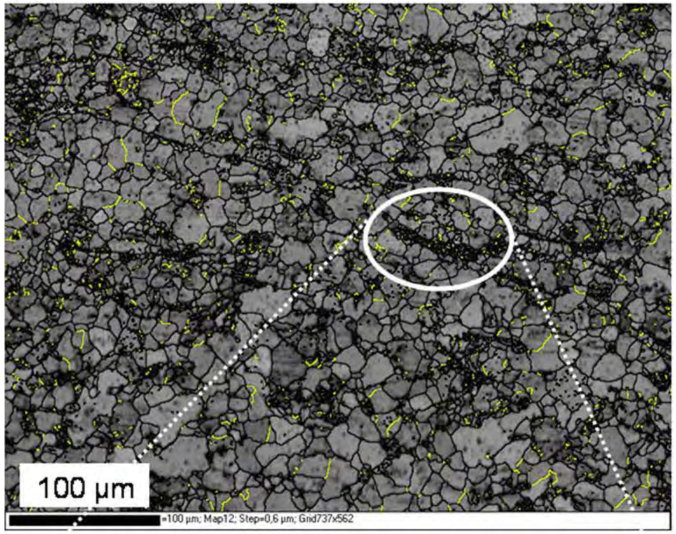
Texture randomization

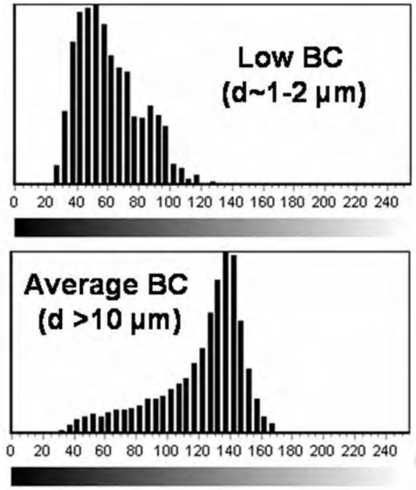
Initial textures

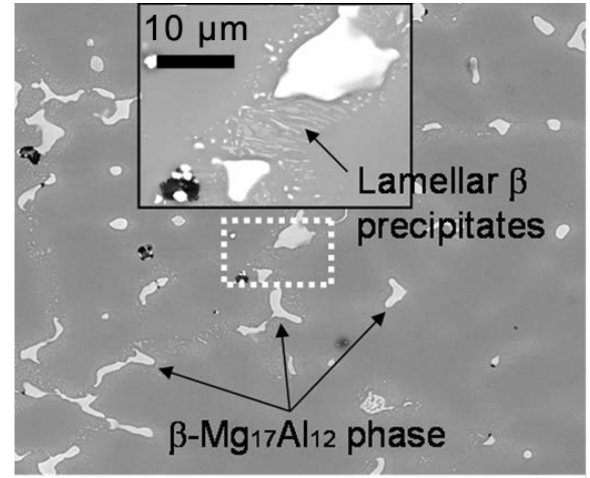
PSC textures at 400°C

PSC: Plane strain compression

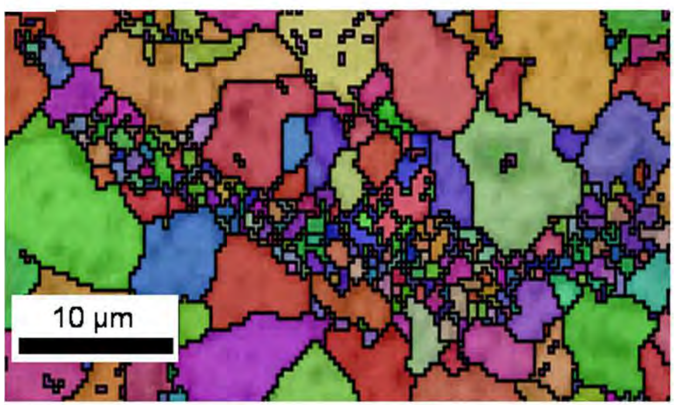
Mg alloy design: influence of Al-content in AZ alloys

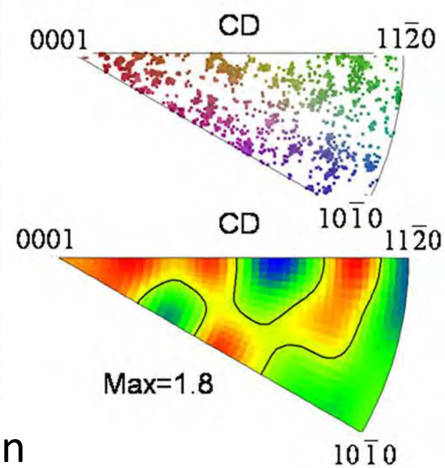






Particle size and distribution in the AZ91 alloy promote PSN of DRX at 200°C. This mechanism lead to texture weakening

