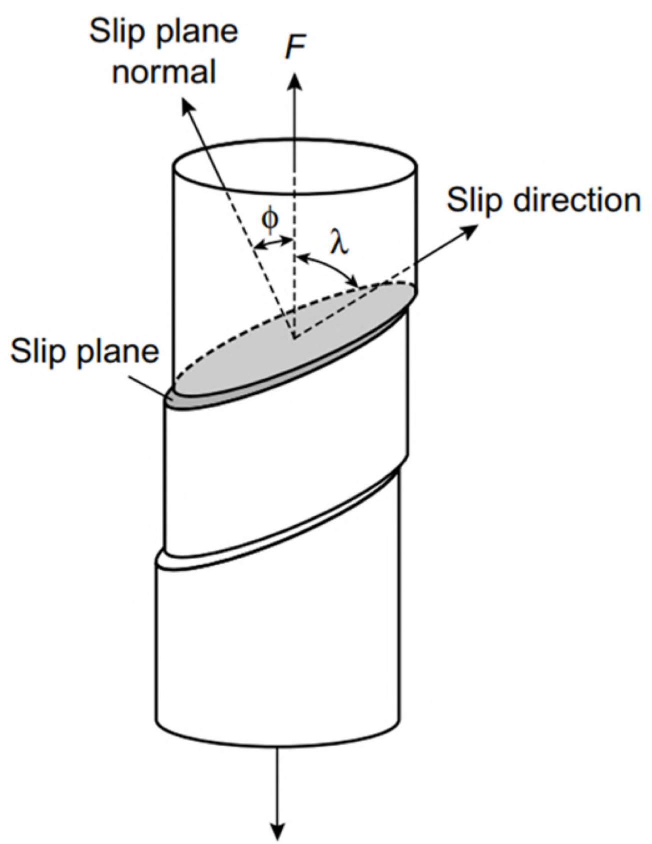
Course goal: Describe deformation and annealing behaviour in terms of slip, twinning and recrystallization mechanisms. And recall the activities of the different slip and twinning systems and how they change with temperature.

# Learning outcomes:

- ***Explain how slip contributes to grain reorientation and recall equations for RSS, CRSS and Schmid Factor.***
- Recall the main slip systems in Ti and Zr alloys and how their activities change with temperature.
- Explain how twinning contributes to grain reorientation and recall the main twinning types in Ti and Zr alloys.
- Describe the driving forces for recrystallization and recovery processes in terms of boundary and stored energy.




Schematic of applied forces acting on a slip plane during tensile deformation

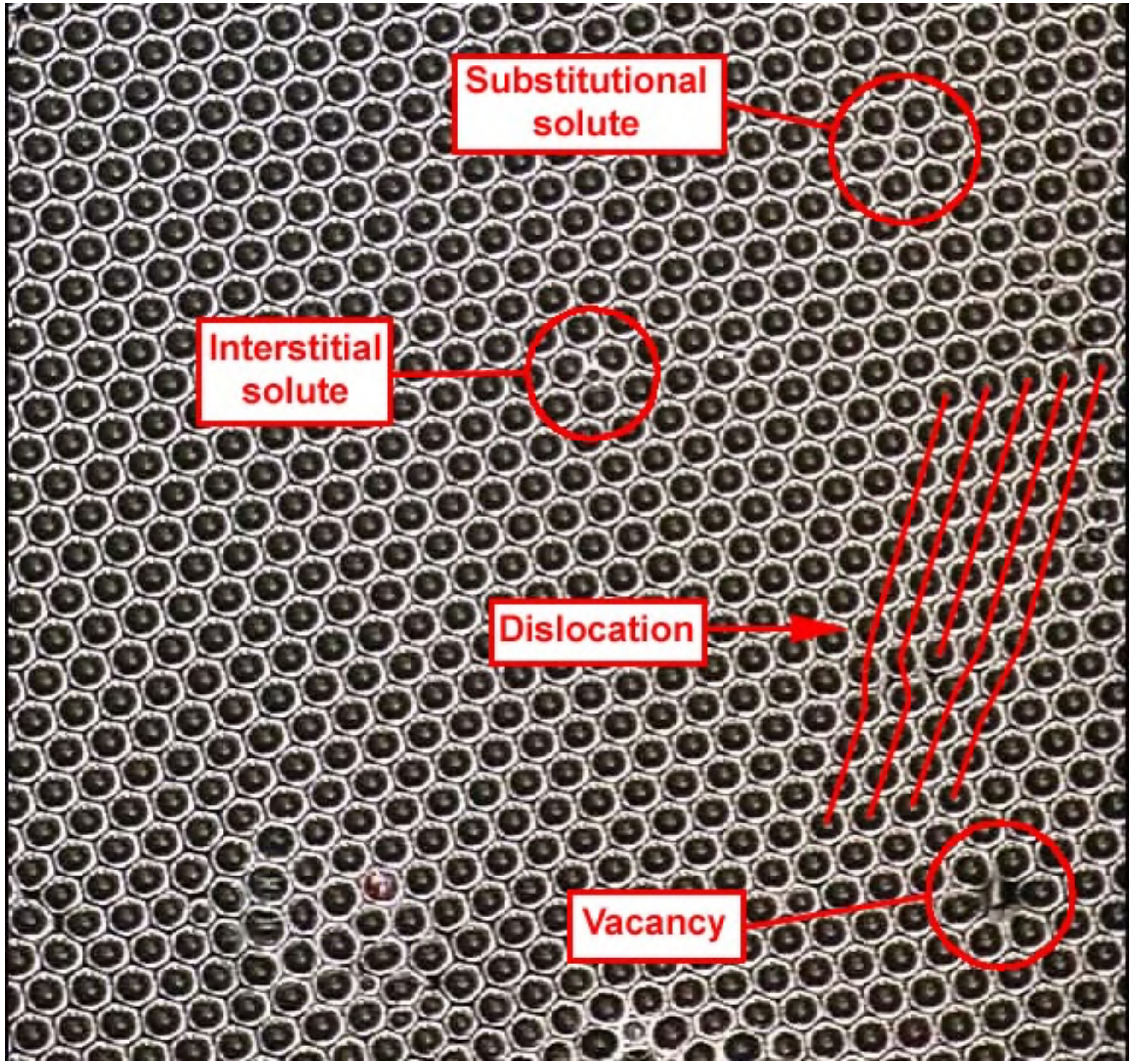
# Dislocations

- ***Grain boundary* –** interface between two regions with different crystal orientation.
- ***Vacancy* –** point defect when atom 'missing' from lattice.
- ***Solute atom*** – different atomic species.

**–** *Substitutional solute:* similar in size substituting for host atom

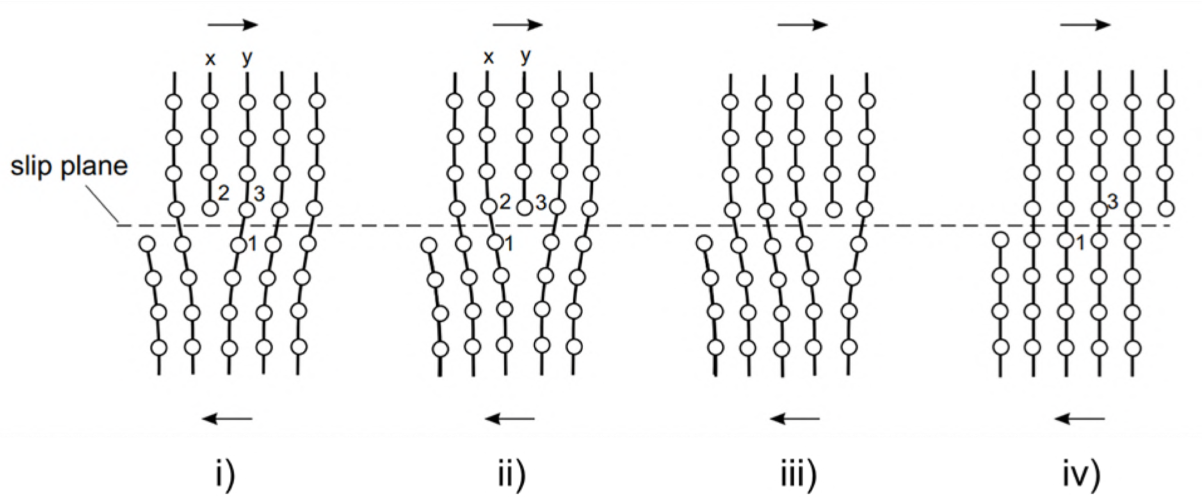
**–** *Interstitial solute:* smaller in size than host and sit in gaps (interstices) of host lattice.

- ***Dislocation*** – Extra 'half-row' of atoms, characterised by Burgers vector ($\boldsymbol{b}$) giving orientation and magnitude.
- ***Dislocation type* –** defined by alignment with line vector ($\boldsymbol{l}$). Edge type ($\boldsymbol{b}||\boldsymbol{l}$). Screw type ($\boldsymbol{b} \perp \boldsymbol{l}$). But, in general, have *mixed* character in 3D.

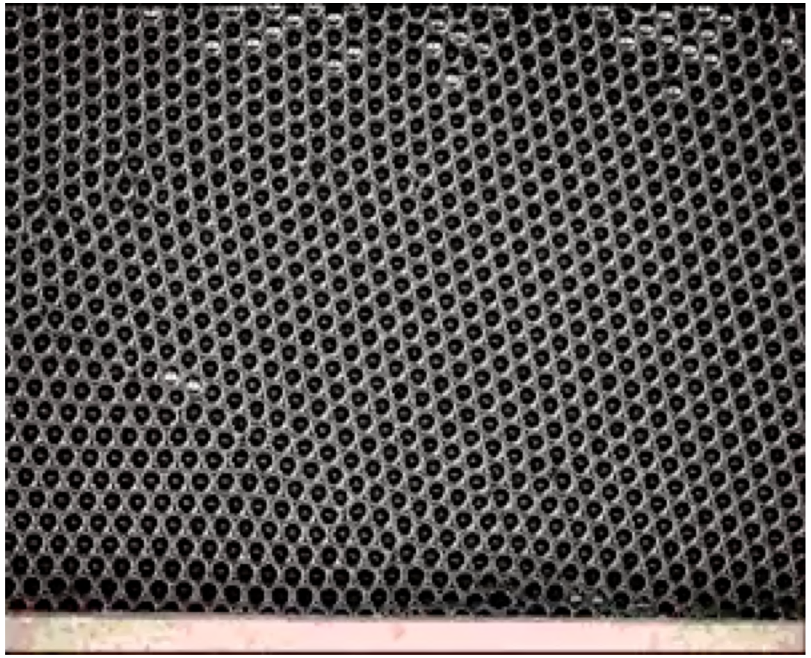


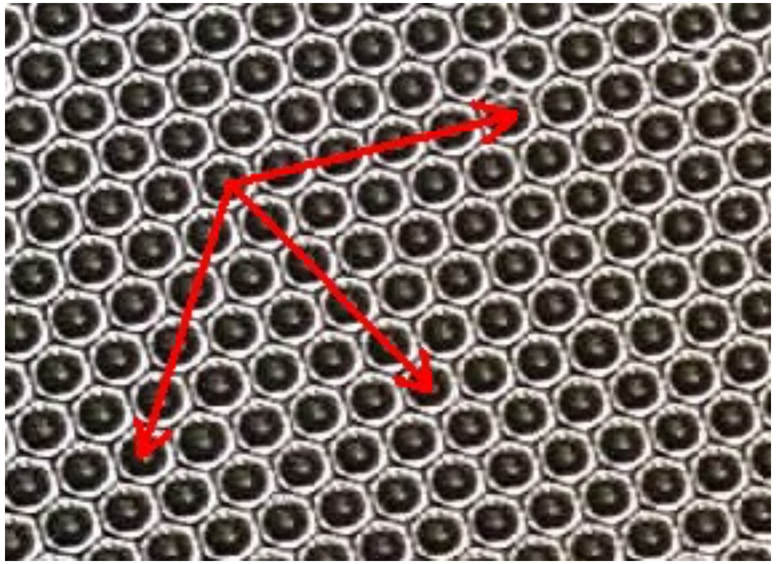
# Slip

- Occurs due to gradual movement of dislocations along specific planes, in specific directions.
- Slip occurs in densely-packed or close-packed planes (lower energy barrier)
- Slip system defined by slip plane and direction.




