Karlsruhe Institute of Technology

Institute for Applied Materials

Plasticity

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

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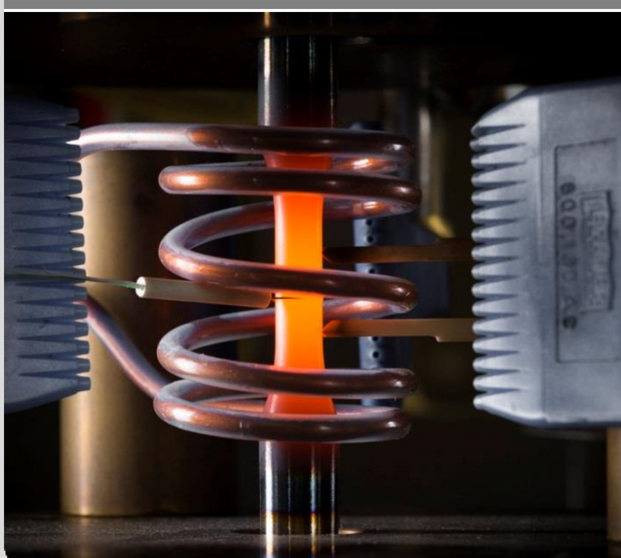
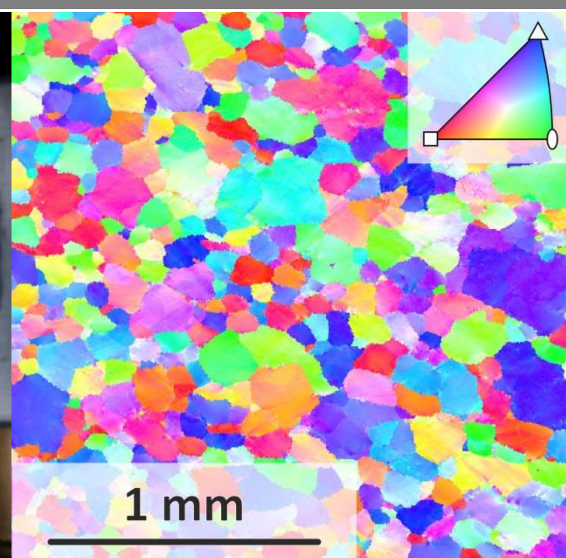
Institute for Applied Materials (IAM-WK)



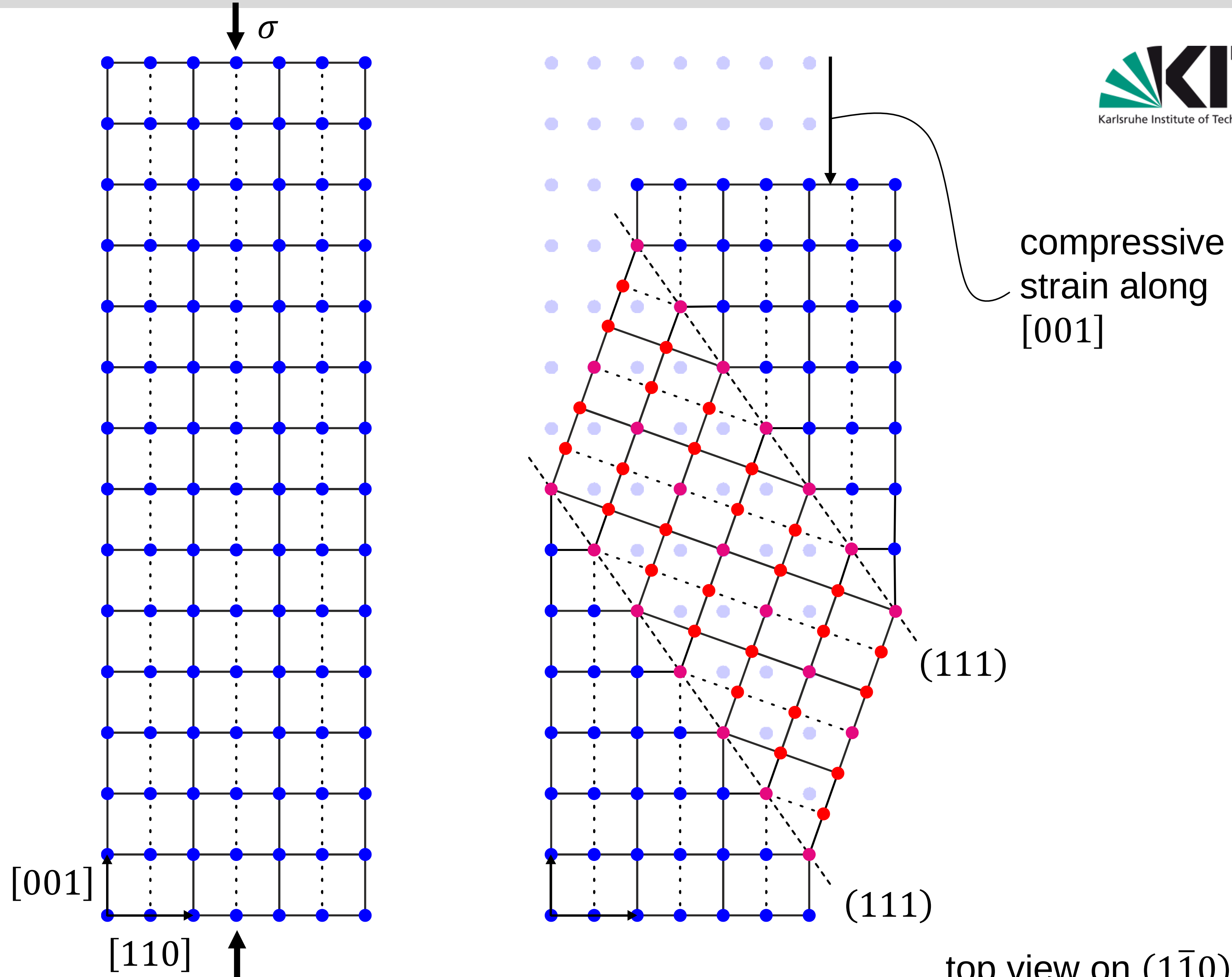


Topics

- Other mechanisms of plastic deformation
  - Deformation Twinning
    - fcc A1 and TWIP
    - Other Crystal Structures
  - Martensite Formation (TRIP)

Deformation Twinning (fcc A1)

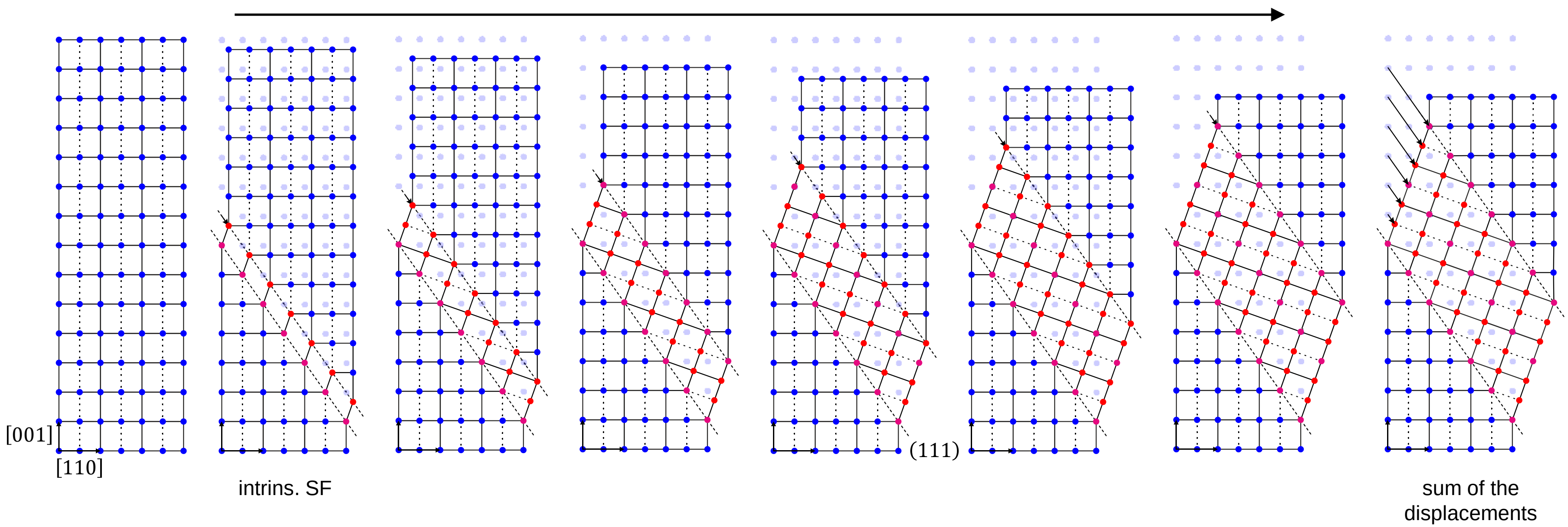
- The shear by twinning occurs within $\{1\bar{1}0\}$ **along** $\langle 11\bar{2}\rangle$. The twin system is usually denoted with $\{111\}\langle 11\bar{2}\rangle$ (habit or composition plane and shear direction). The magnitude of the shear is $^{1}/_{\sqrt{2}} = {}^{\sqrt{2}}/_{2}$.