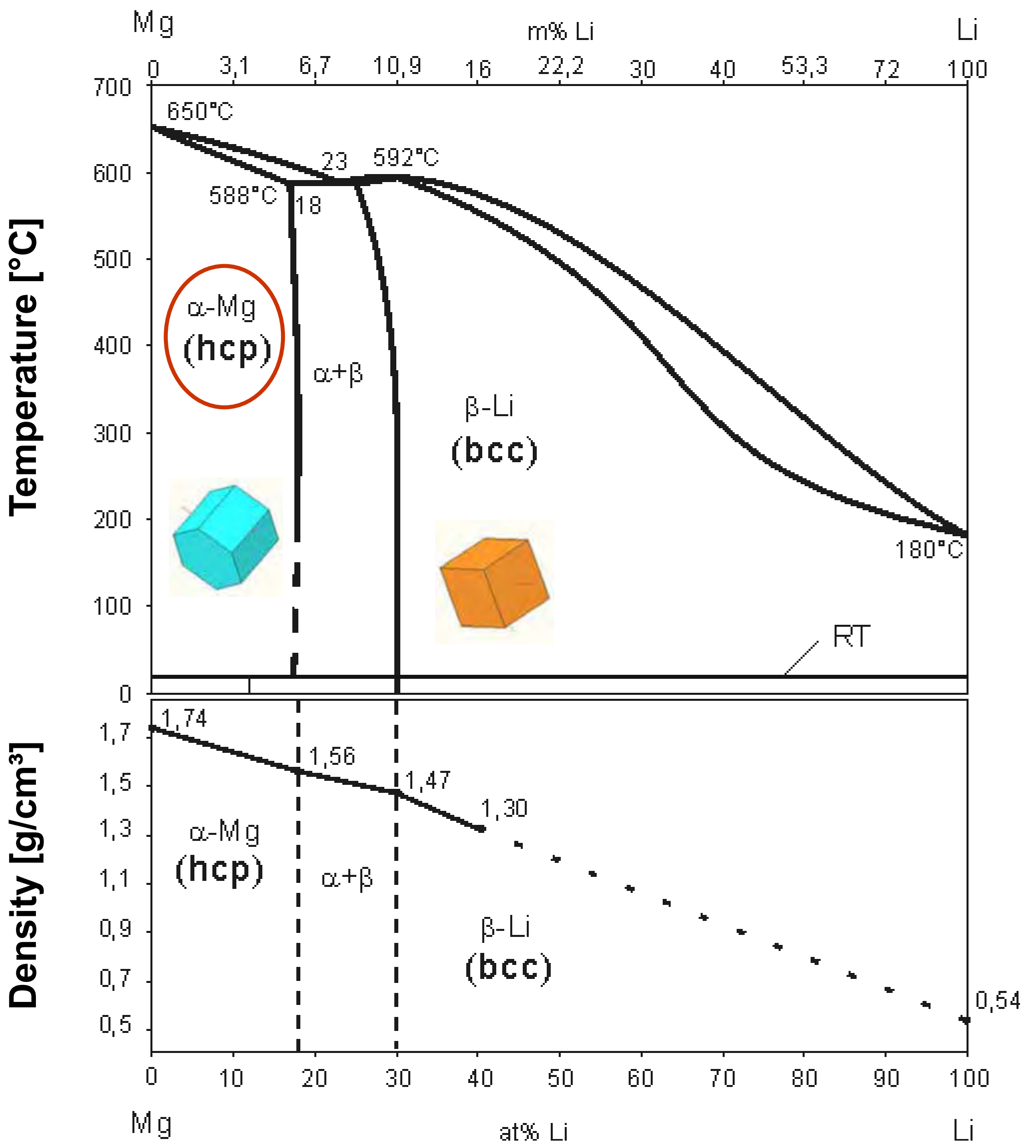




PSN: Particle Stimulated Nucleation

At 400°C the particles are dissolved in the matrix and the PSN effect is removed

Mg alloy design: Li addition

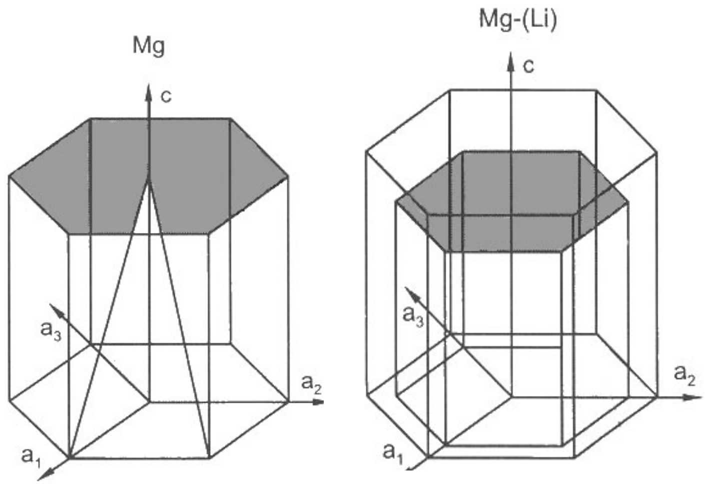


Effects of Li alloying

- **Change of crystal structure**
- **Further decrease of density**

Focus on hexagonal alloys

- **Reasonable production efforts and price**
- **Reduction of *c/a* ratio**
- **Excellent formability**