Movement of edge dislocation under applied shear stress





- Dislocation glide allows plastic deformation at much lower stresses than otherwise required.

# Critically Resolved Shear Stress (CRSS)

- Resolved shear stress (RSS), acting on slip plane;

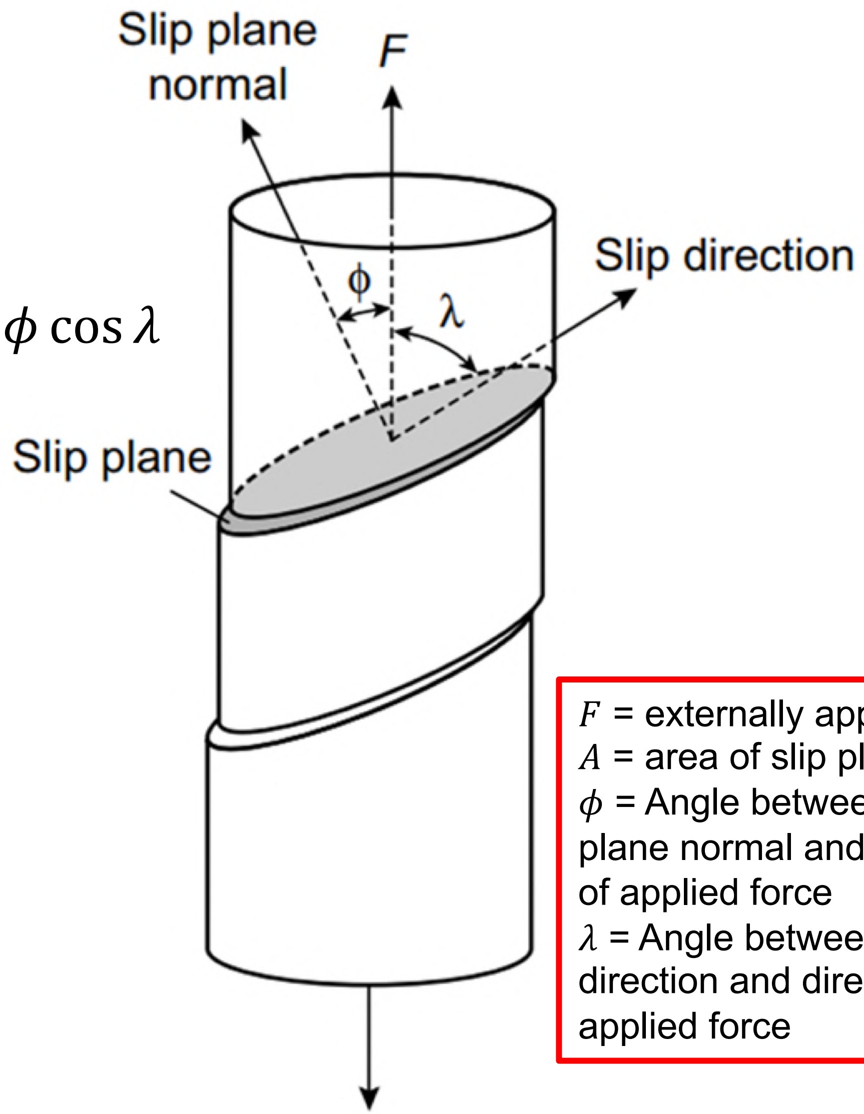
$$\tau = \frac{resolved\ force\ acting\ on\ slip\ plane}{area\ of\ slip\ plane} = \frac{F\cos\lambda}{A/\cos\phi} = \frac{F}{A}\cos\phi\cos\lambda$$

- Critically resolved shear stress (CRSS) of slip plane;

$$\tau_C = \sigma_Y \underbrace{\cos\phi\cos\lambda}_{\text{Schmid factor}}$$

Yield stress → $\sigma_Y$; Schmid factor → $\cos\phi\cos\lambda$

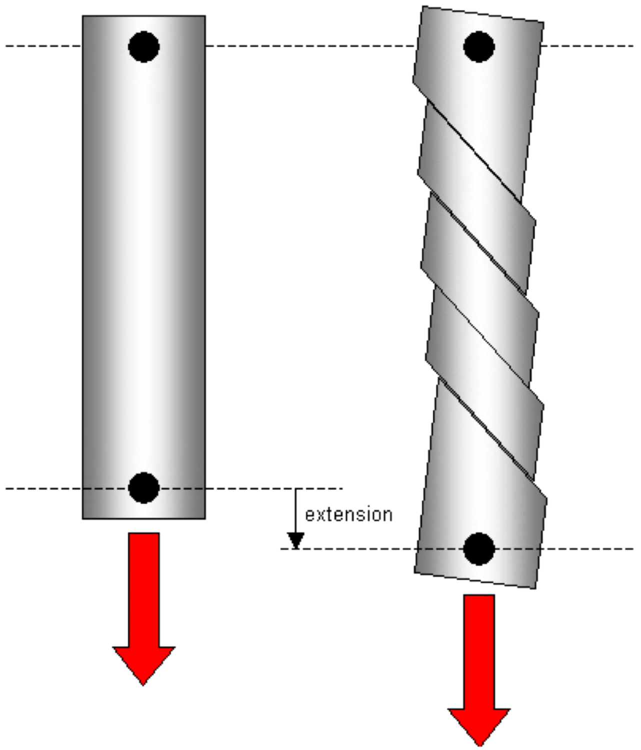
- If **RSS > CRSS**, then slip occurs.

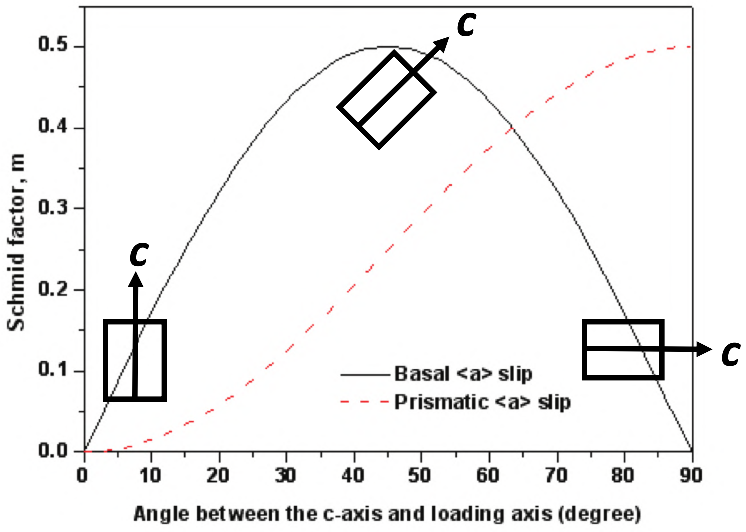



$F$ = externally applied force
$A$ = area of slip plane
$\phi$ = Angle between slip plane normal and direction of applied force
$\lambda$ = Angle between slip direction and direction of applied force

# Grain Rotation

- Slip primarily occurs on grains with highest Schmid factor value.
- In uniaxial tension and compression, slip plane at 45° to loading axis has highest Schmid Factor (soft orientation).
- Edge constraints mean planes cannot glide freely and rotate towards loading axis.
- ***Single slip Sachs model*** → lattice rotation aligns slip direction with loading axis. *But, this would fracture material.*
- ***Multi-slip Taylor model*** → number of different slip systems (each with CRSS) accommodate lattice rotation and shape change.



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# Learning outcomes:

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- Explain how twinning contributes to grain reorientation and recall the main twinning types in Ti and Zr alloys.
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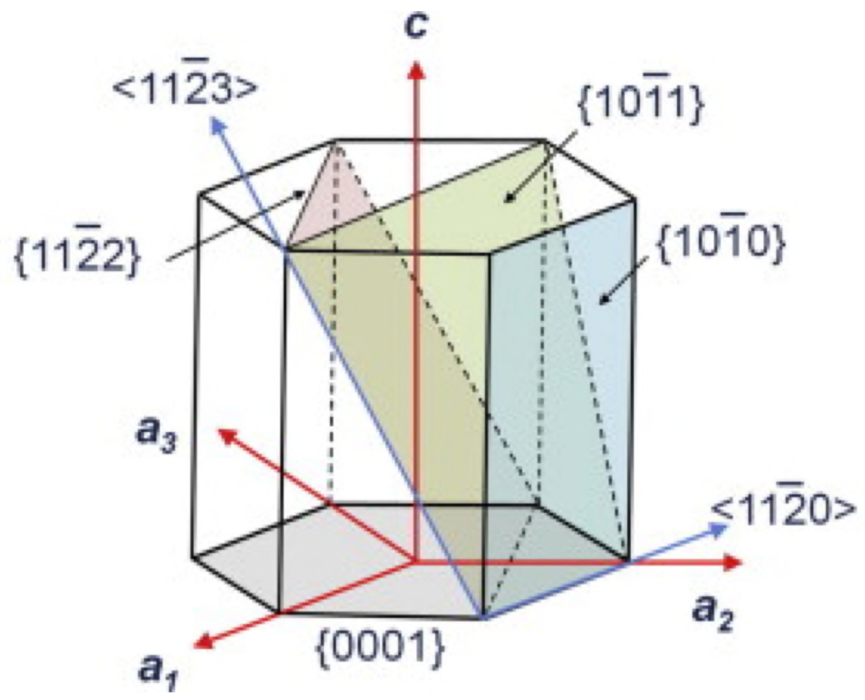
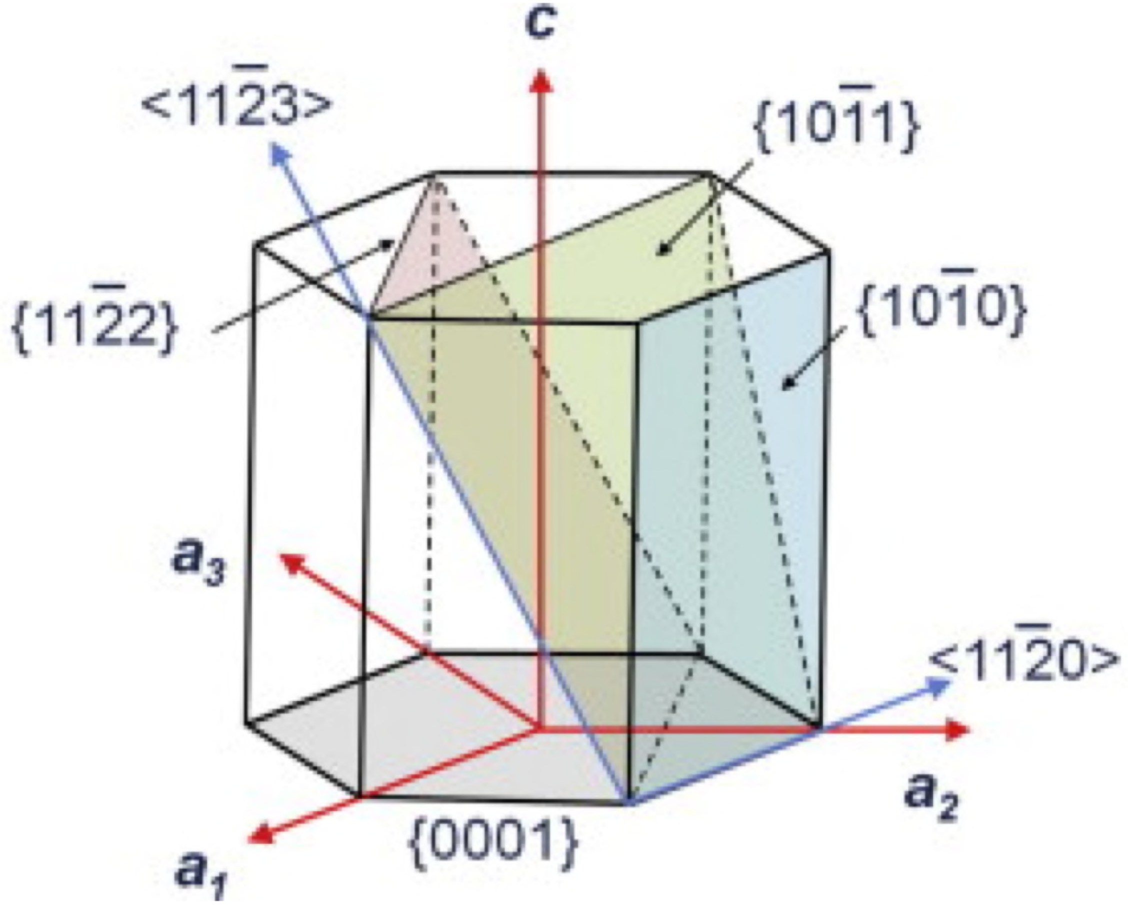
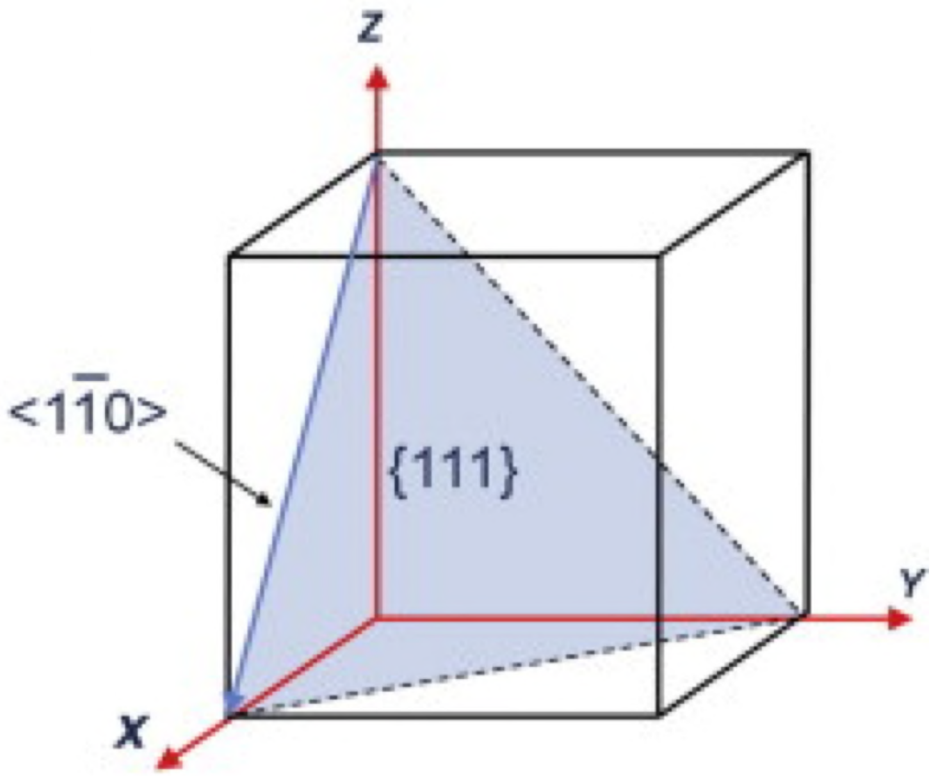