σ
[001]
[110]
compressive
strain along
[001]
(111)
(111)
top view on $(1\bar{1}0)$

Deformation Twinning (fcc A1)

- **Deformation twinning in metals of high symmetry is not a sudden homogeneous shear process.** It still involves dislocation activity, but glide of partial dislocations!

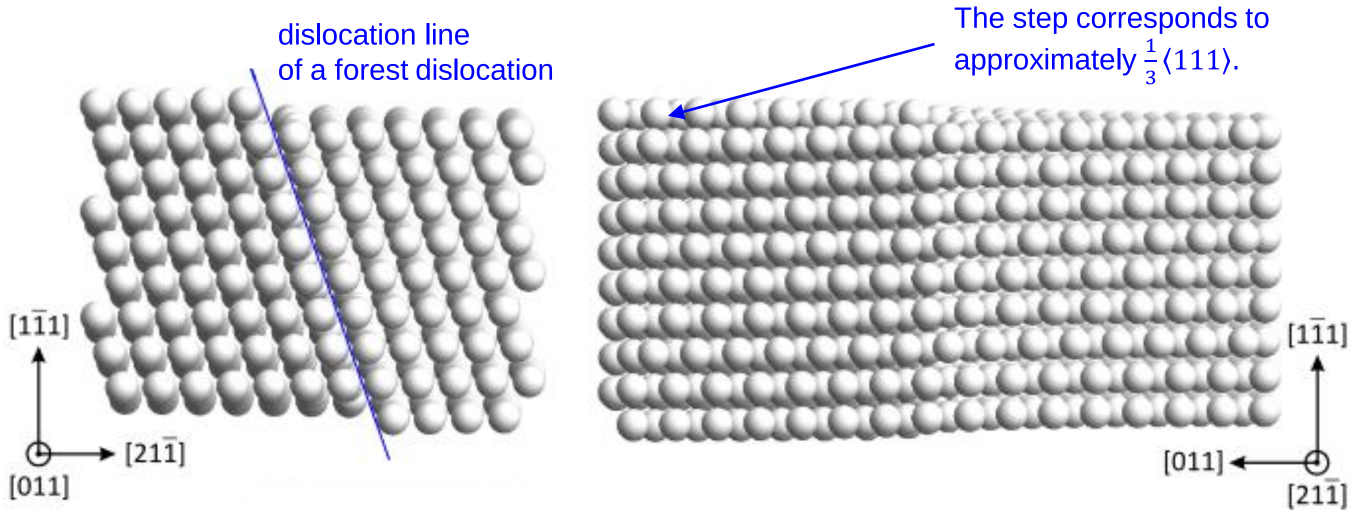
glide of Shockley partials $\frac{1}{6}[11\bar{2}]$ on consecutive slip planes



top view on $(1\bar{1}0)$

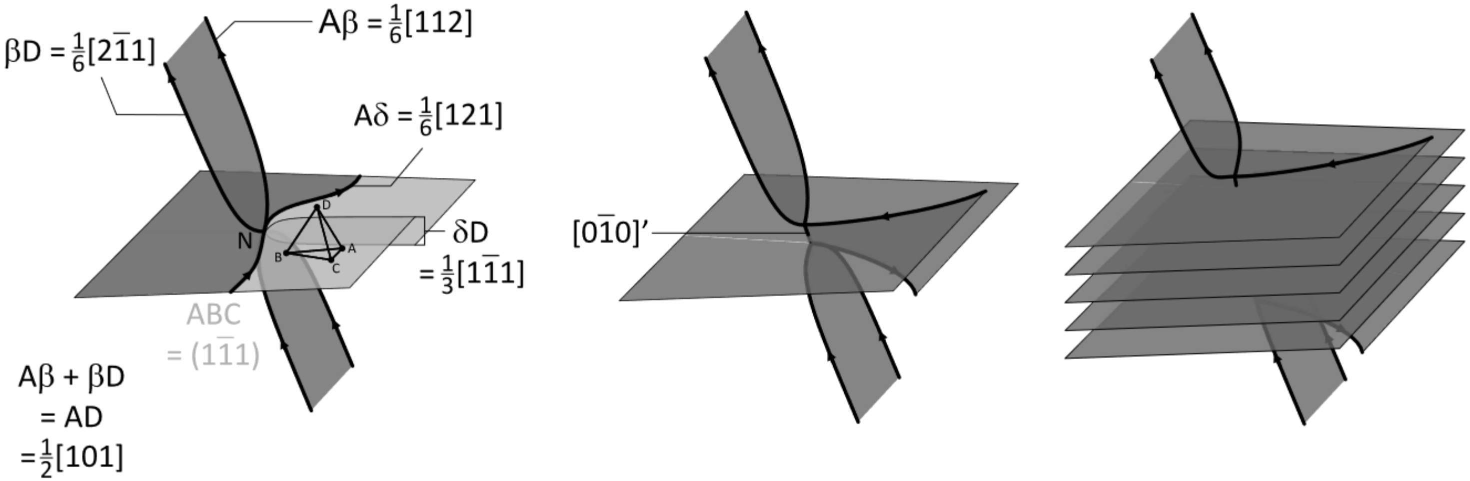
Deformation Twinning (fcc A1)

- It needs to be answered, how a lot of individual Shockley partials can slip on consecutive slip planes.
- Several mechanisms exists that rely on forest dislocations that mediate a rotation motion of a Shockley partial dislocation with automatic change of the slip plane. This results in only one Shockley producing the twin.
- An important issue is that a mixed forest dislocation in fcc A1 metals alloys mediates a screw-like deformation of the primary slip plane:



Deformation Twinning (fcc A1)