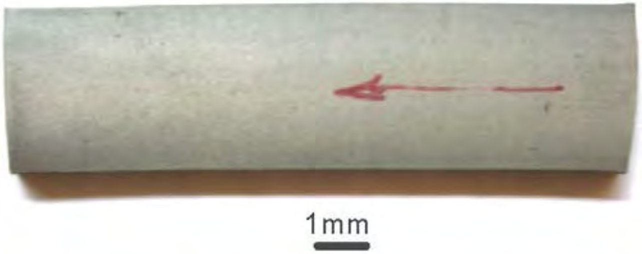


Pure Mg
c/a = 1.624

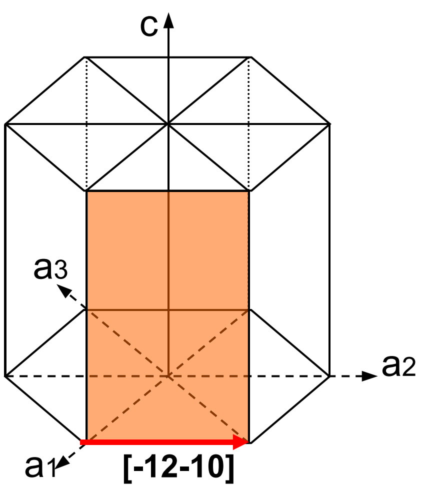
Mg- 17at.% Li
c/a = 1.607

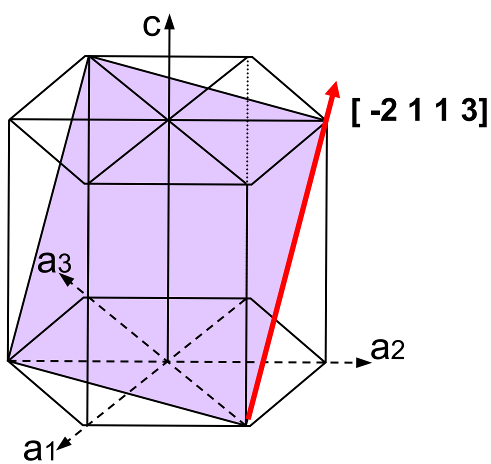
Mg alloy design: Li addition

Mg4Li (26% reduction)



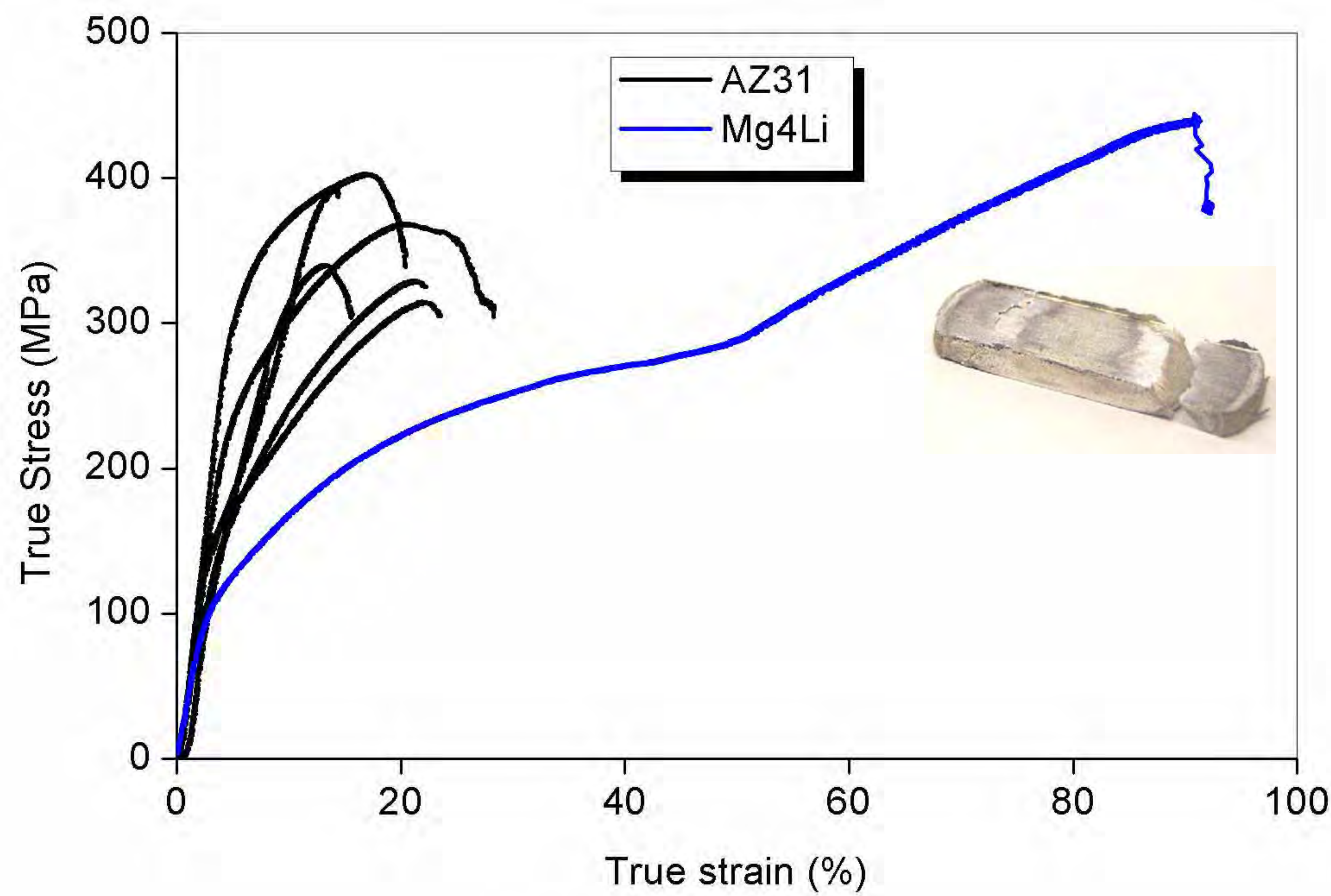
AZ31 (26% reduction)
Sample failed !