Prismatic, basal and pyramidal slip systems in the HCP phase.

# Deformation in HCP vs FCC Crystal



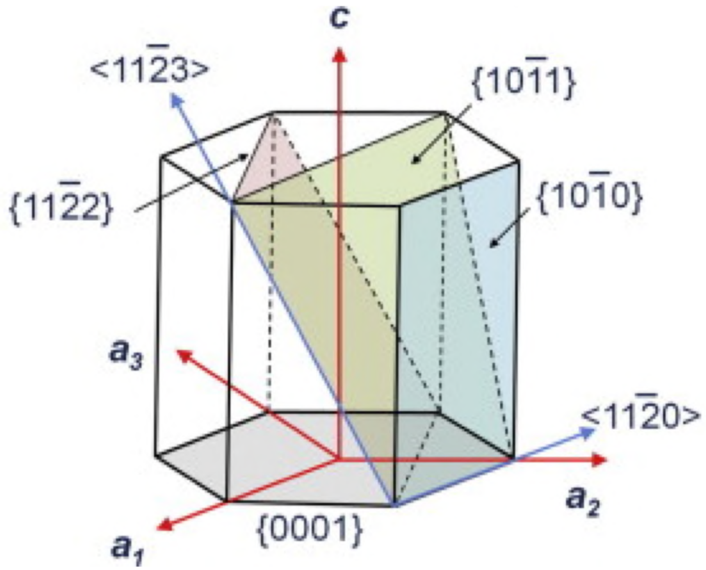

Fewer slip systems, asymmetrically distributed → **plastic anisotropy**

4x {111} planes, each with 3x <1-10> directions **= 12 evenly distributed slip systems**

Both crystal structures close-packed, but HCP deformation is very different.

# HCP Slip Systems

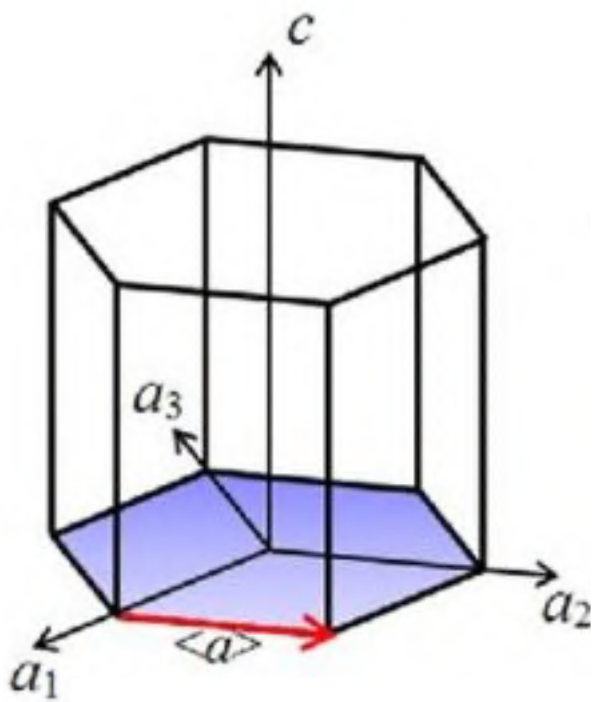
| *Slip system type* | *Slip direction* | *Slip plane* | *No. of slip systems* | | *CRSS* |
|---|---|---|---|---|---|
| | | | *Total* | *Independent* | |
| Prismatic <a> | $\langle 11\bar{2}0\rangle$ | $\{10\bar{1}0\}$ | 3 | 2 | *lowest* |
| Basal <a> | $\langle 11\bar{2}0\rangle$ | $\{0002\}$ | 3 | 2 | |
| Pyramidal <a> | $\langle 11\bar{2}0\rangle$ | $\{10\bar{1}1\}$ | 6 | 4 | |
| Pyramidal <c + a> | $\langle 11\bar{2}3\rangle$ | $\{11\bar{2}2\}$ | 6 | 5 | *highest* |



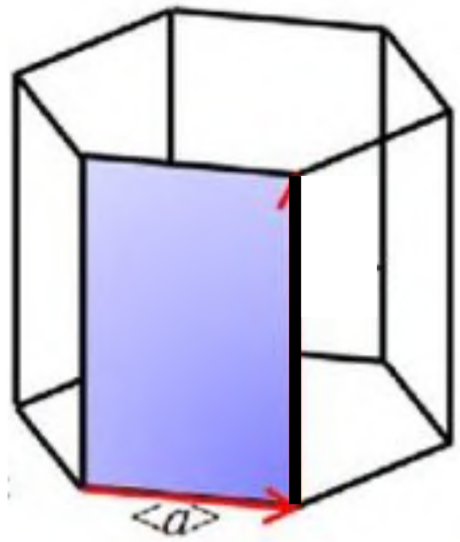

*According to the Von-Mises criterion, homogeneous deformation of a polycrystalline material requires 5 independent slip systems.*

# Prismatic vs Basal <a> Slip

- *Live lecture – Why is prismatic <a> slip easier than basal <a> slip?*
- Ideal c/a ratio: 1.633
- Zr c/a ratio: 1.593
- Ti c/a ratio: 1.587