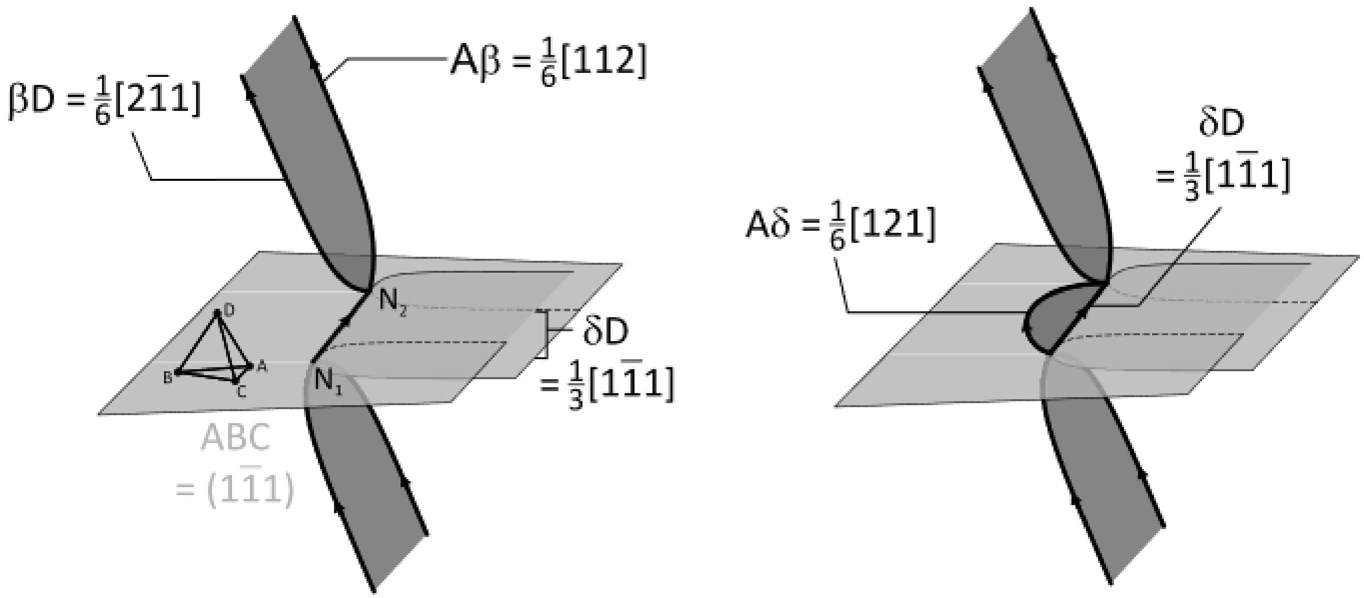
- A primary Shockley partial dislocation can start to rotate around the forest dislocation leaving stacked stacking faults behind by every revolution in between a change of the slip plane occurs:



- Since stacking faults are produced on every consecutive slip plane, the crystal portion between the Shockley partials corresponds to a twin orientation.
- Bypass stress of the partial dislocation segments is very high due to close spacing of the segment.

Deformation Twinning (fcc A1)

- An extension of this mechanism is built up from a dissociated slip source. This solves the question where the individual partial dislocation in the mechanism on the previous slide stems from.
- The dissociation occurs in a glissile Shockley partial and a sessile Frank partial: $\frac{1}{2}\langle 101\rangle = \frac{1}{6}\langle 121\rangle + \frac{1}{3}\langle 1\bar{1}1\rangle$



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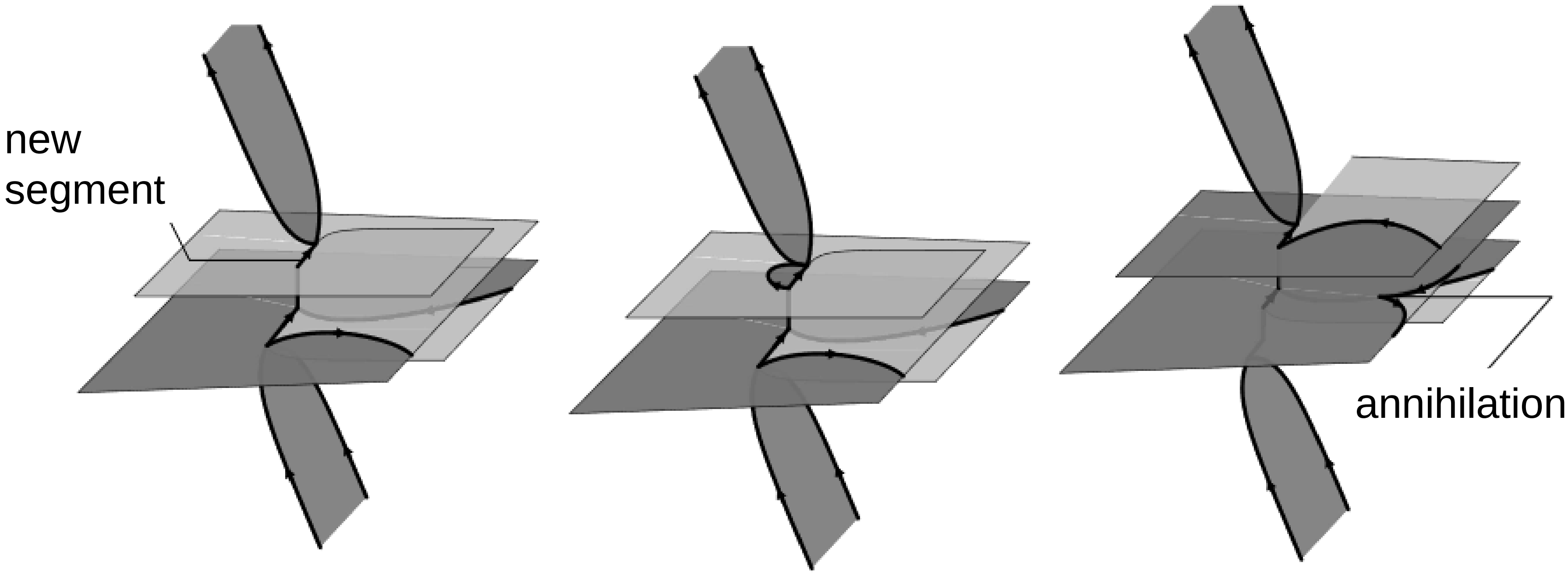
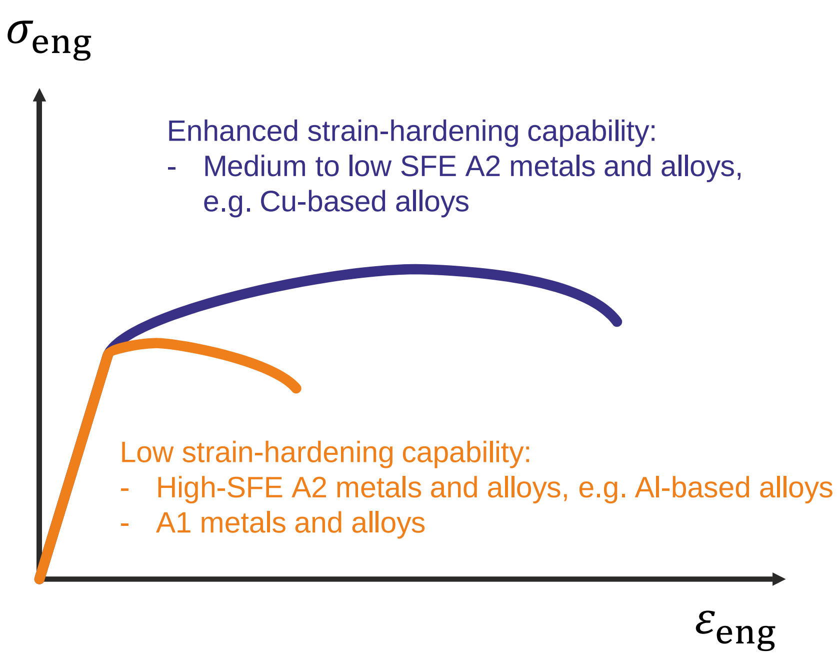
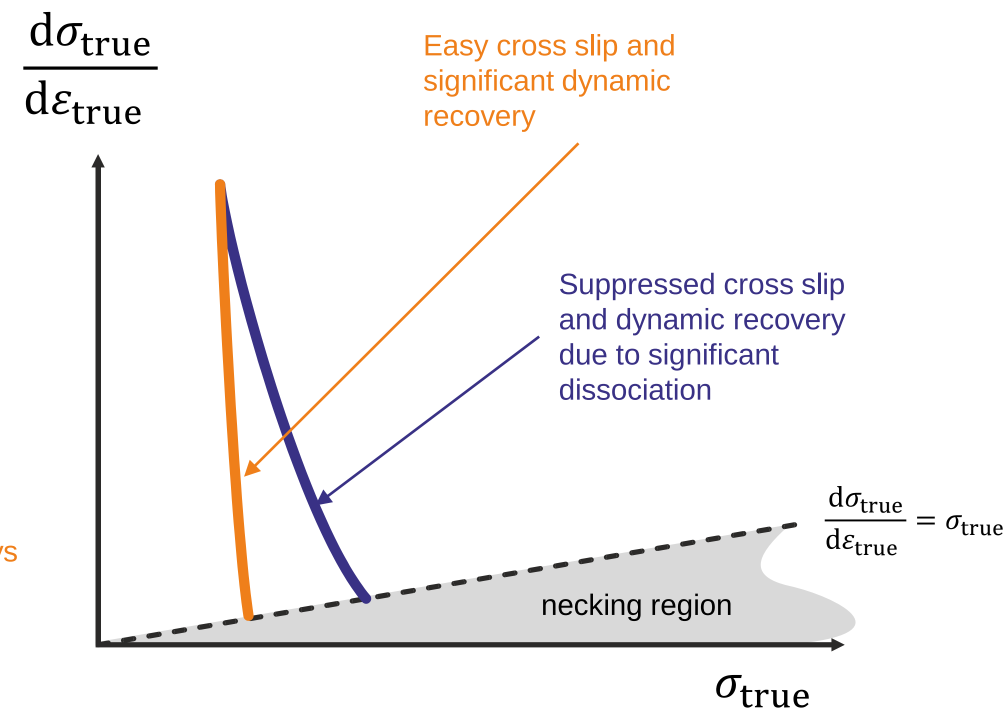