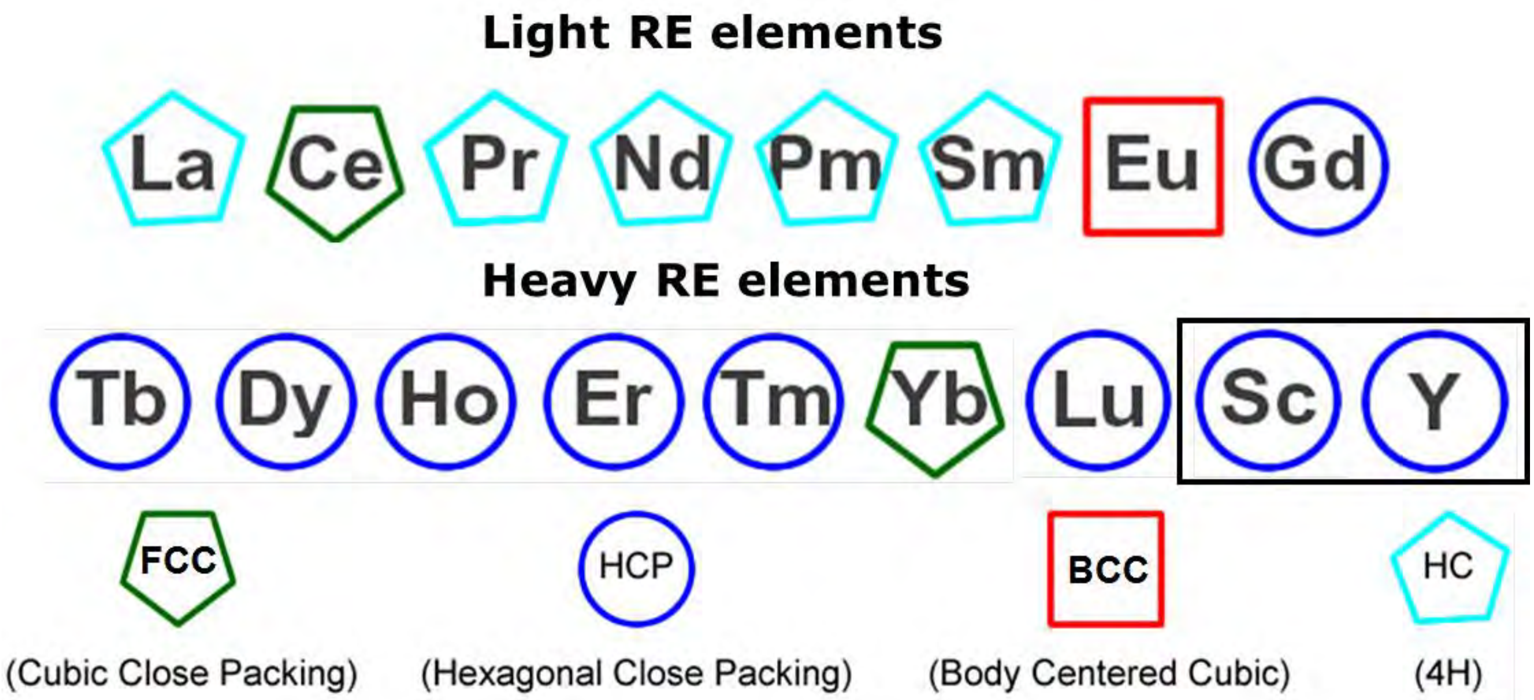


Texture measurements, TEM investigations and plasticity simulations show activation of prismatic and <c+a>-slip even at low temperatures