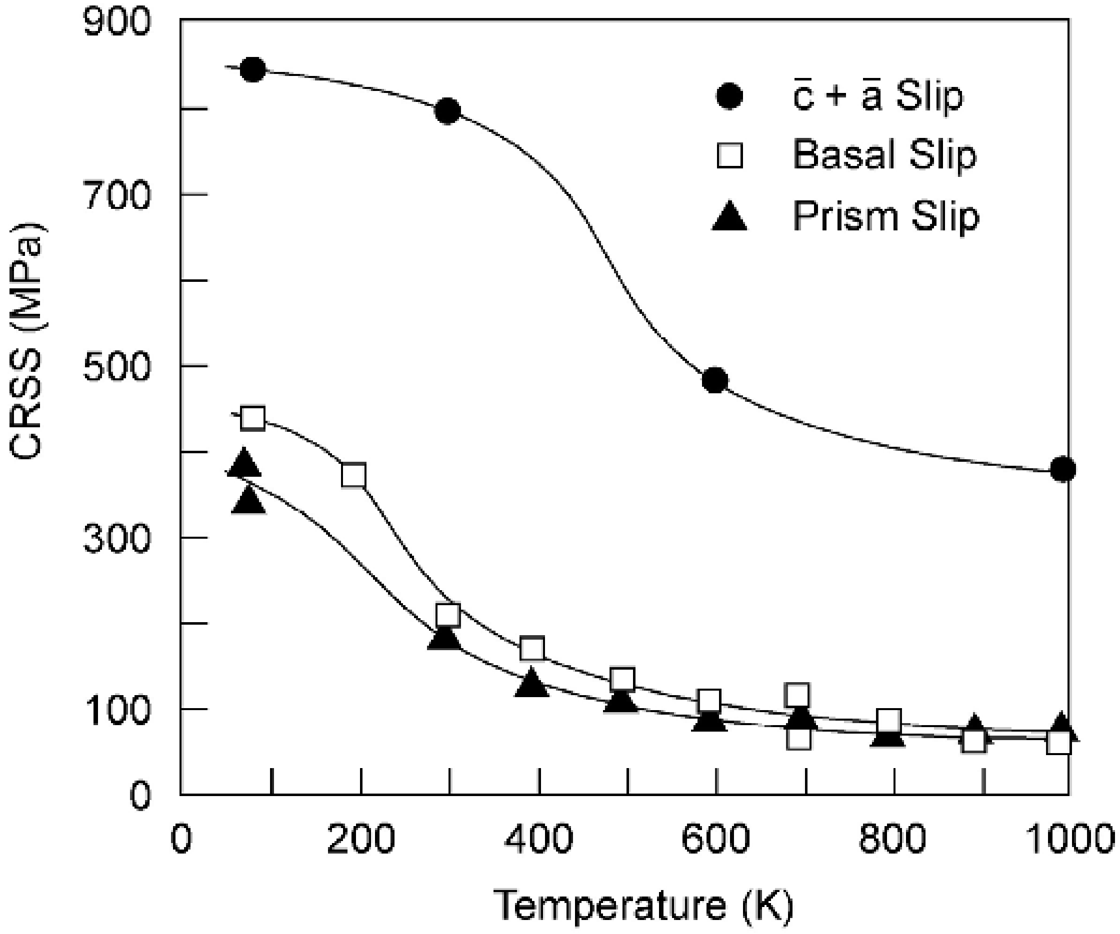

Basal Slip
$^1/_3\langle 11\bar{2}0\rangle(0002)$

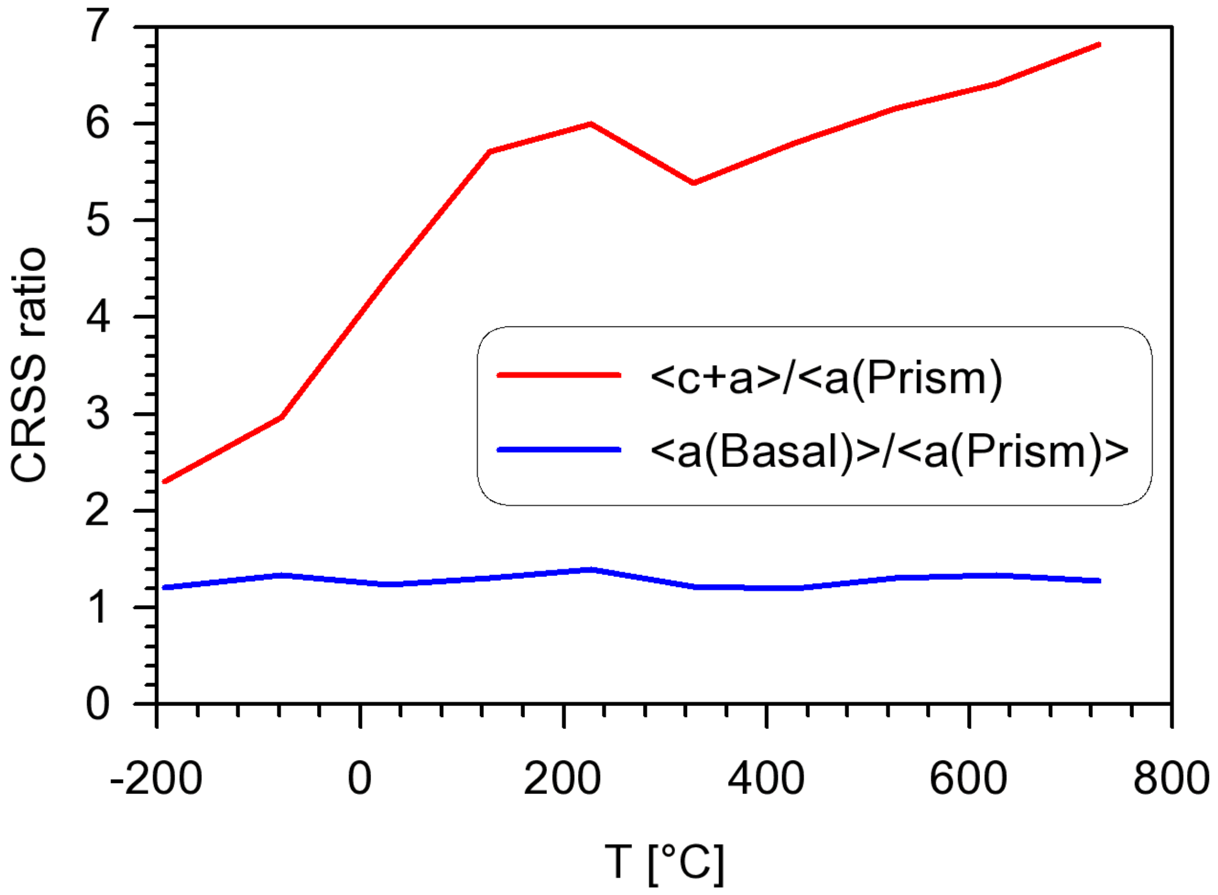



Prismatic Slip
$^1/_3\langle 11\bar{2}0\rangle\{10\bar{1}0\}$

# Slip Activity with Temperature

- CRSS values for Ti-6Al…

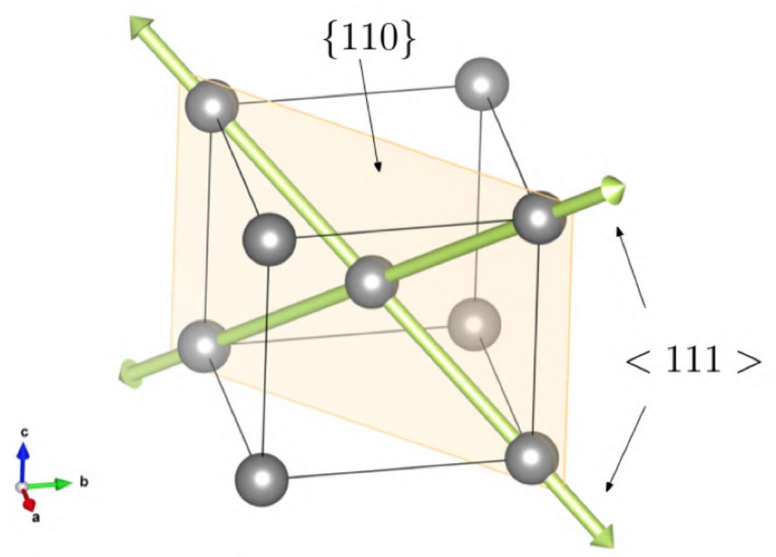


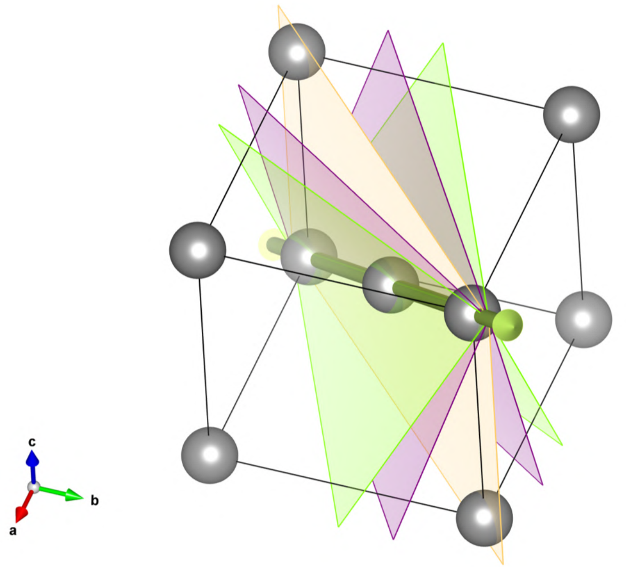



# Slip in β-phase

- Slip along close-packed <111> direction.
- Different planes can accommodate slip → pencil glide.

$\{110\}\langle\bar{1}11\rangle$



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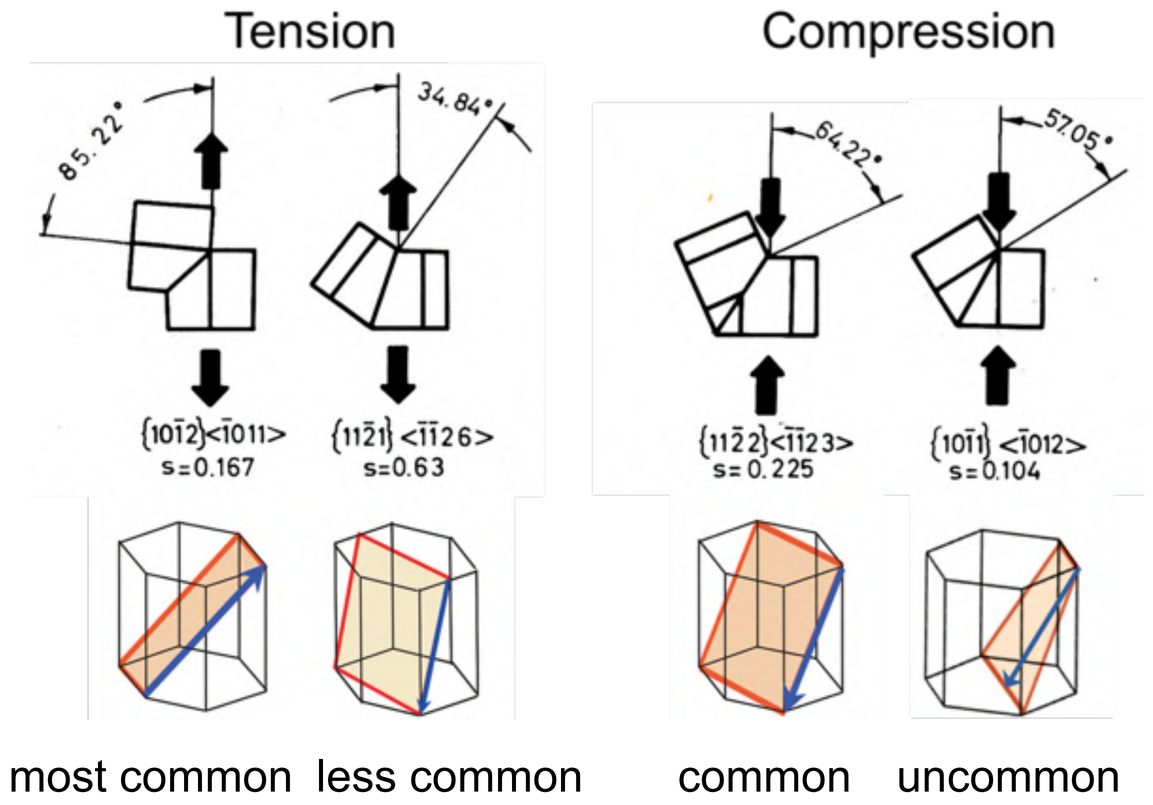
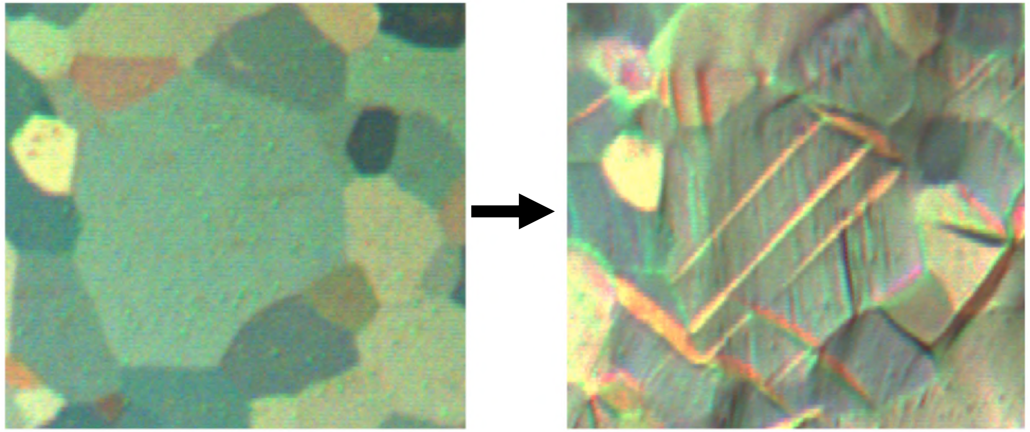
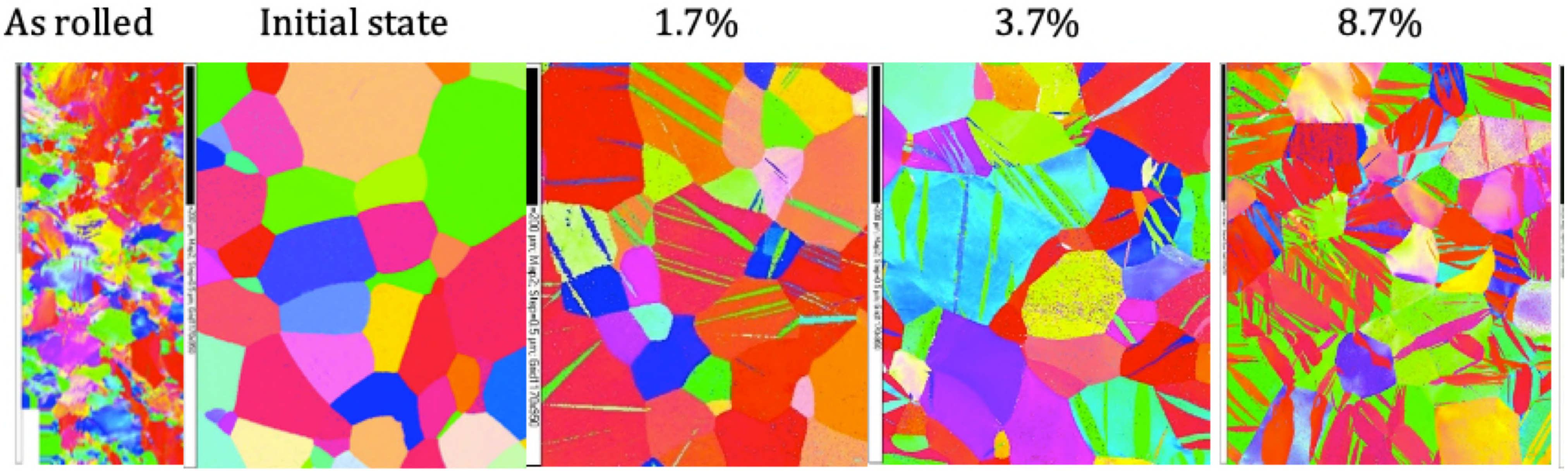