Stress-Strain Behavior of Single-Phase Materials

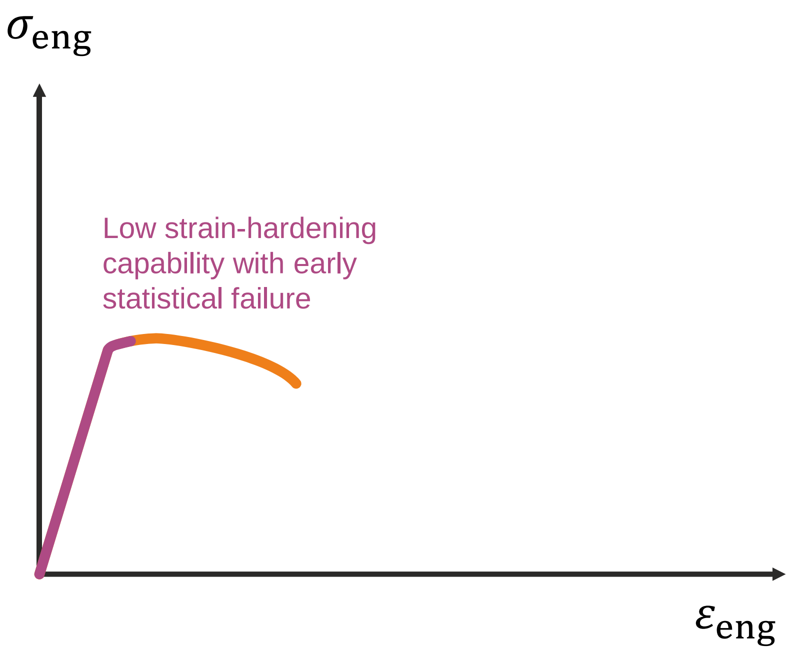
- Depending on the strain-hardening behavior, different types of stress-strain curves might be obtained:

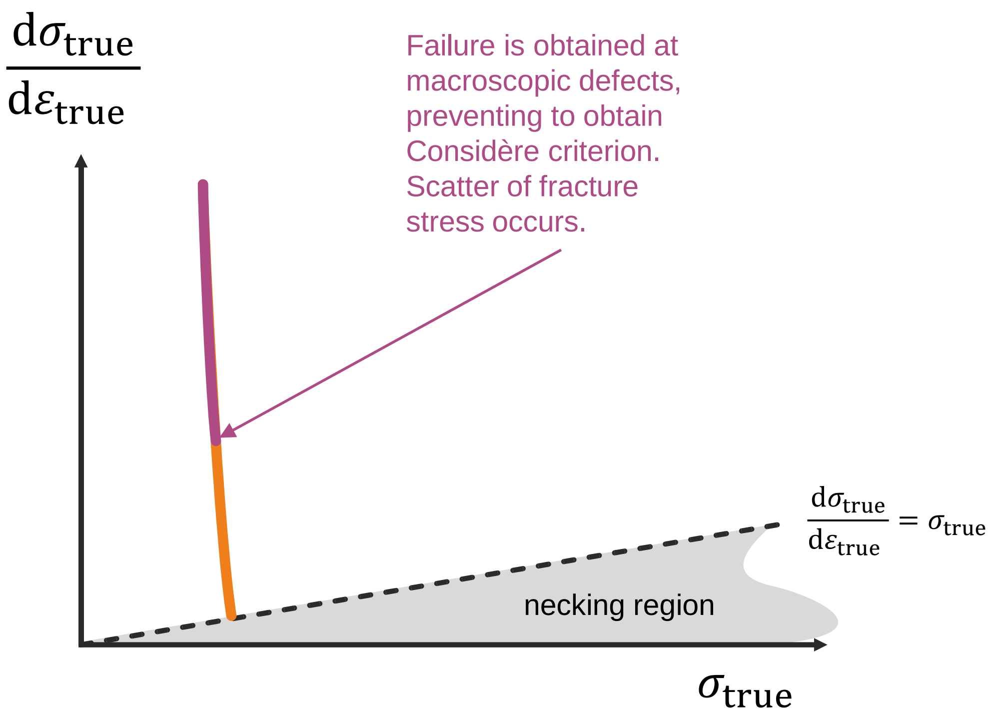




Stress-Strain Behavior of Single-Phase Materials

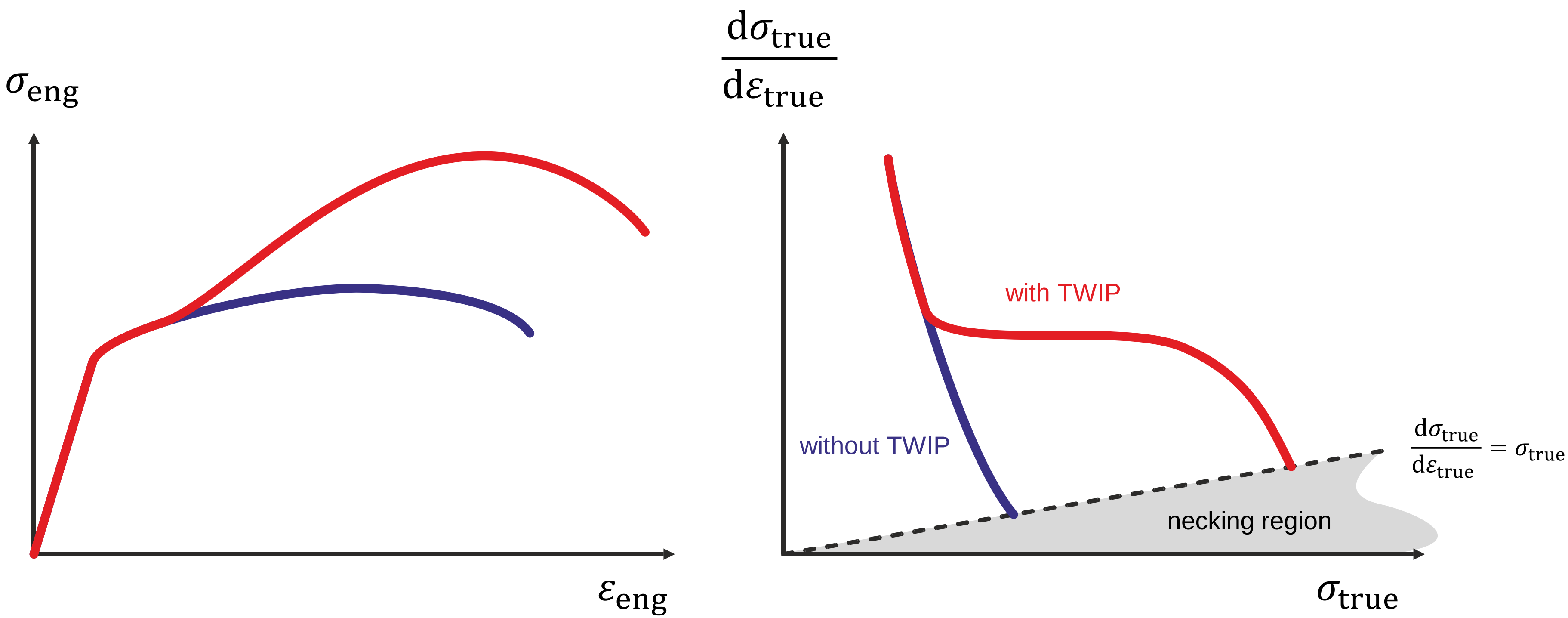
- Low strain-hardening capability might even lead to early failure due to macroscopic defects rather than due to mechanical-geometrical instability:





Twinning Induced Plasticity (TWIP)

- Twinning can be used to tailor the work-hardening behavior of fcc A2 metals alloys and therefore result in significant improvement of workability and ductility:



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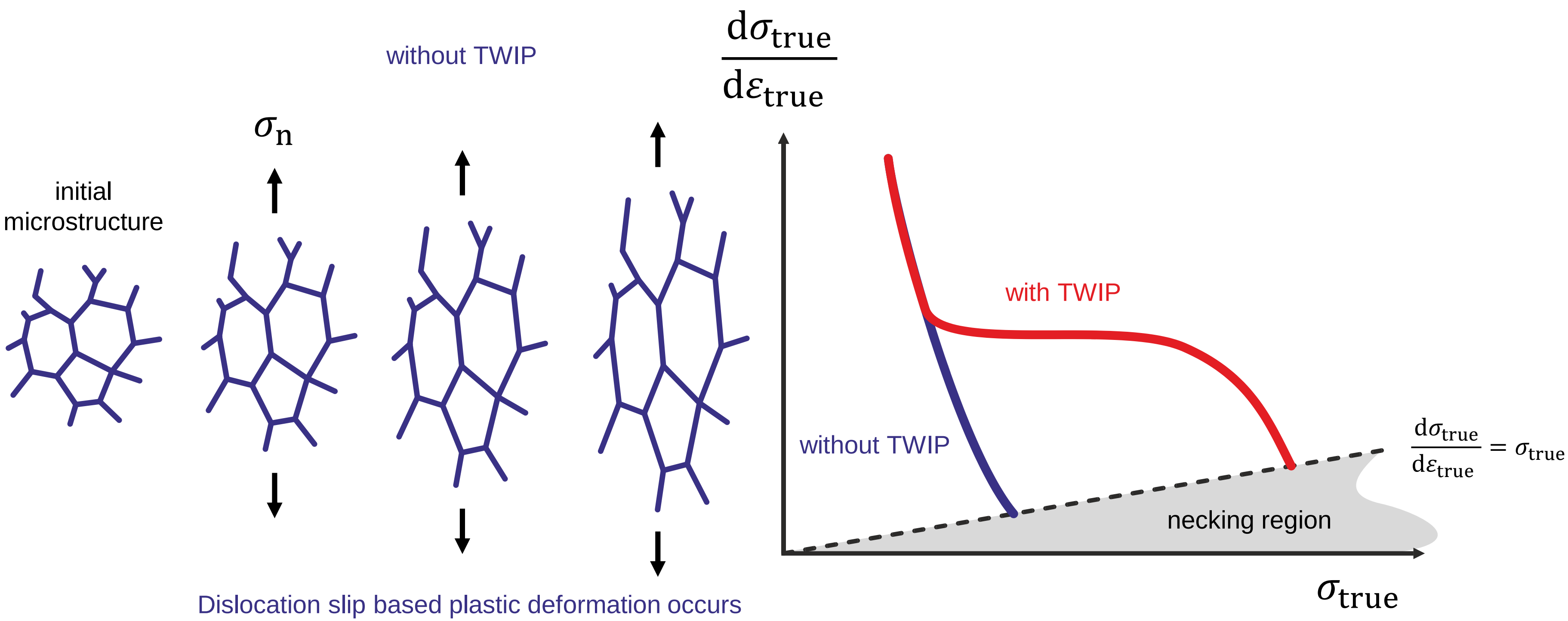

Dislocation slip based plastic deformation occurs with dominance of bypass, intersection and lock interaction dislocations; limitation of strain-hardening by dynamic recovery.

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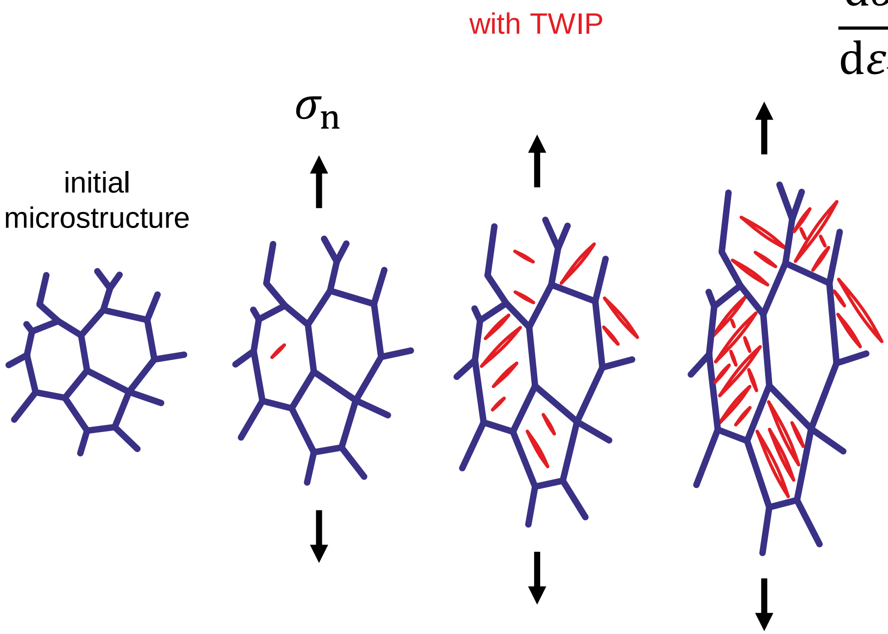
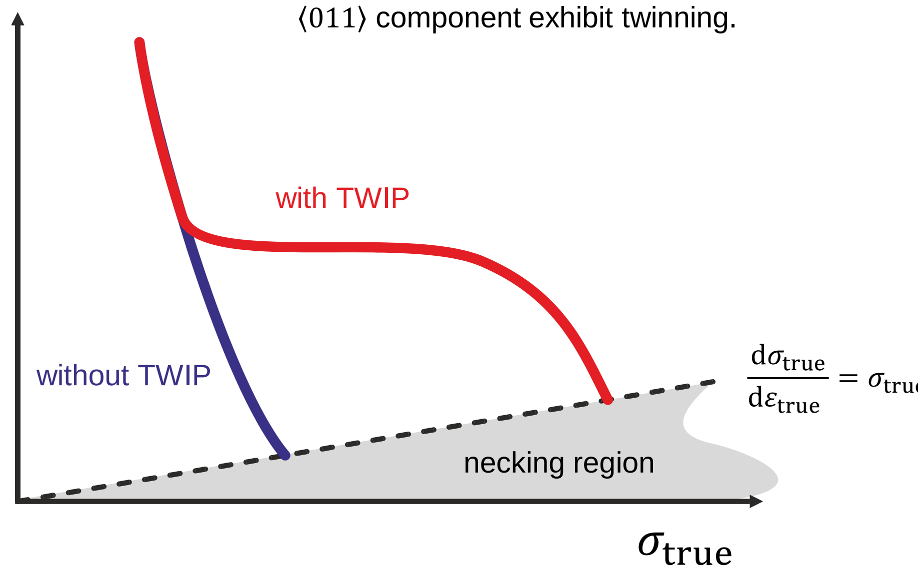