Mg alloy design: Li addition



Mg alloy design: Rare Earth (RE) addition

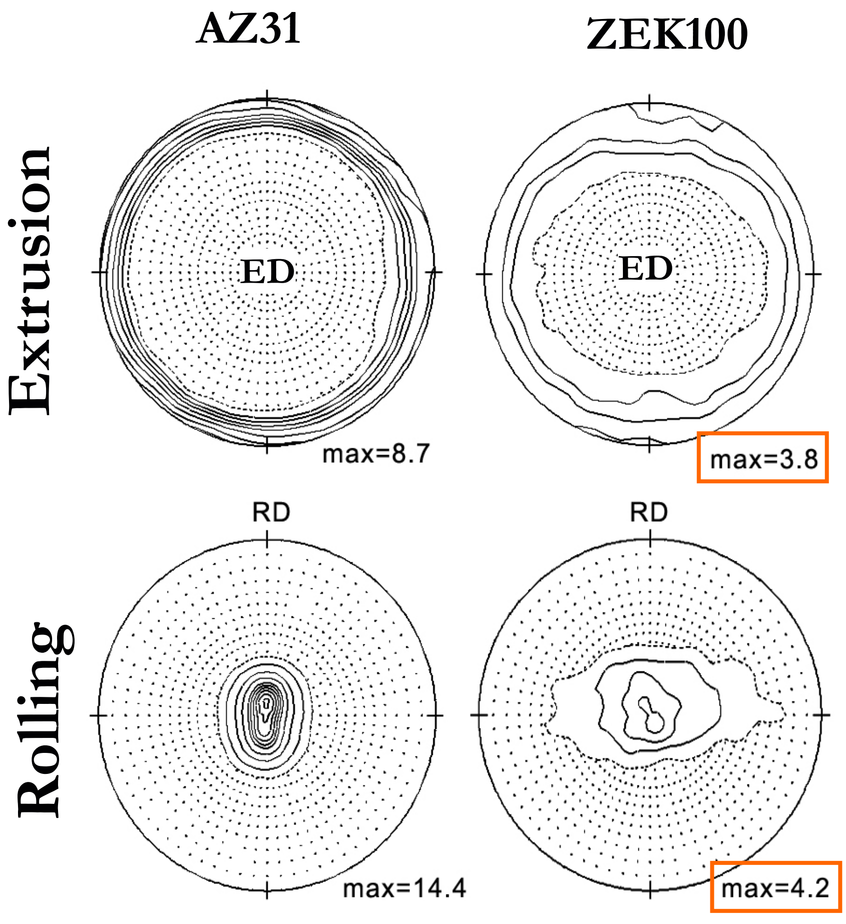


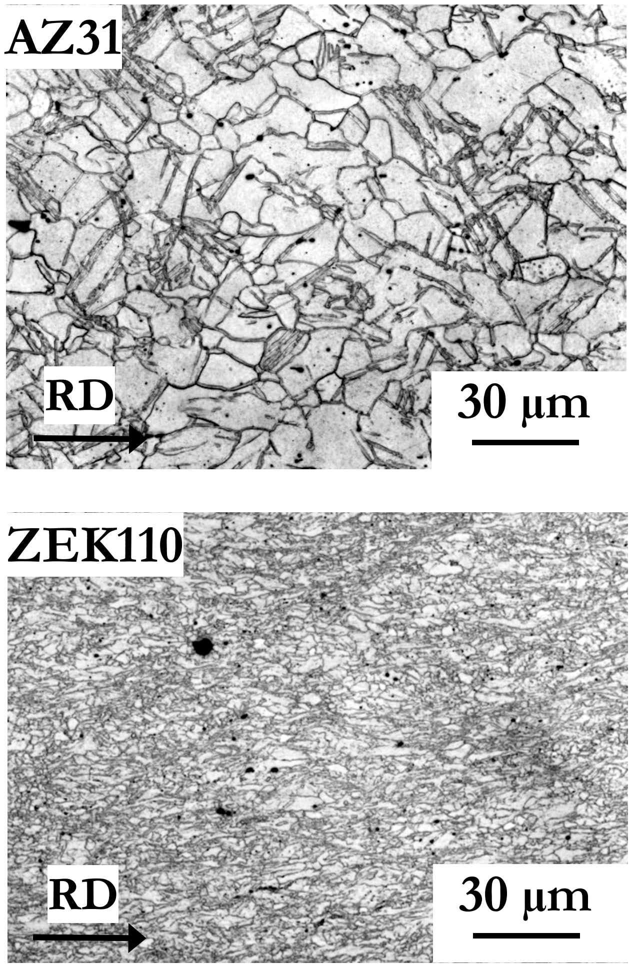
- Strategische Elemente
- Ziemlich teuer

- Größere Atomradien als Mg
- Unterschiedliche Löslichkeiten in Mg

- SE werden oft in der Community als „Magic Elements“ bezeichnet
- Großes Verbesserungspotenzials vieler Eigenschaften (Festigkeit, Duktilität, Anisotropie, Korrosion, Kriechbeständigkeit, etc.)

Mg alloy design: Addition of RE-Mischmetal





Rolled sheet and extruded bars of the ZEK100 alloy posses both a weak texture and a finer grain size

Mg alloy design: Addition of RE-Mischmetal

AZ31

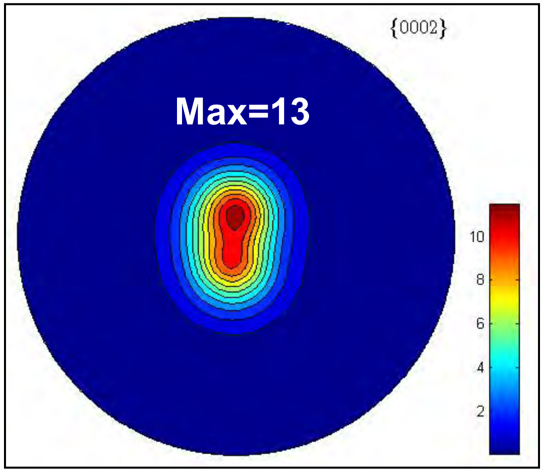
ZEK100

➡ ZEK alloys show improved cold rolling response

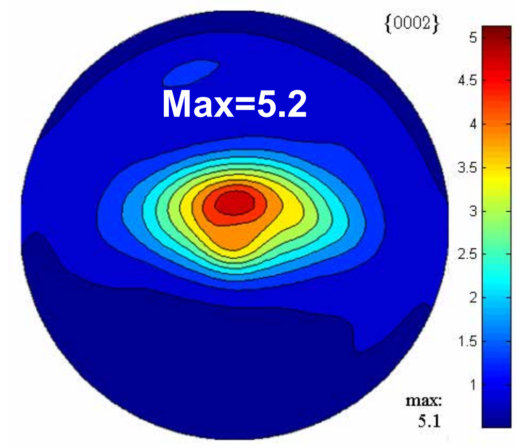
Courtesy of Dirk Bormann – IW Hannover

Mg alloy design: Addition of individual RE elements

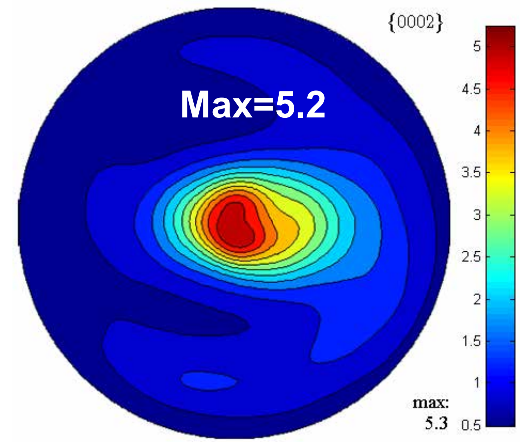
ZK10 (standard alloy)