The main twinning types in Ti and Zr alloys.

# Twinning Appearance

- Twins appear as thin lens-shaped structures.
- Characterised by specific misorientation with parent crystal.

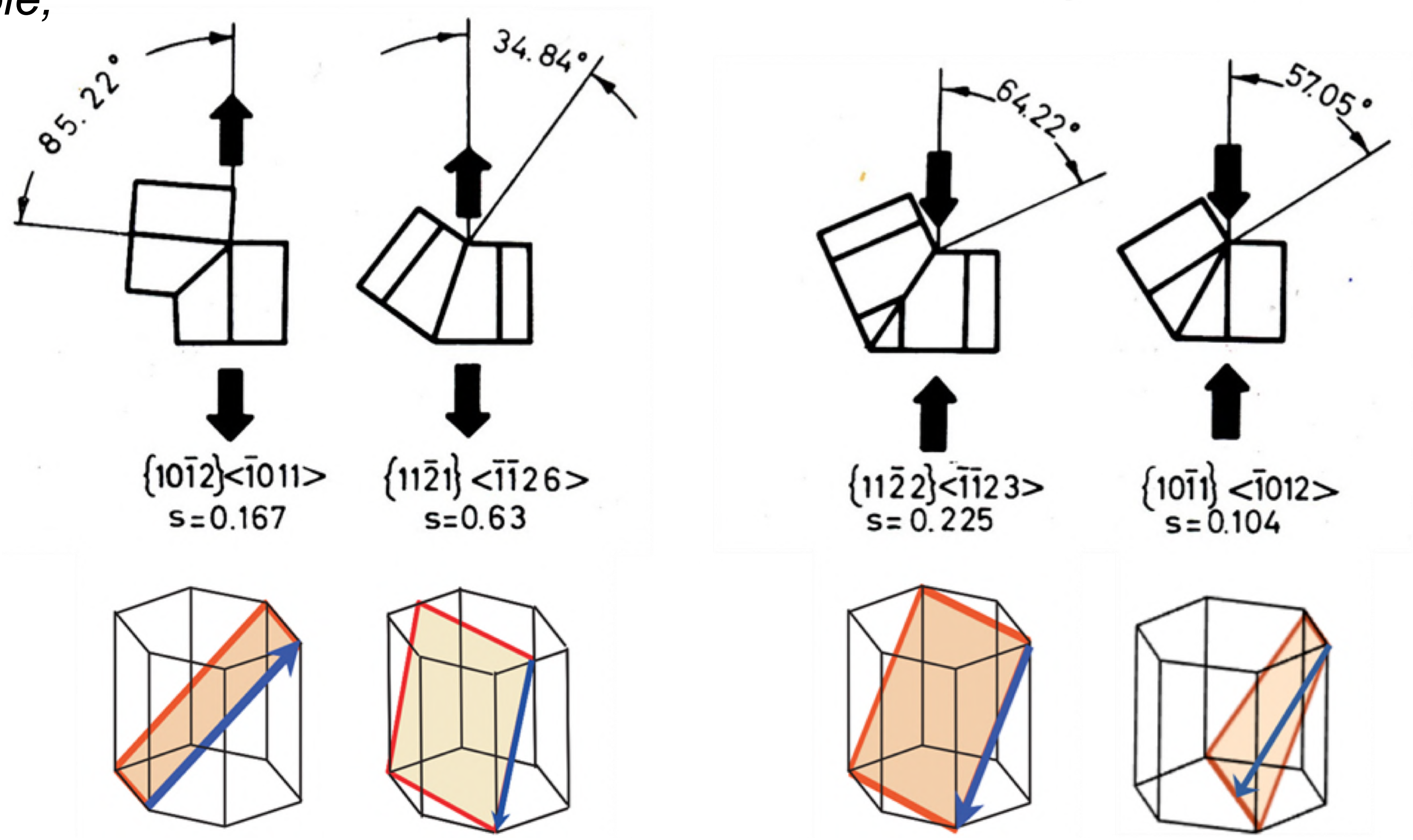




# Twinning Types

- *When insufficient slip systems available, deformation can occur via twinning.*
- Atoms reshuffling (small distances) results in grain rotation, with significant shear strain.
- Provides shear with <c> component.
- ***Tension twin:*** <c> axis in tension, rotates towards compression
- ***Compression twin:*** <c> axis in compression, rotates toward tension

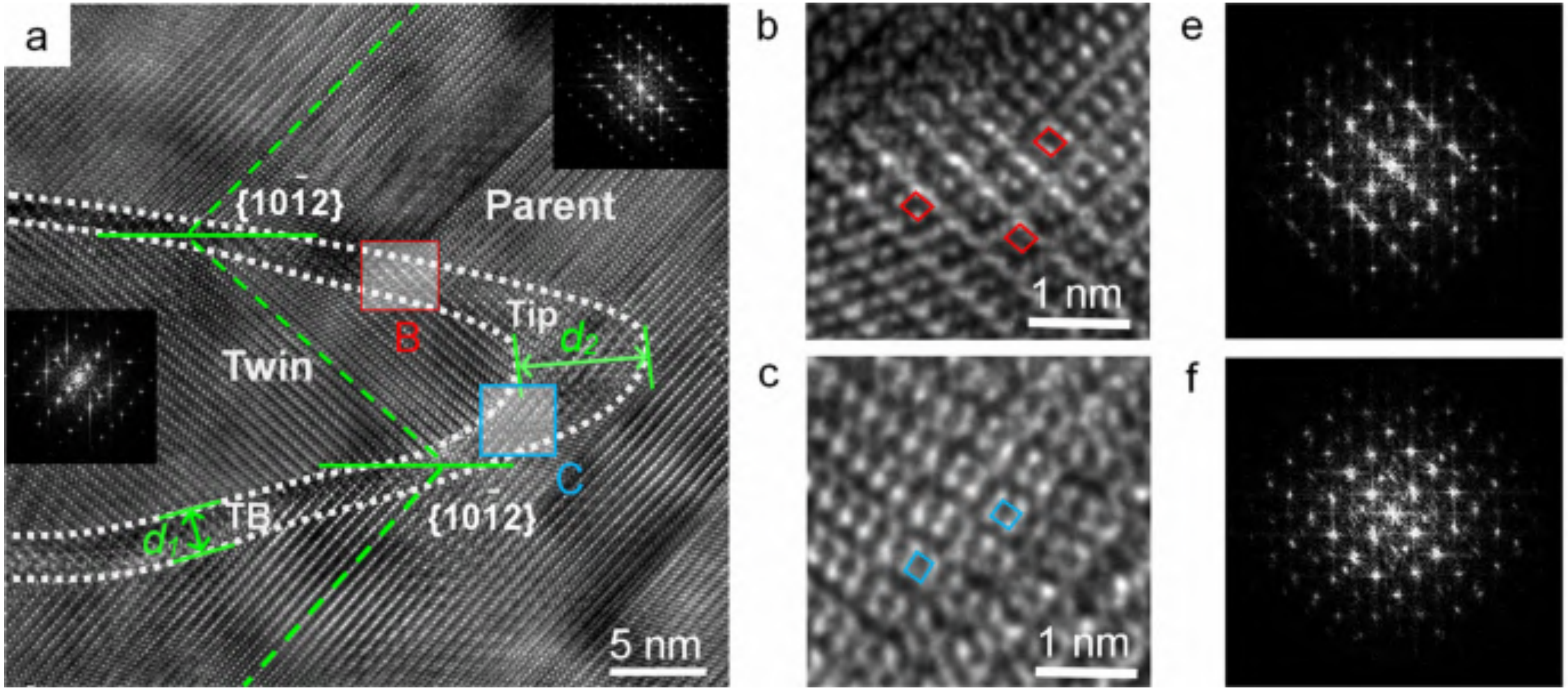
Tension　　　　Compression




most common　less common　common　uncommon

# Twinning Image

- Using TEM, we can see the new crystallographic alignment of atoms within the twin.

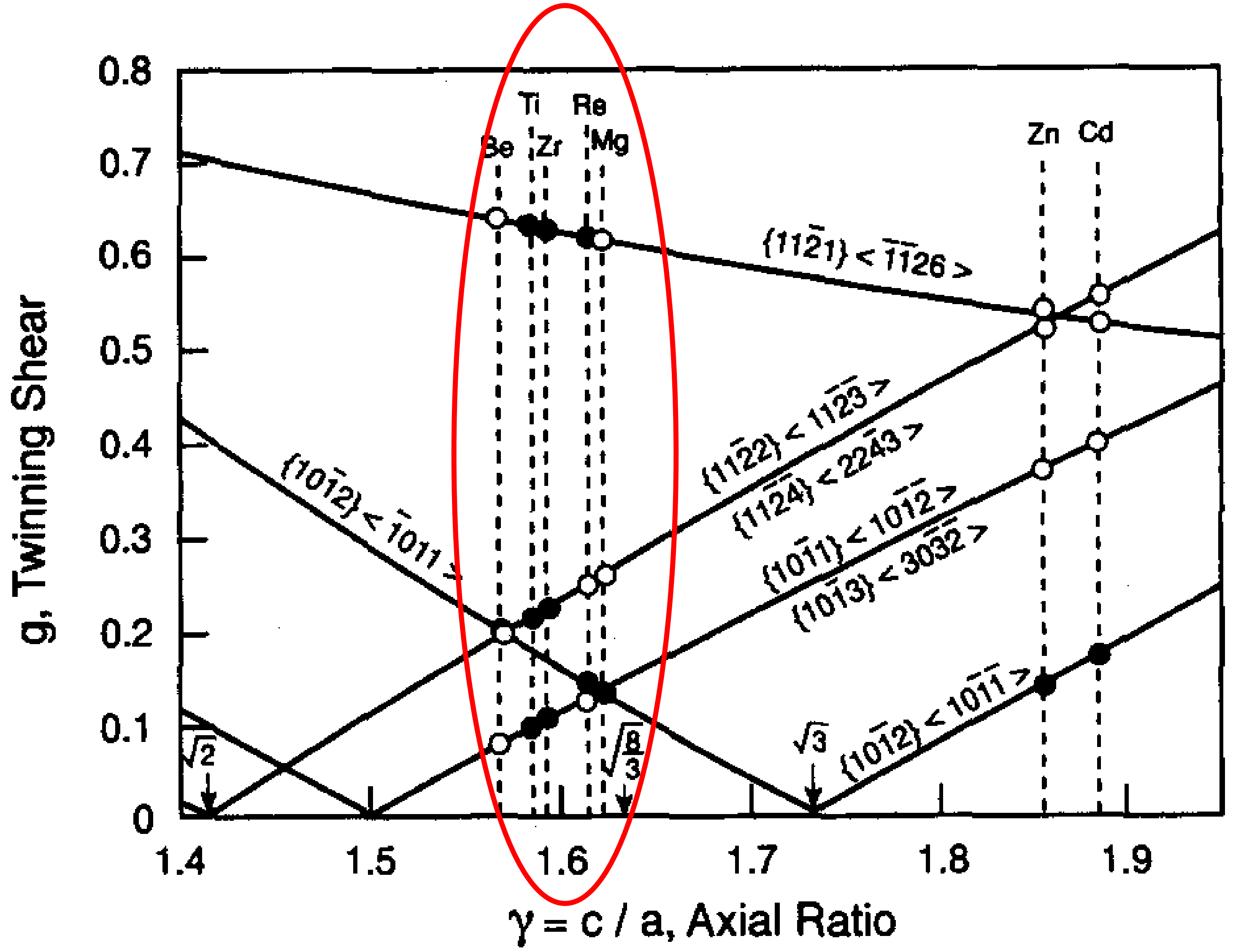


# Twinning Shear

- Crystallography determines the twinning shear.