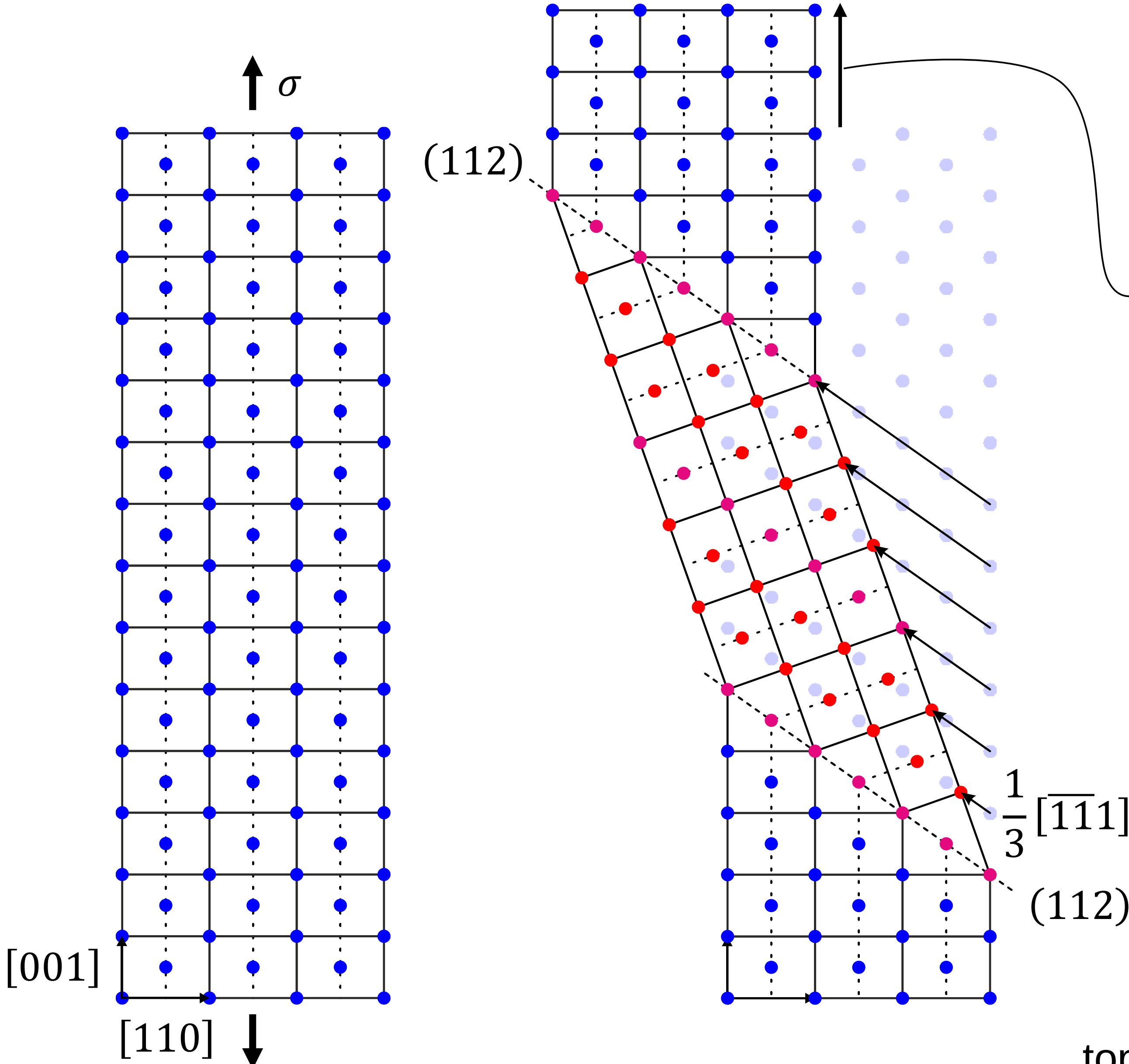
Onset of deformation twinning leads to dynamic refinement of the microstructure (deformation twin boundaries are high angle grain boundaries) and, hence, dynamic strengthening of the material.

Note that not all grains can undergo twinning. In tension, the dominant $\langle 111 \rangle$ fiber fraction possess twinning, the minor $\langle 001 \rangle$ remains untwinned. In compression, the $\langle 001 \rangle$ and the $\langle 011 \rangle$ component exhibit twinning.



Deformation Twinning (bcc A2)

- The shear by twinning occurs within $\{121\}$ **along** $\langle 1\bar{1}1\rangle$. The twin system is usually denoted with $\{121\}\langle 1\bar{1}1\rangle$ (habit or composition plane and shear direction). The magnitude of the shear is ${}^{1}/_{\sqrt{2}} = {}^{\sqrt{2}}/_{2}$.
- Due to the strong geometrical similarity to fcc A2, information about twinning can be transferred between the structures. The orientation dependence of activation is for example exactly opposite to fcc A2.



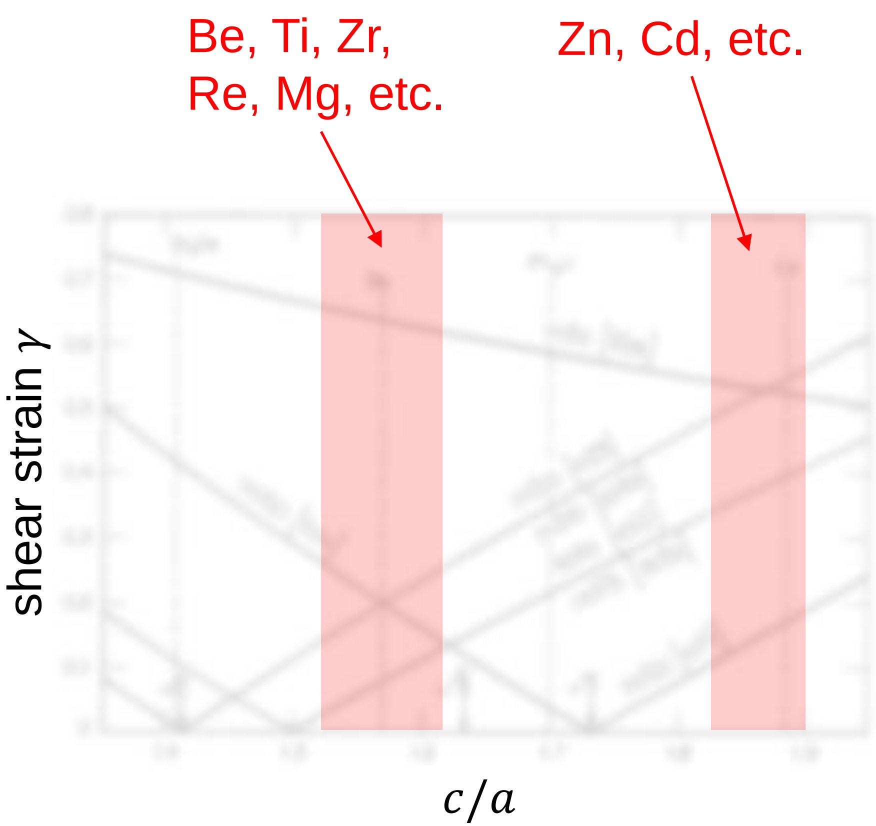
top view on $(1\bar{1}0)$

Deformation Twinning (Other Crystal Structures)

- The analysis of deformation twinning of (i) unusual twinning systems in fcc A2 and bcc A1 or (ii) in other crystal structures (hcp A3 or intermetallic compounds) involves a lot many different considerations (note that the considerations before where more or less only of geometrical nature):
  - Geometrical considerations on projected stress and released strain
  - Elastic interaction of the twinned volume with the surrounding
  - Stacking fault energy (in disordered alloys) and conservation/re-formation of order (in ordered intermetallic materials)
  - Directionality of bonds (in transition elemental alloys)
  - Interaction of existing twins with dislocations