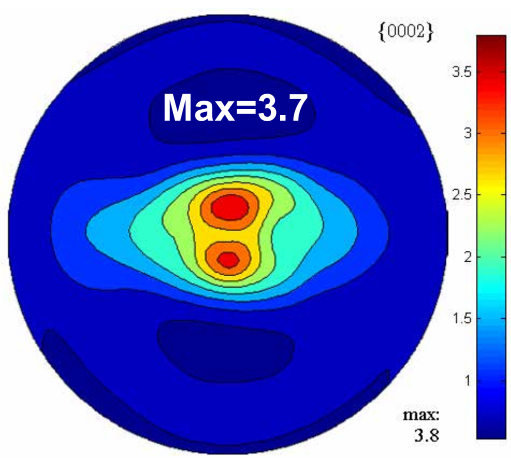
ZK10 + 1% MM



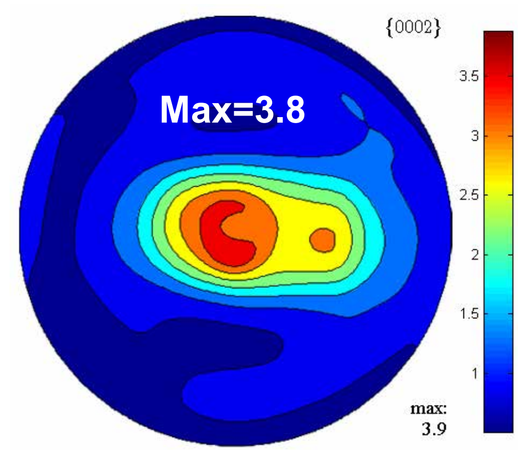
ZK10 + 1% La



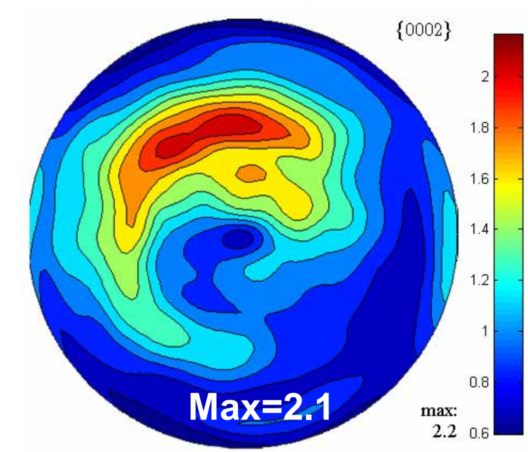
ZK10 + 1% Ce



ZK10 + 1% Nd

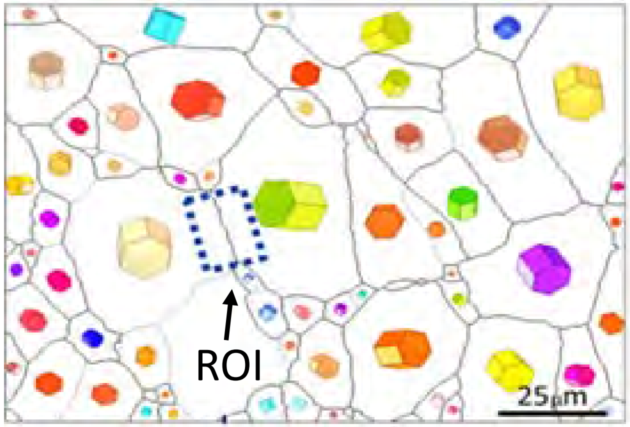


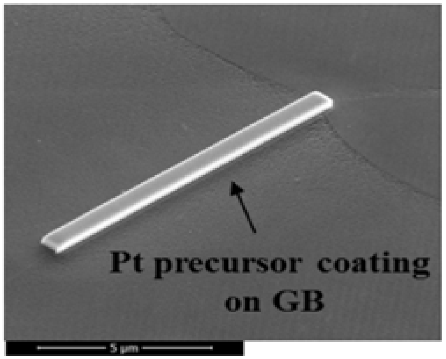
ZK10 + 1% Gd

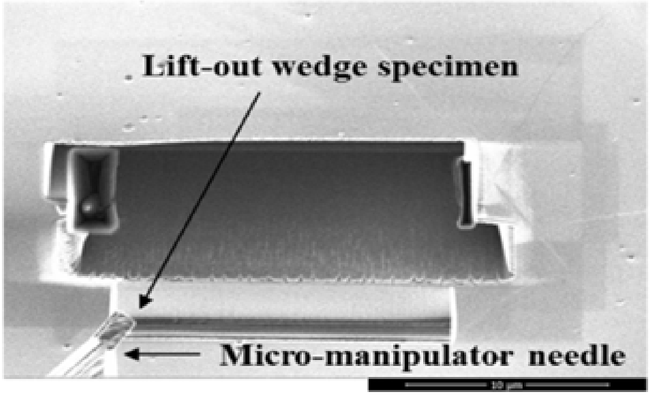


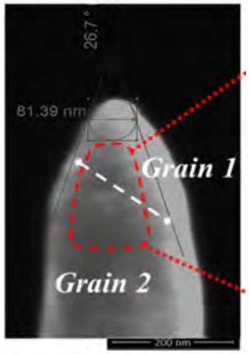
Hot rolled at 400°C to 75% reduction then annealed at 400°C for 1h