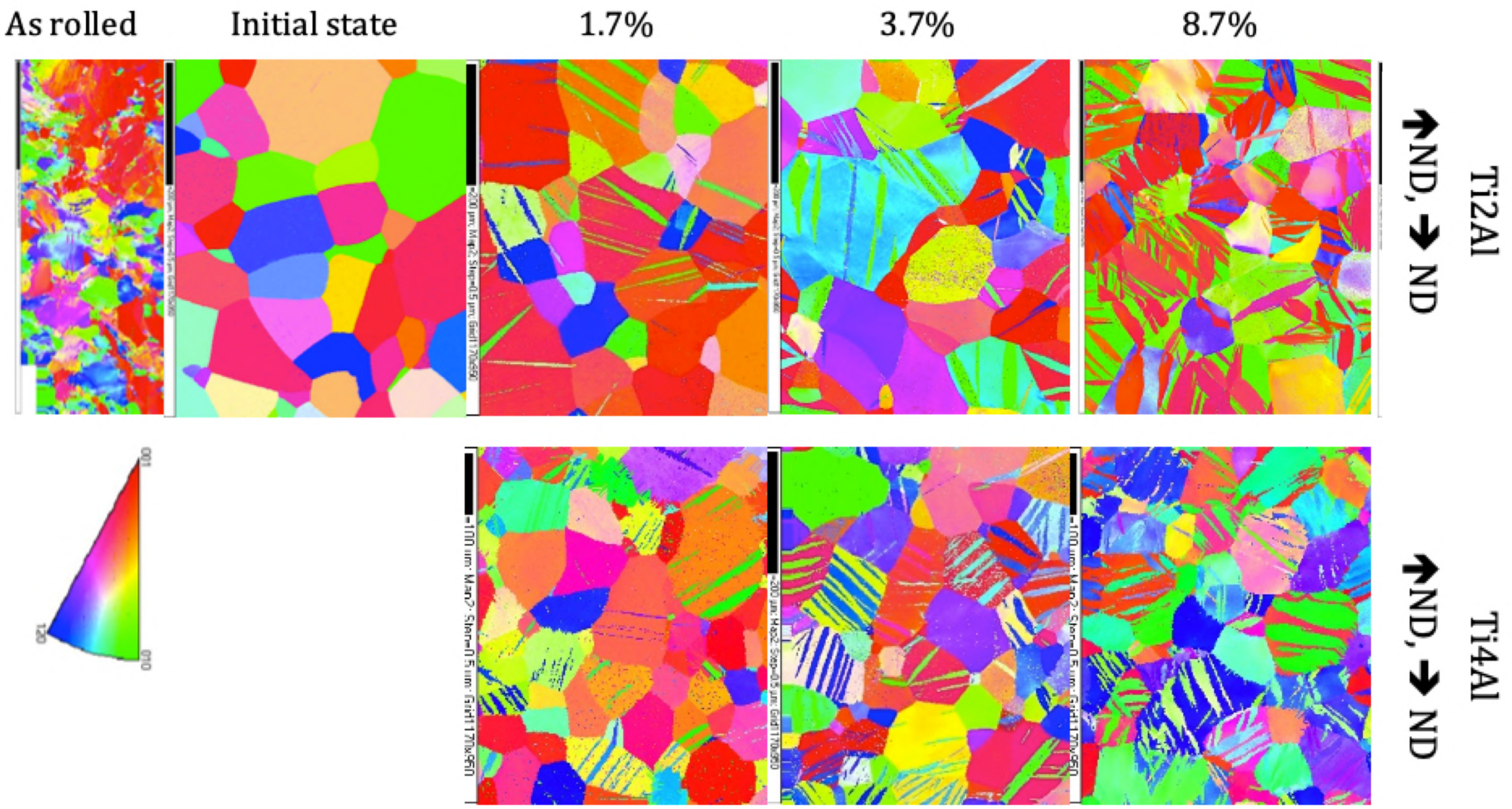
↓

- c/a ratio characterises the twinning shear of the crystal.



# Twinning with Strain and Temperature

- ***Strain:*** Twinning tends to only occur at low strains, which align grains for further slip.
- ***Temperature:*** Twinning reduces at higher deformation temperatures.
- *But, tensile and compression twinning has been reported at >550°C in Zr alloys.*



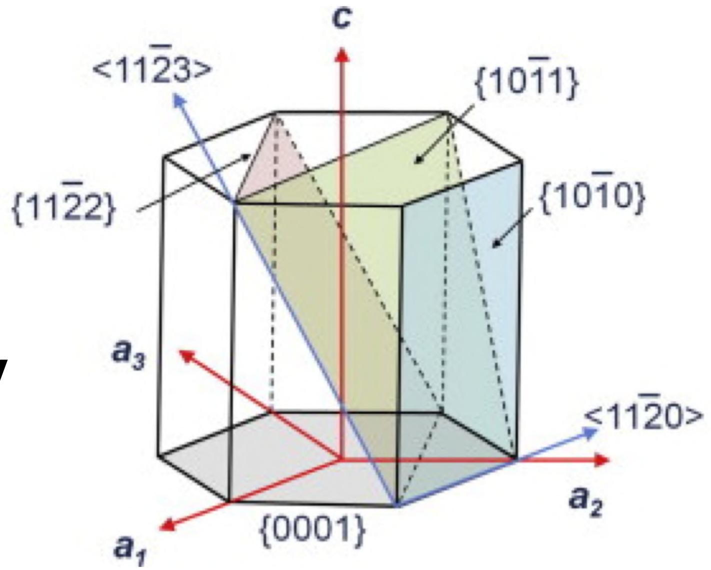
# Why is Slip and Twinning Important?

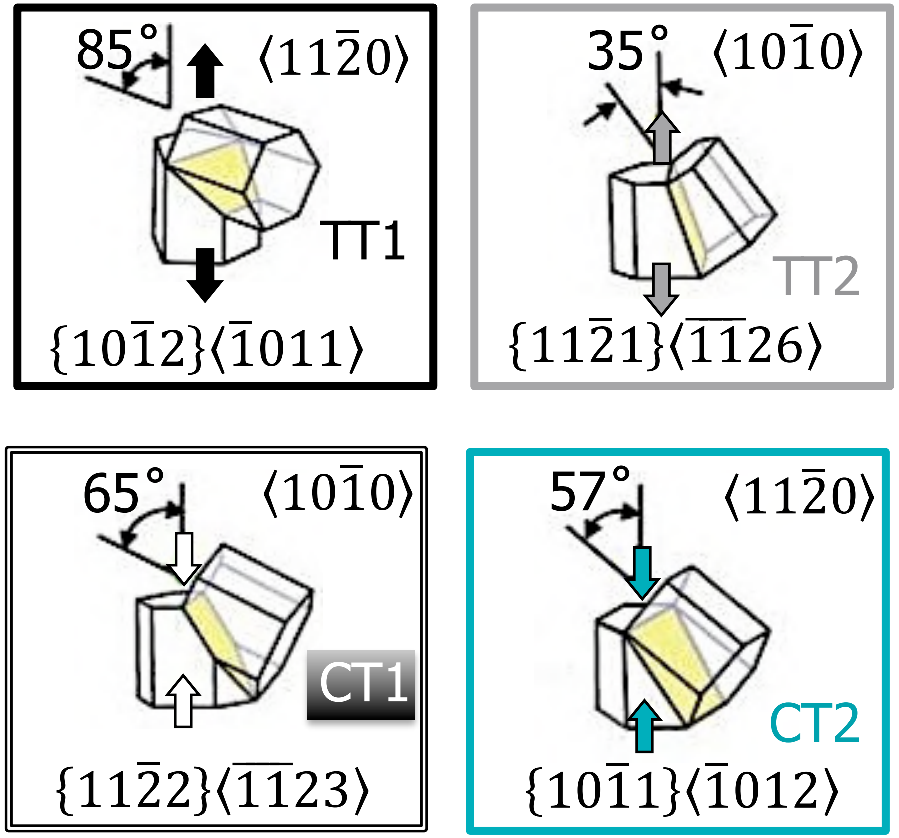
- HCP lattice in Ti and Zr alloys;

- *Elastically and plastically anisotropic.*
- *Low offer of slip systems.*
- *Asymmetrical distribution of slip systems.*
- *Strict crystallographic orientation relationships for twinning.*

- Therefore…

- **Strong deformation texture *(crystallographic orientation)*.**
- **Strong mechanical anisotropy in-service.**



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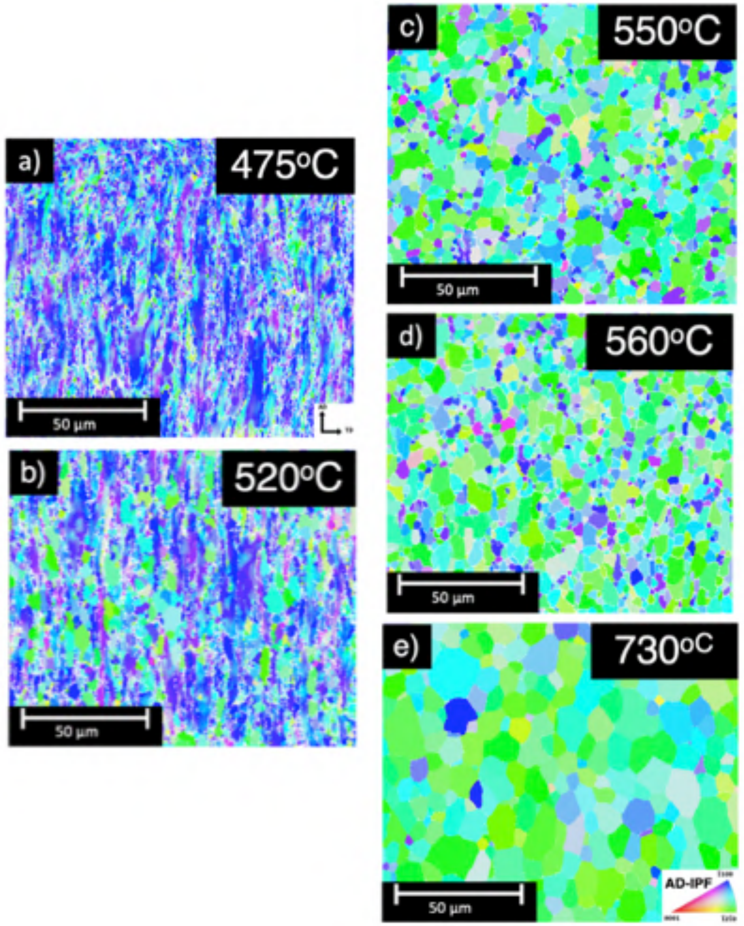
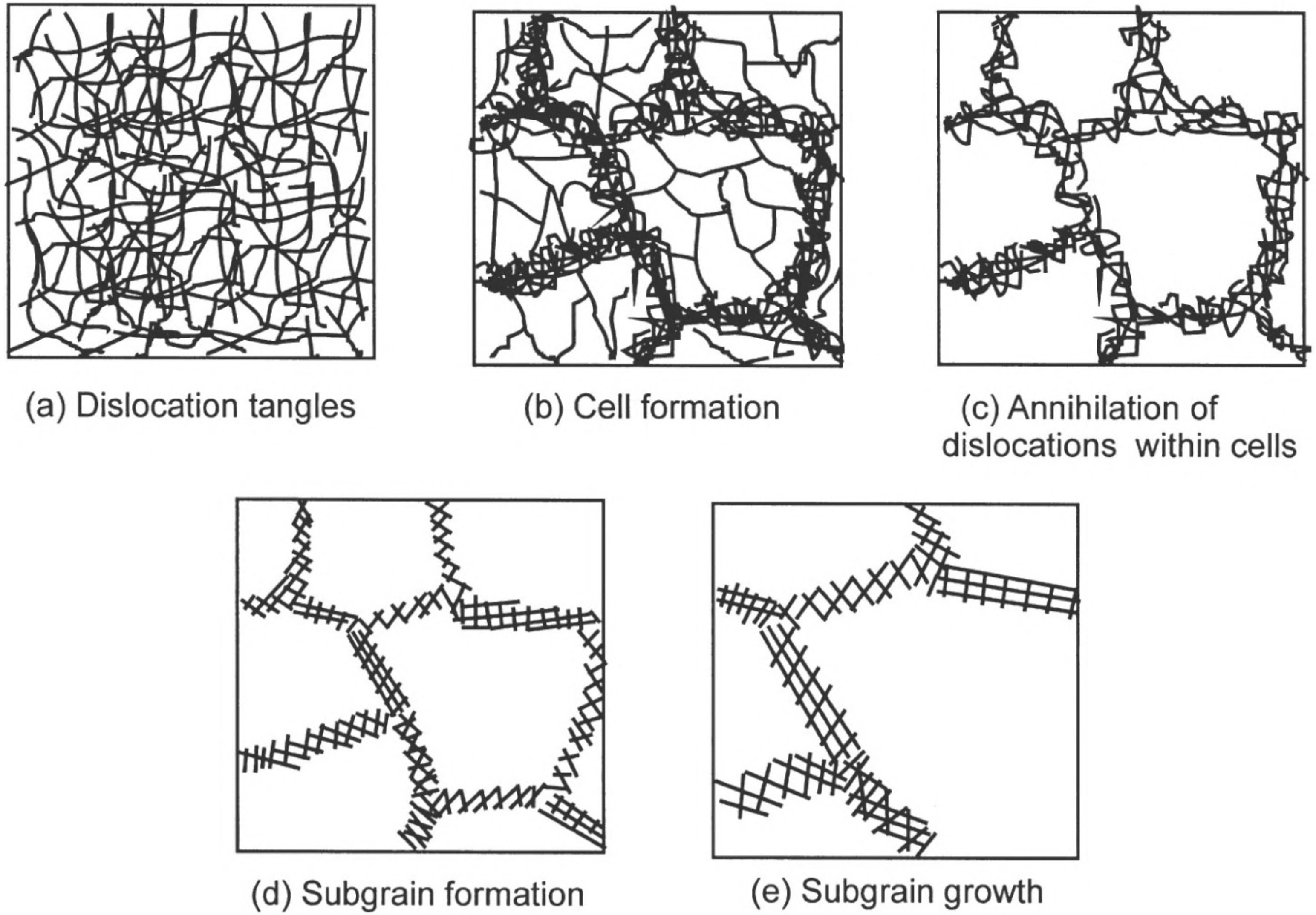


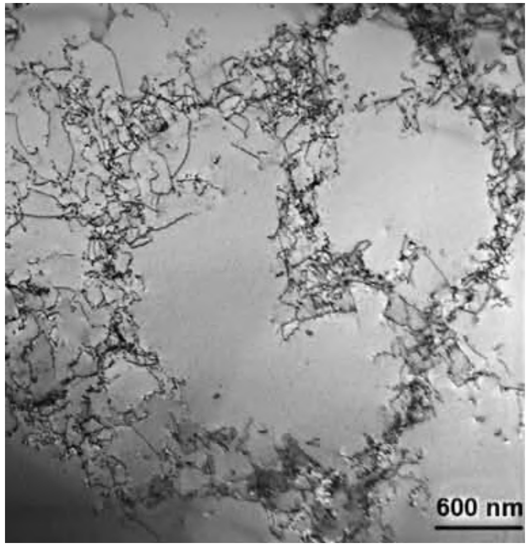

EBSD images showing the effect of annealing at different temperatures, forming fully recrystallized grains at higher temperatures.

# Recovery

*Ti and Zr materials undergo changes during annealing;*

- ***Recovery:*** dislocations annihilate and rearrange, forming new sub-structures.
- Driven by reduction in boundary area.



# Recrystallization and Grain Growth

*Ti and Zr materials undergo changes during annealing;*

- ***Recrystallization:*** new dislocation-free grains within deformed structure.

\- New grains have ***stored energy*** advantage to consume old grains;

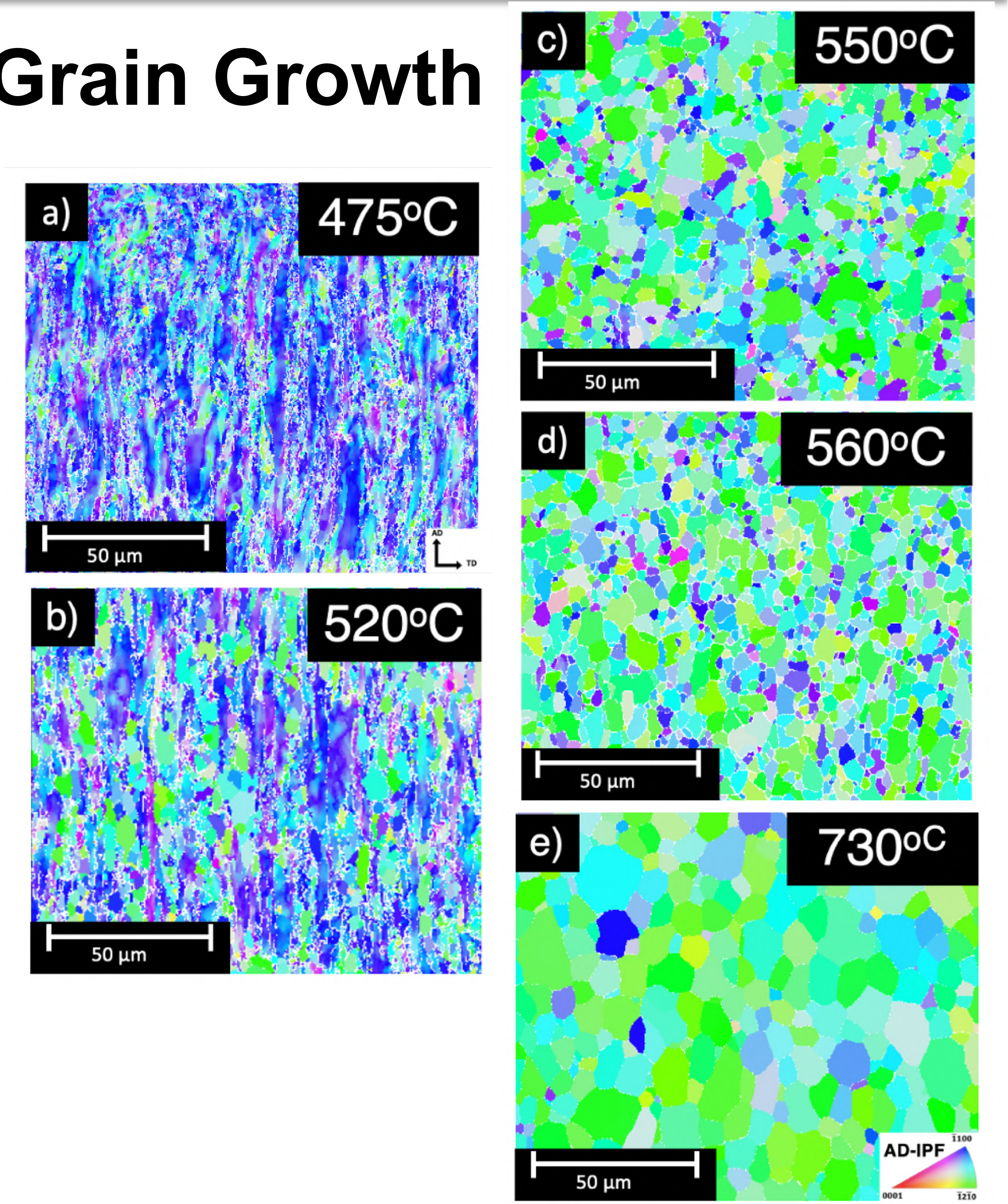
$$E_D = c\rho G b^2 \text{ and } E_D \approx \frac{3\gamma_S}{D} \approx \frac{K\theta}{D}$$

$E_D$ = Stored energy per volume

$c$ = constant, ~ 0.5
$\rho$ = dislocation density
$G$ = shear modulus
$b$ = Burgers vector

$\gamma_S$ = boundary energy
$D$ = subgrain diameter
$K$ = constant
$\theta$ = boundary misorientation

- ***Grain Growth:*** Growth of larger grains, driven by lowering boundary area.



# Stacking Fault Energy (SFE)

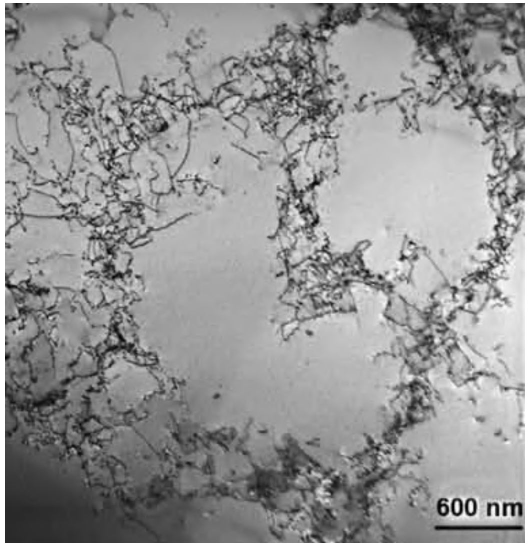
- Stacking Fault Energy (SFE) – Related to atomic bonding in material.
  Determines dissociation of dislocations.

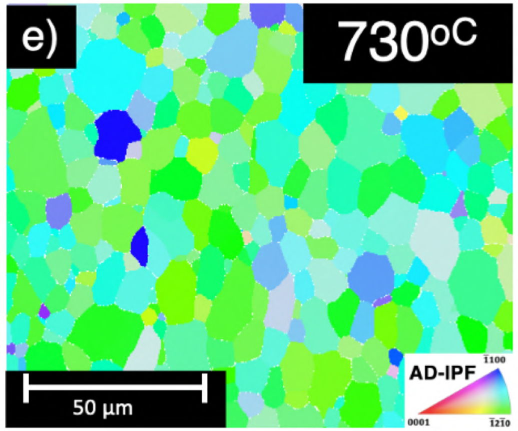
- **High SFE** → Full dislocations.
  Promotes climb, cross-slip and annihilation.
  ***(Recovery)***

- **Low SFE** → Dissociation into partial dislocations.
  Hinders recovery and promotes new grains forming.
  ***(Recrystallization)***

- In Zr and Ti alloys,

  - some dislocation types have high SFE and some have low SFE.
  - recrystallization favoured at grain boundaries and twinned sites.

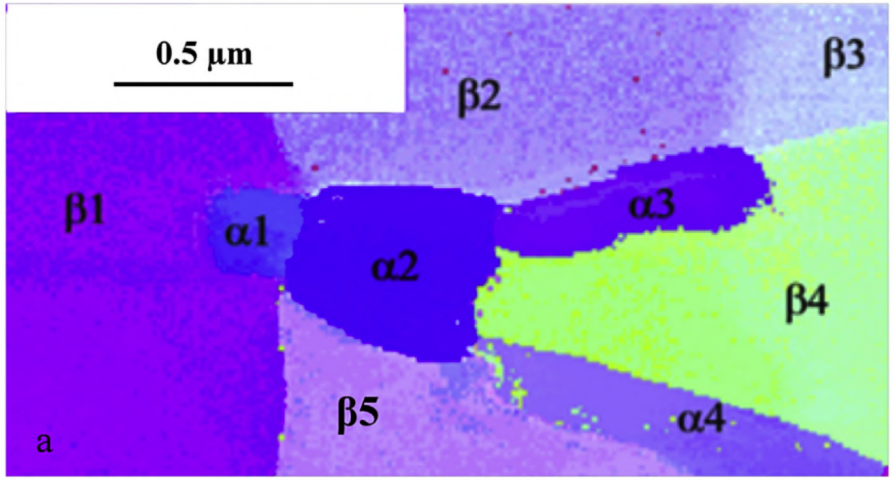


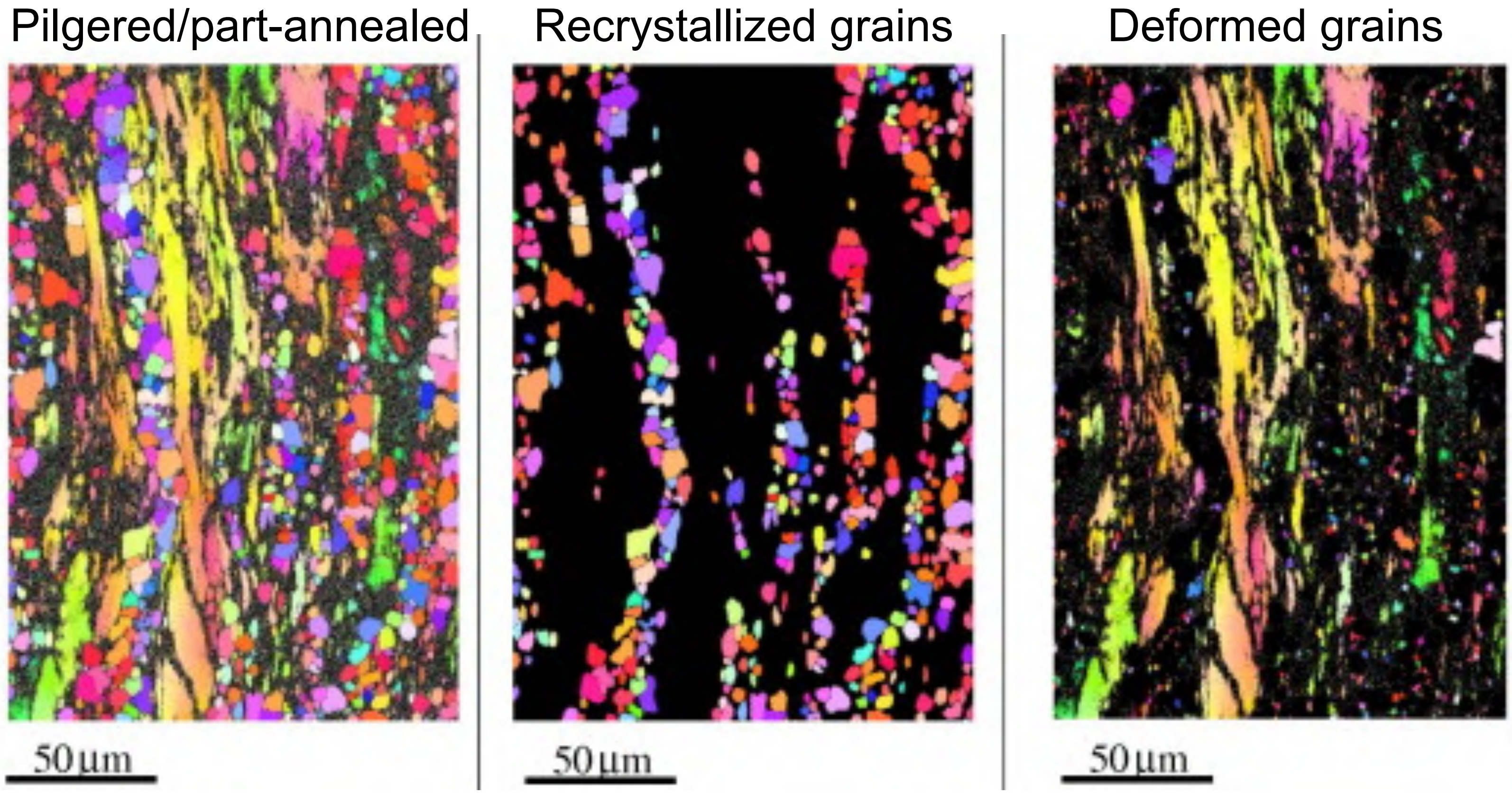



# Dynamic Recovery and Dynamic Recrystallization

- In Zr and Ti alloys which are processed at higher temperatures…

- Processes of Recovery and Recrystallization can occur during high temp. deformation (dynamically).




→ Resulting in new spheroidised grains / orientations forming during deformation.

# Globularisation

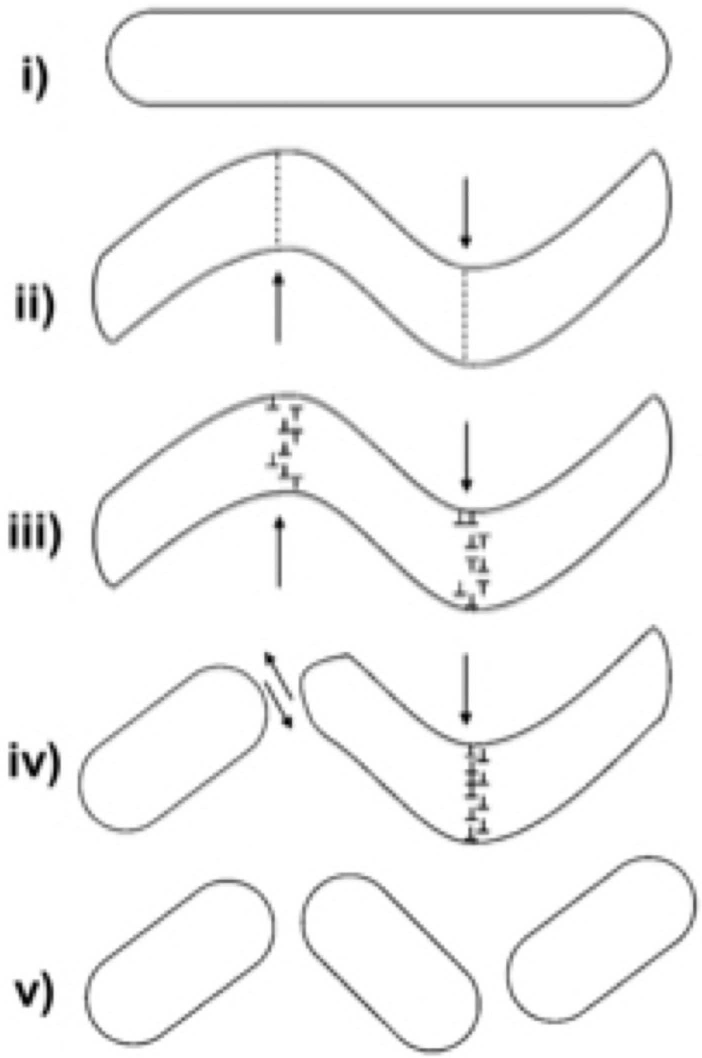
i) Starting α-lath

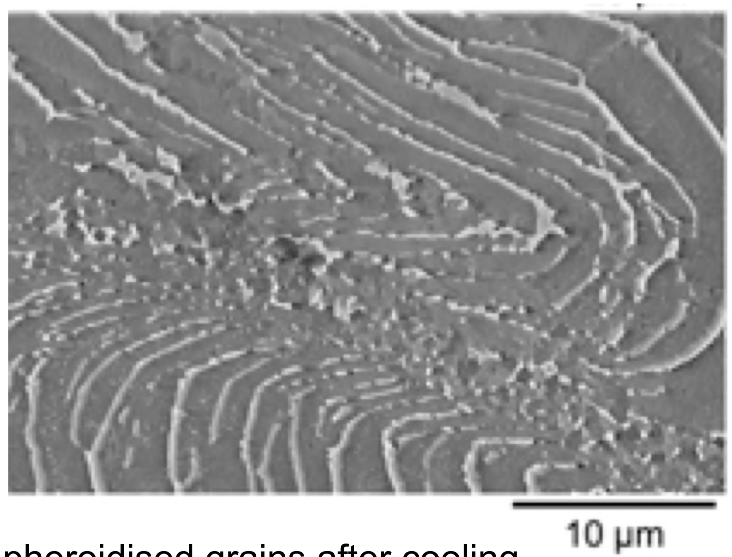
ii) Deformation band formation

iii) Dislocation formation and rearrangement (via recovery)

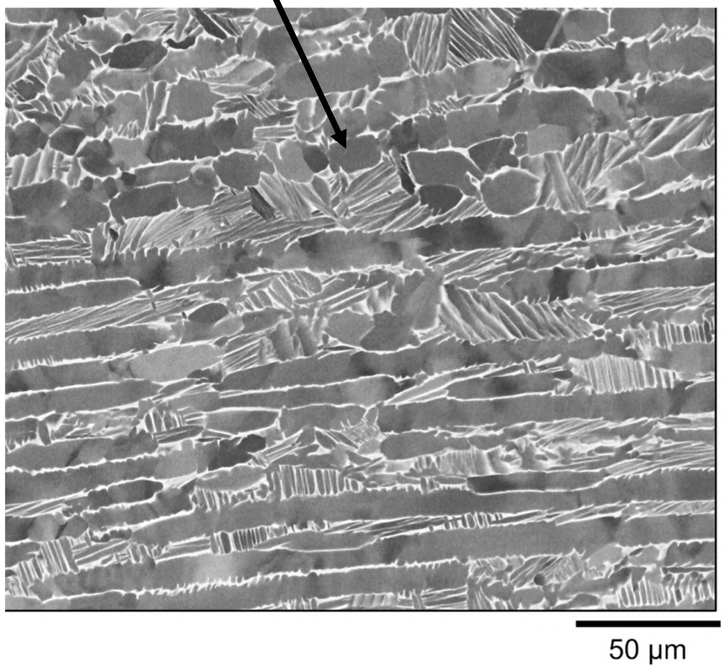
iv) β-phase ingress at points of high dislocation density

v) Spheroidised α-grains




Spheroidised grains after cooling.



# Dynamic Transformation

- On top of this, new observations also show phase transformation during processing (dynamic transformation).

- **All of these processes make analysing and modelling microstructure and texture evolution in Zr and Ti alloys a very interesting job!**