Deformation Twinning (Other Crystal Structures)

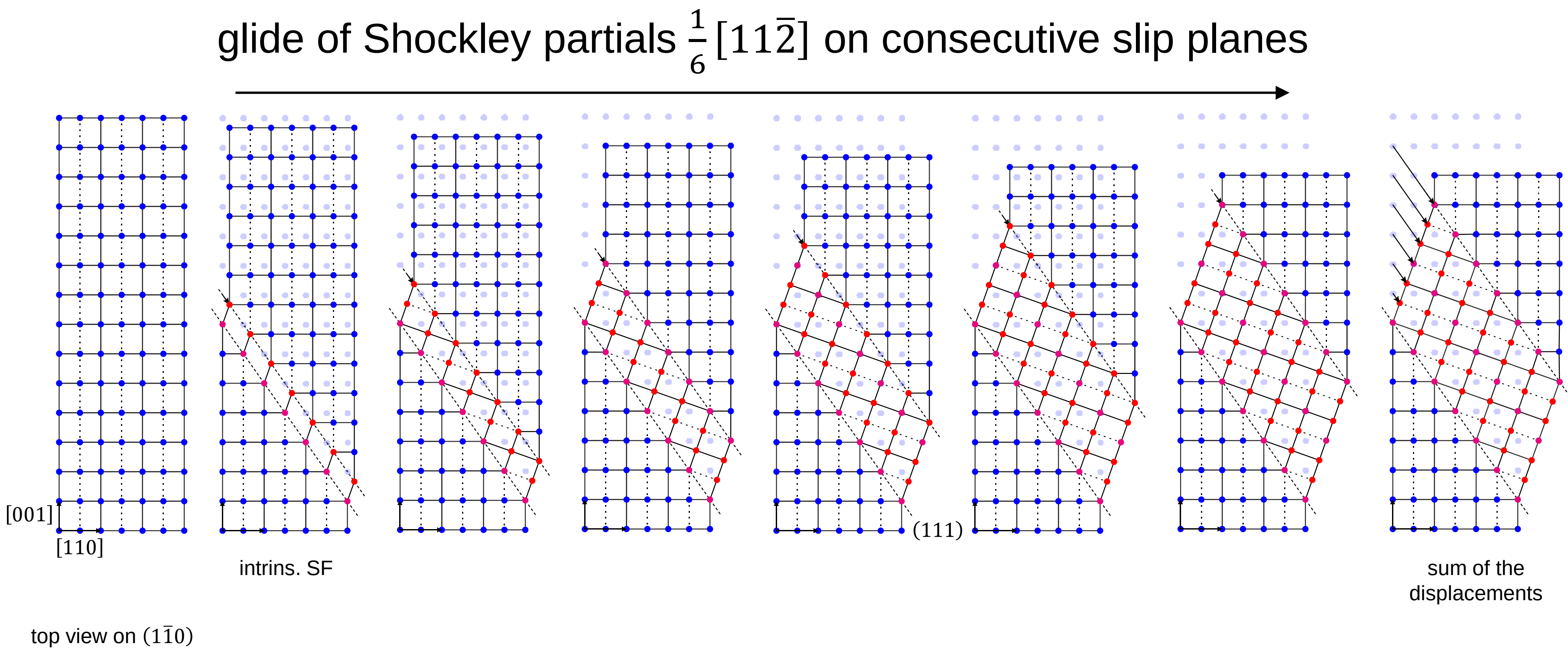
- For example, the released strain by twinning in hcp A3 metals and alloys depends on the c/a ratio.
- Depending on the slope of this dependence, the twin can either contribute to total strain under compression or tension.
- Note that the same twinning system can be "compression twin" or "tension twin" for different hcp metals.



M.H. Yoo, J.K. Lee: "Deformation twinning in h.c.p. metals and alloys" in Philosophical Magazine A 63 (1991) 987-1000

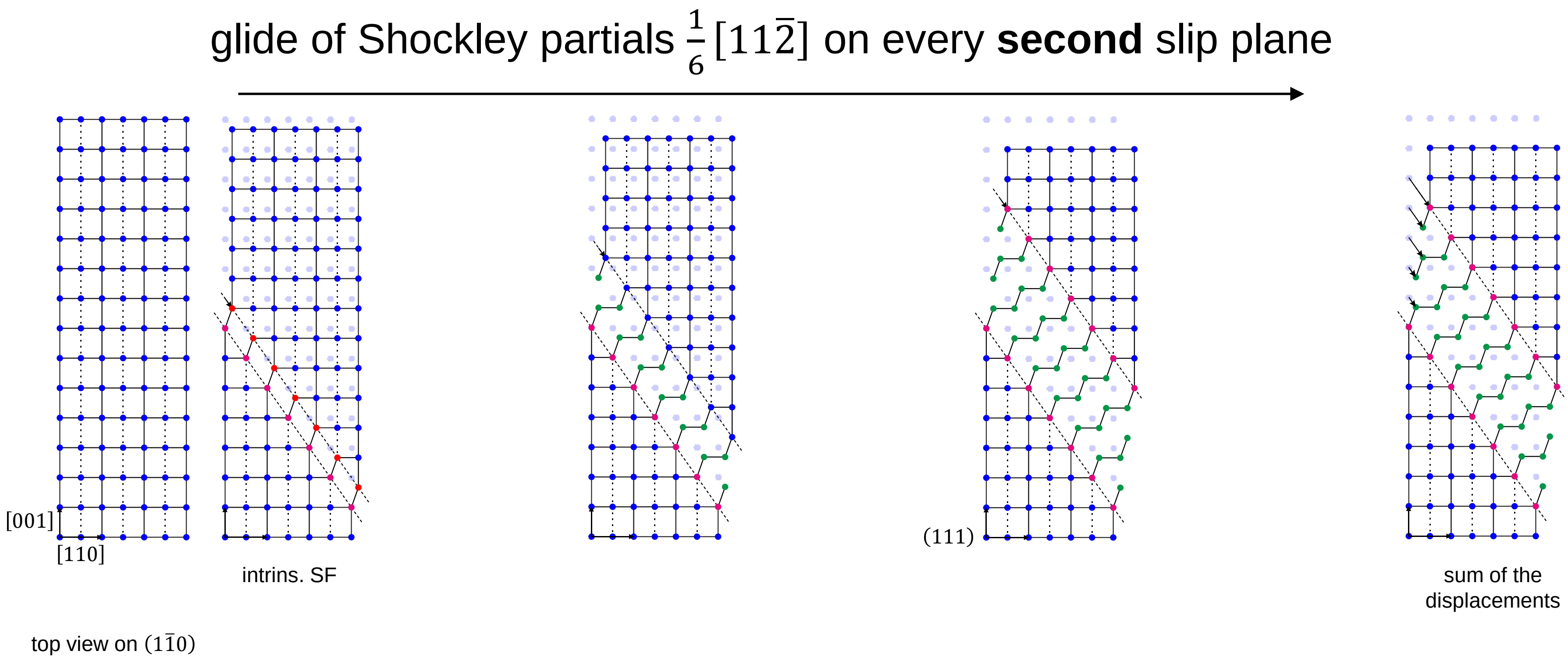
Transformation Induced Plasticity (TRIP)