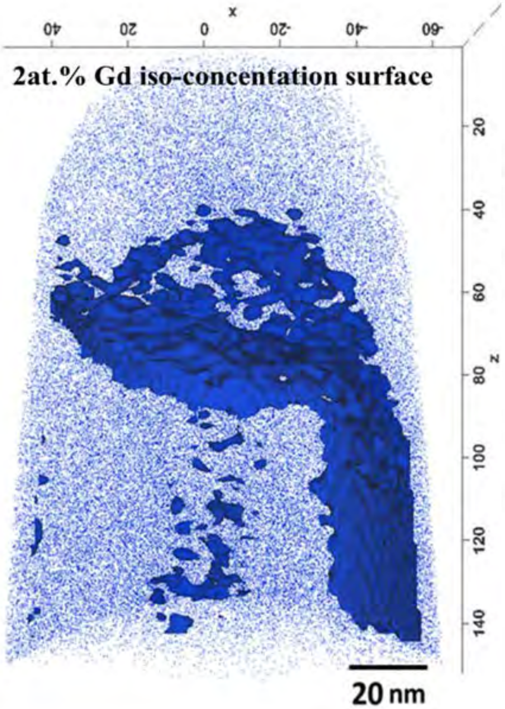
GB segregation of solute REs: 3D atom probe tomography

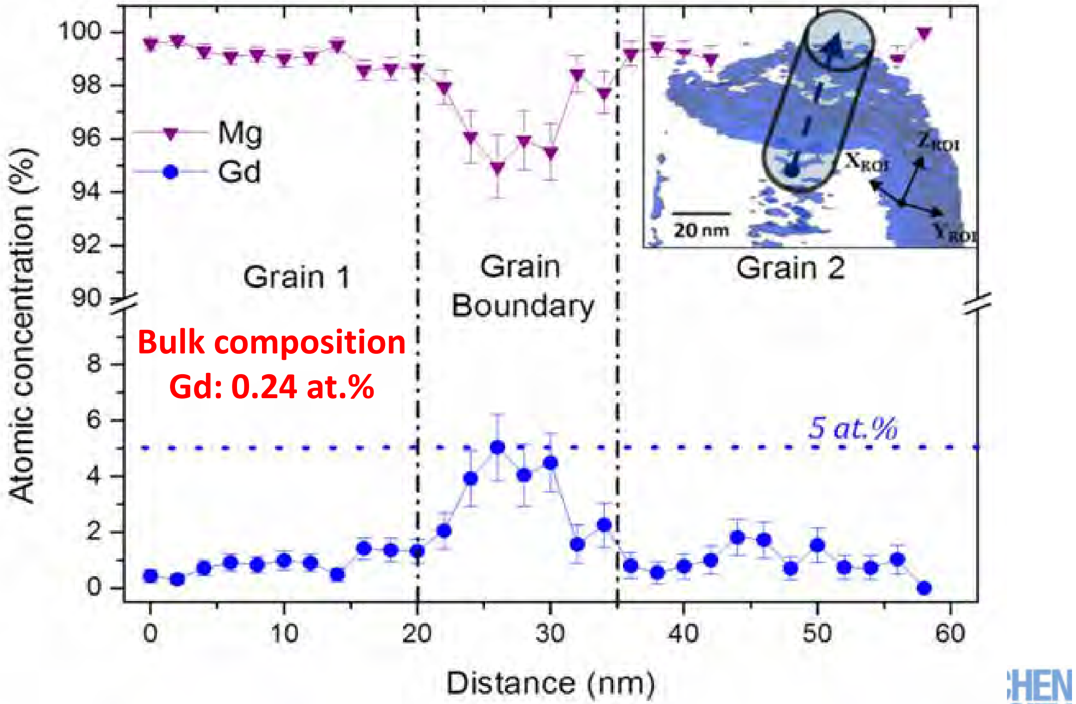




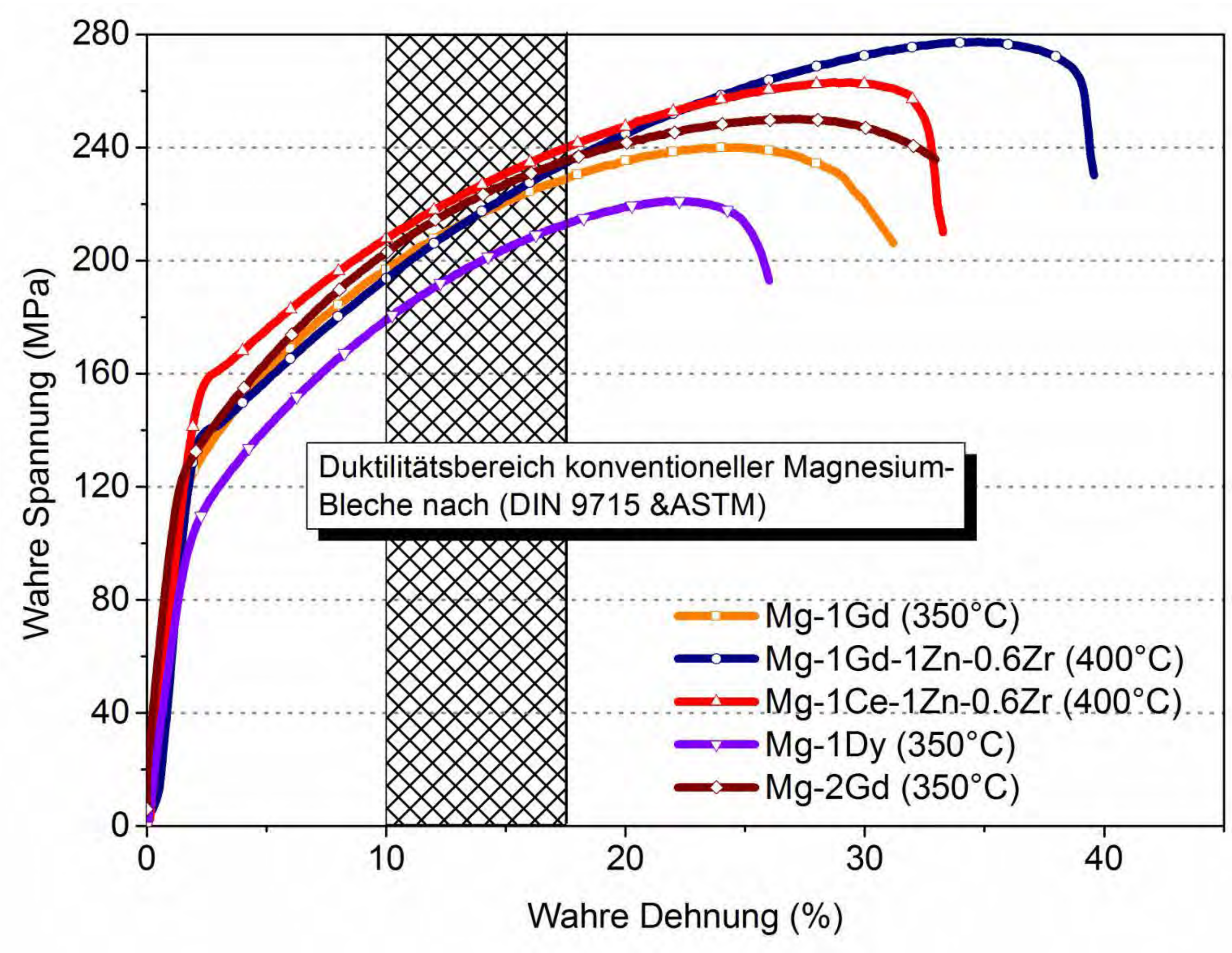






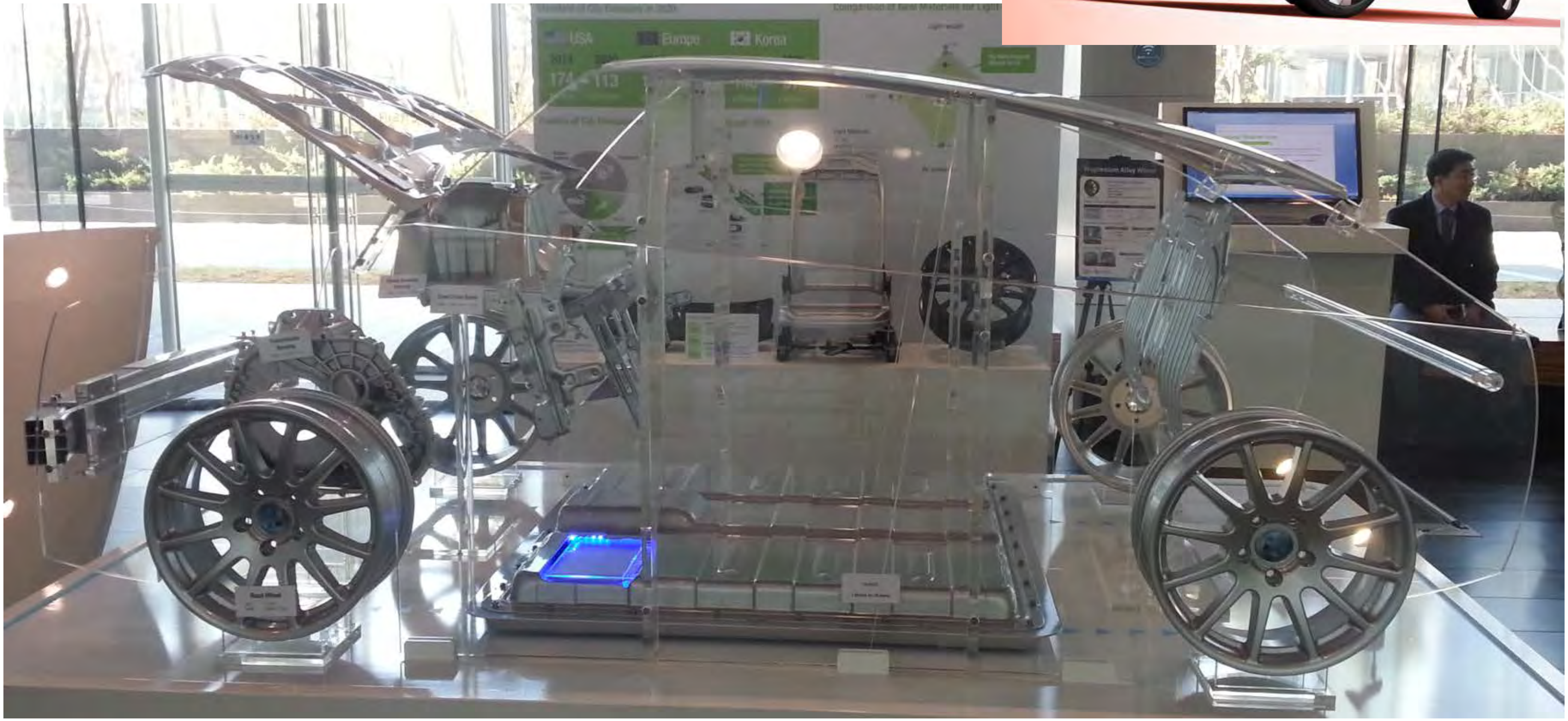


Superior mechanical properties of Mg-RE alloys



POSCO's research program: Mg in every mobile

Renault Eolab



Global POSCO EVI Forum 2014

Thank you for your kind attention…

For a complete list of publications you can visit http://orcid.org/0000-0002-2900-0827