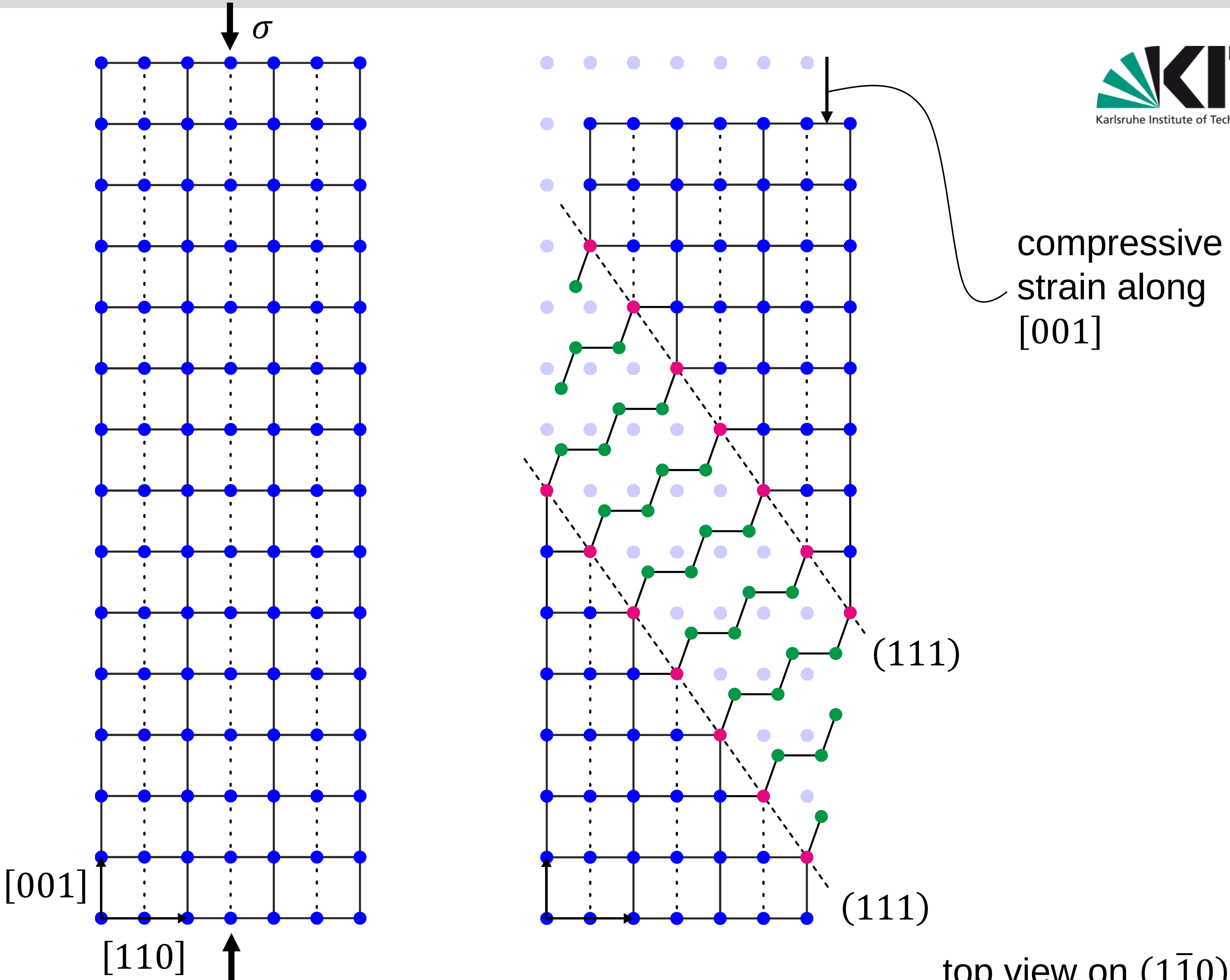
- In fcc A2 metals and alloys, slip of Shockley partial dislocations causes the formation of a twin lath:

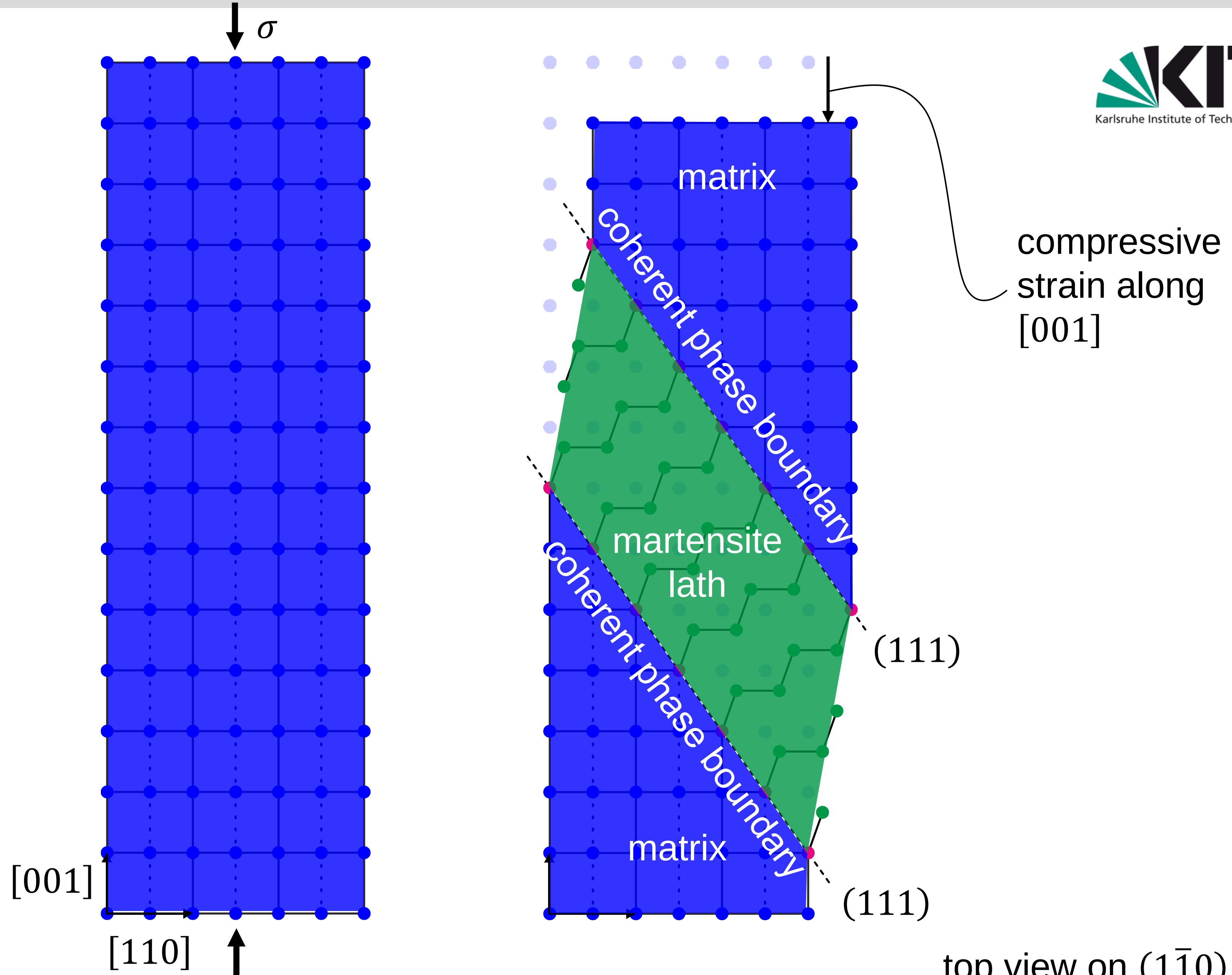


Transformation Induced Plasticity (TRIP)

- In fcc A2 metals and alloys, slip of Shockley partial dislocations on each second $\{111\}$ plane causes the formation of an hcp lath with $\ldots \mathrm{ABABAB} \ldots$ stacking sequence:




σ
compressive strain along [001]
(111)
(111)
[001]
[110]
top view on (1$\bar{1}$0)


σ
matrix
coherent phase boundary
martensite
lath
coherent phase boundary
matrix
compressive
strain along
[001]
(111)
(111)
[001]
[110]
top view on $(1\bar{1}0)$

Transformation Induced Plasticity (TRIP)

- Transformation induced plasticity might even improve the situation caused by TWIP by incorporation of a second (hard) crystallographic phase: