HOMEWORK
From Dieter
4-16

Module #12

Deformation Twinning and Kink Bands

Reading
DIETER: Ch. 4, Pages 132-138

HERTZBERG: Ch. 3
References in Bibliography

Bibliography

1. Mahajan, S; Williams, DF; “Deformation Twinning in Metals and Alloys,” International Metallurgical Reviews, June 1973, Vol. 18, pp. 43-61.
2. J.W. Christian and S. Mahajan; “Deformation Twinning,” Progress in Materials Science, 1995, Vol. 39, pp. 1-157.
3. R.E. Reed-Hill and R. Abbaschian, Physical Metallurgy Principles, 3rd edition (PWS-Kent, Boston, MA, 1992), pp. 538-560.
4. A. Kelly, G.W. Groves, and P. Kidd, Crystallography and Crystal Defects, Revised Edition (John Wiley & Sons, 2000), chapter 10, pp.315-338.
5. Pages 132-135 in Dieter (Ch. 4).
6. Pages 170-185 in Hosford.
7. C.N. Reid, Deformation Geometry for Materials Scientists, (Pergamon Press, Oxford, UK, 1973), chapter 7, pp. 179202

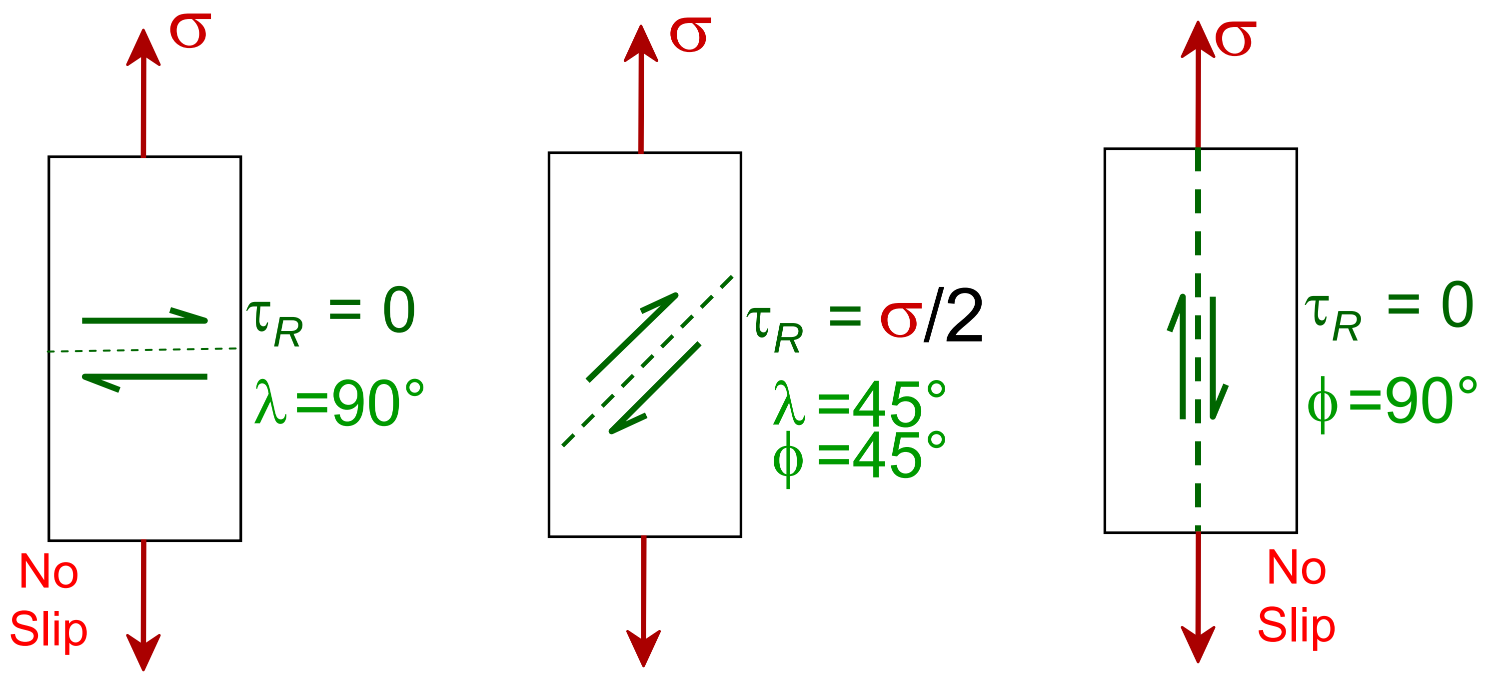
Critical Resolved Shear Stress

- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically 10^{-4} GPa to 10^{-2} GPa

- Crystal orientation can make it easy or hard to move dislocation

$$\tau_R = \sigma \cos\lambda \cos\phi$$



τ maximum at $\lambda = \phi = 45°$

Forms of deformation other than slip

- Shear transformations represent an alternative to slip for inelastic (i.e., plastic) deformation.

- Types of shear transformations:

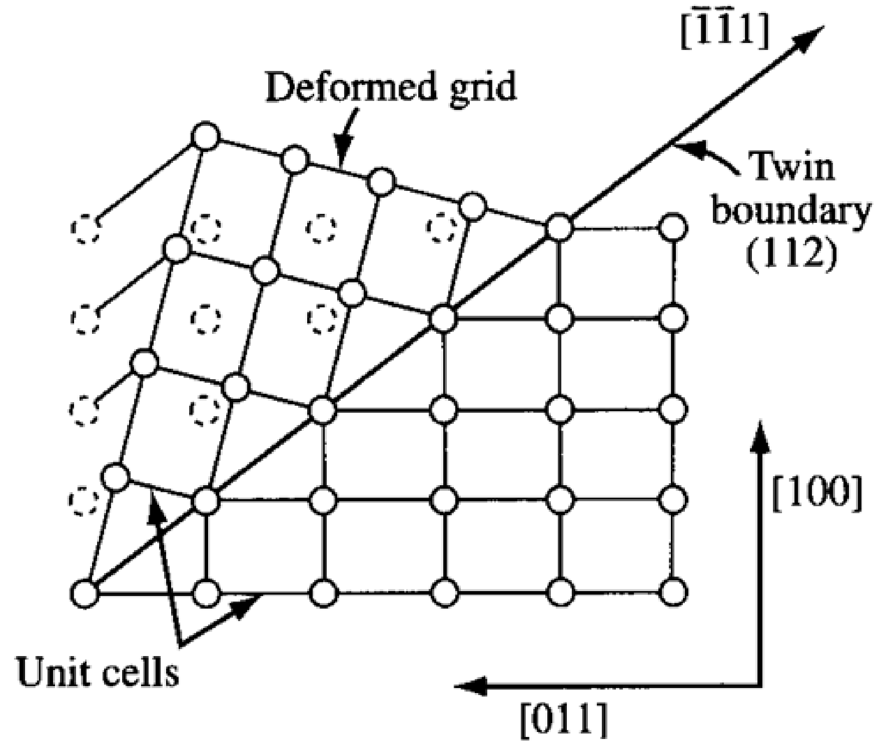
  – Deformation Twinning

  – Stress-induced Martensitic Transformations

  – Macroscopic Kinking

Deformation twinning

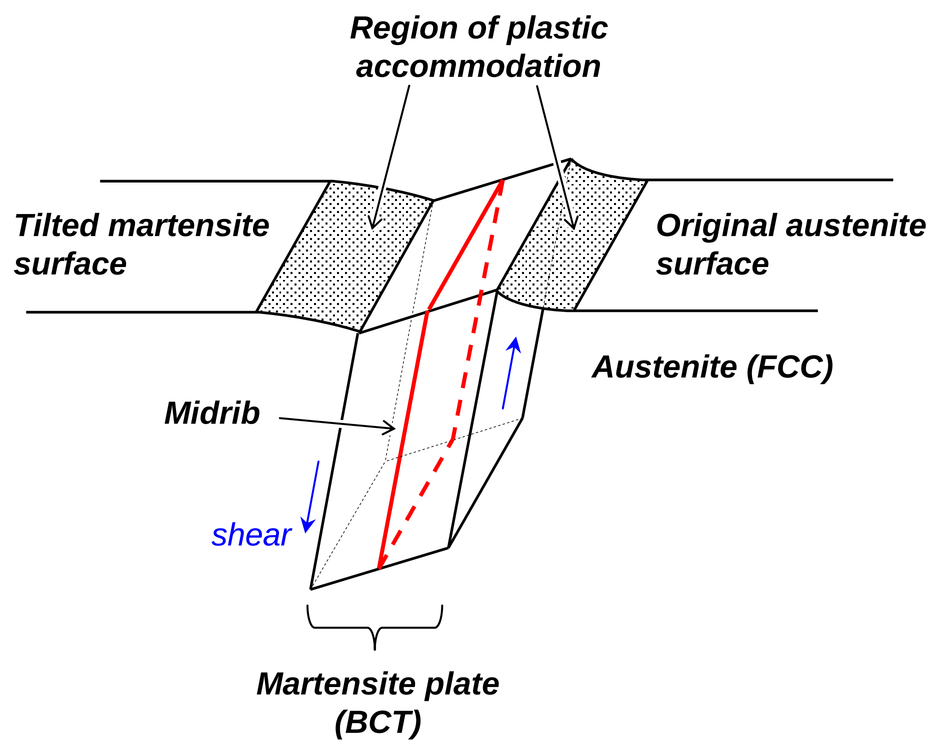
- The lattice inside a specific volume element undergoes an atomically homogeneous shear strain.
- This strain transforms the lattice into a mirror image of the exterior with respect to a reference plane (i.e., the twin plane/boundary).



Geometry of twinning in a BCC crystal. Figure adapted from A.S. Argon, Strengthening Mechanisms in Crystal Plasticity, (Oxford University Press, Oxford, 2008) p. 63.

Stress-induced Martensitic Transformation

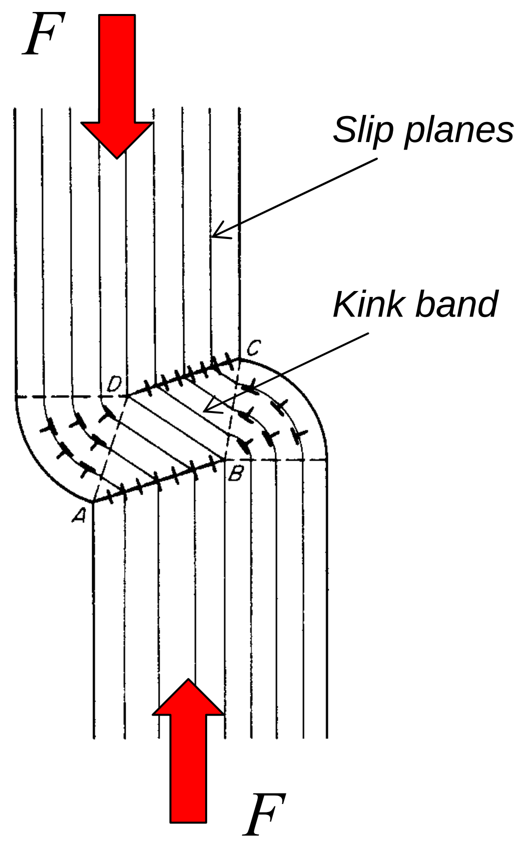
- Phase transformation. Produces a sheared region.
- Observed many materials:
  - Carbon Steels:
    - FCC γ-Fe $\rightarrow$ BCT
  - Ti alloys
    - BCC $\rightarrow$ HCP
  - Cu-Zn alloys
    - BCC $\rightarrow$ FCT
  - ZrO_2
    - Tetragonal $\rightarrow$ Monoclinic
  - Etc…



Schematic of shear that occurs during martensite formation. Figure adapted from G. Krauss, Steels: Processing, Structure, and Performance, (ASM International, Materials Park, 2005) p. 58.

Kink Bands

- Observed in some materials oriented such that there is no resolved shear stress for slip.
- The crystal essentially buckles locally.
- Can occur in compression and tension.

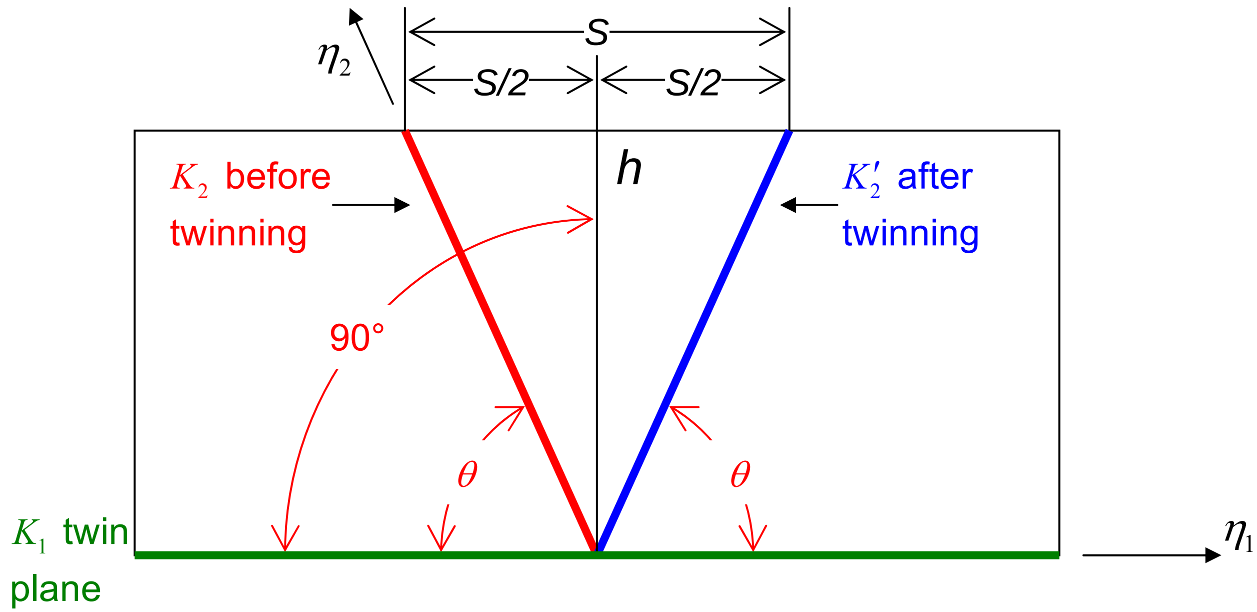


Schematic of a kink band and associated dislocation distribution. Adapted from R.W.K. Honeycombe, The Plastic Deformation of Metals, 2nd Ed., (ASM, 1984) p. 201.

Deformation Twinning

- Also known as ‘mechanical twinning’.
- Second most important mechanism of plastic deformation after slip.
- It is not as common as slip, but it <u>can be</u> a main cause of plastic deformation.
- Twinning can also occur along with slip.

Crystallography of twins



Every structure has its own specific set of twinning elements.

θ = angle between K_1 and K_2

S = the shear displacement of the upper surface relative to the bottom

h = width of the twin

K_1 = the twinning plane (1st undistorted plane)

K'_2 = the 2nd undistorted plane

η_1 = shear direction

η_2 = direction defined by intersection of shear plane with K_2

$$\gamma = \frac{S}{h} = 2\tan(90° - \theta) = 2\cot\theta$$

Crystallography of twins

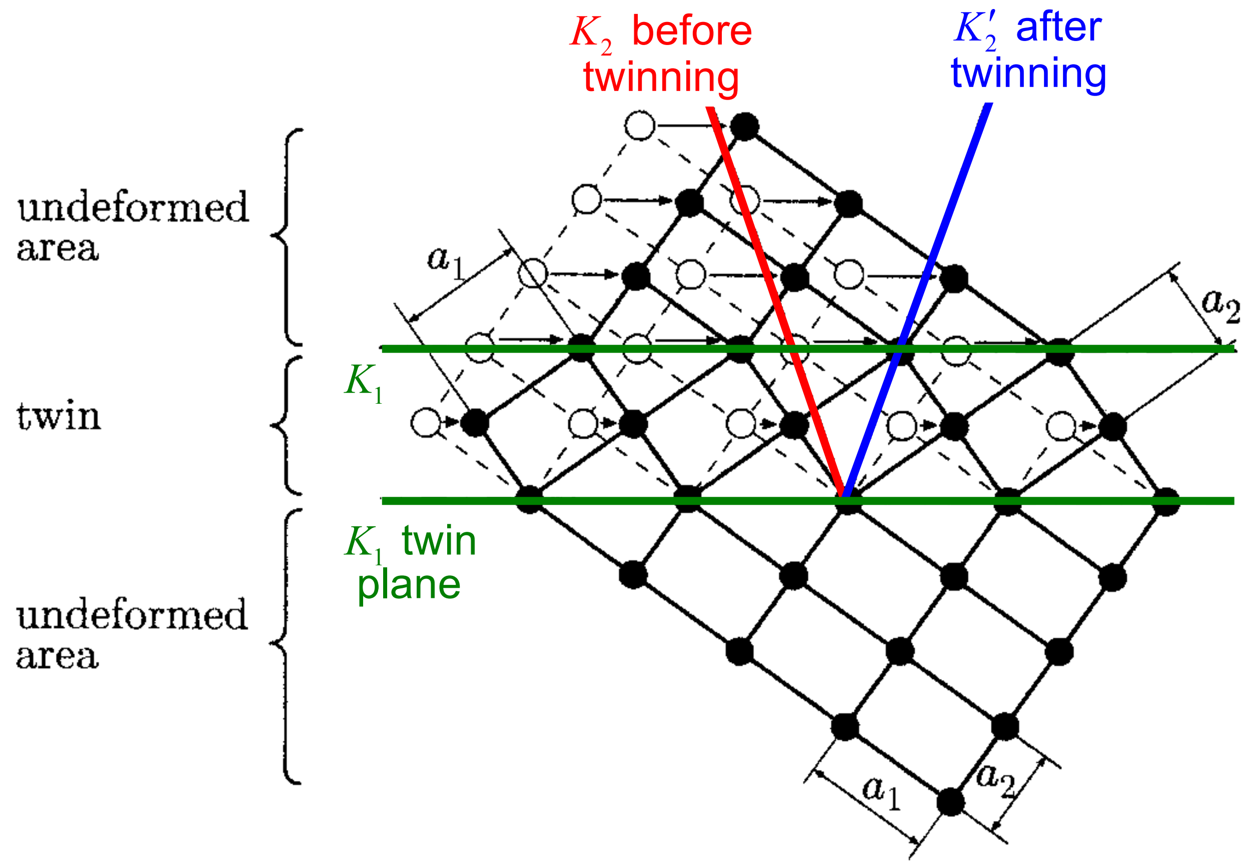


Figure showing the formation of a twin band. Figure adapted from Roesler et al., Mechanical Behavior of Engineering Materials, (Springer, New York, 2008) p. 224.

Where does deformation twinning occur?

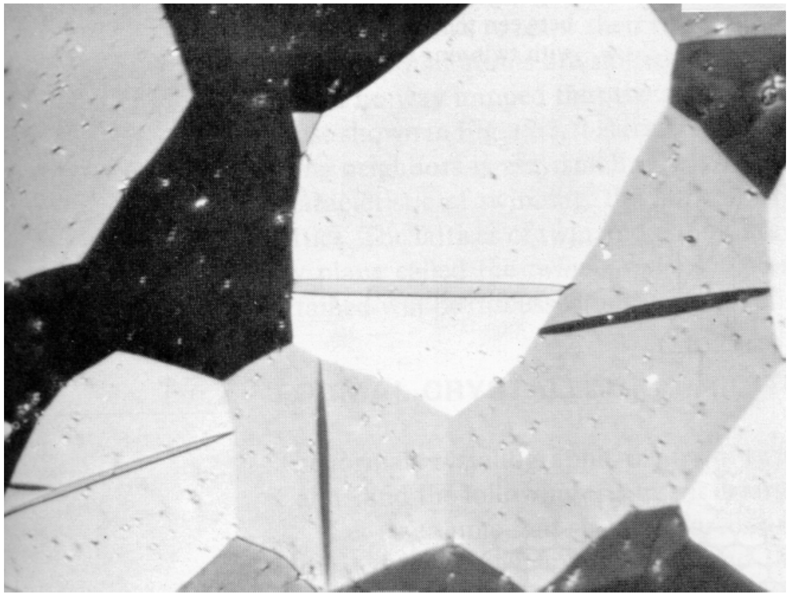
- Hexagonal metals such as Zn and Mg twin when they are deformed at ambient temperatures.

- BCC metals such as Fe twin when they are deformed at sub-ambient temperatures.

Twinning Planes, Directions, and Shears

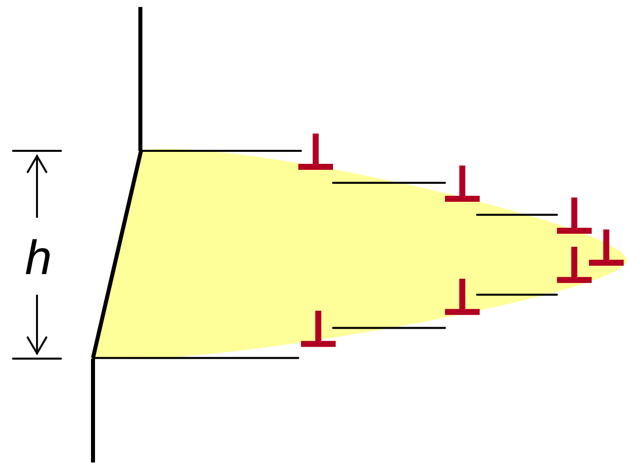
Structure	Twin Plane & Direction	Shear	Max. strain
FCC	(111)[112]	0.707	41.4%
BCC	(112)[111]	0.707	41.4%
		Cd: 0.171	8.9%
		Zn: 0.139	7.2%
HCP	$(10\underline{1}2)[10\underline{1}\underline{1}]$	Mg: 0.129	6.8%
		Ti: 0.139	8.7%
		Be: 0.199	10.4%

What do deformation twins look like?



Deformation twins in Zr
[Reed-Hill, p. 539]

- Tend to be lens-shaped.



- Can be represented by arrays of dislocations.

- Central plane is approximately parallel to K_1.
- Many models for deformation twins (e.g., pole mechanisms).
- See a reference like Hirth and Lothe or one of the review articles on the reading list for more details.

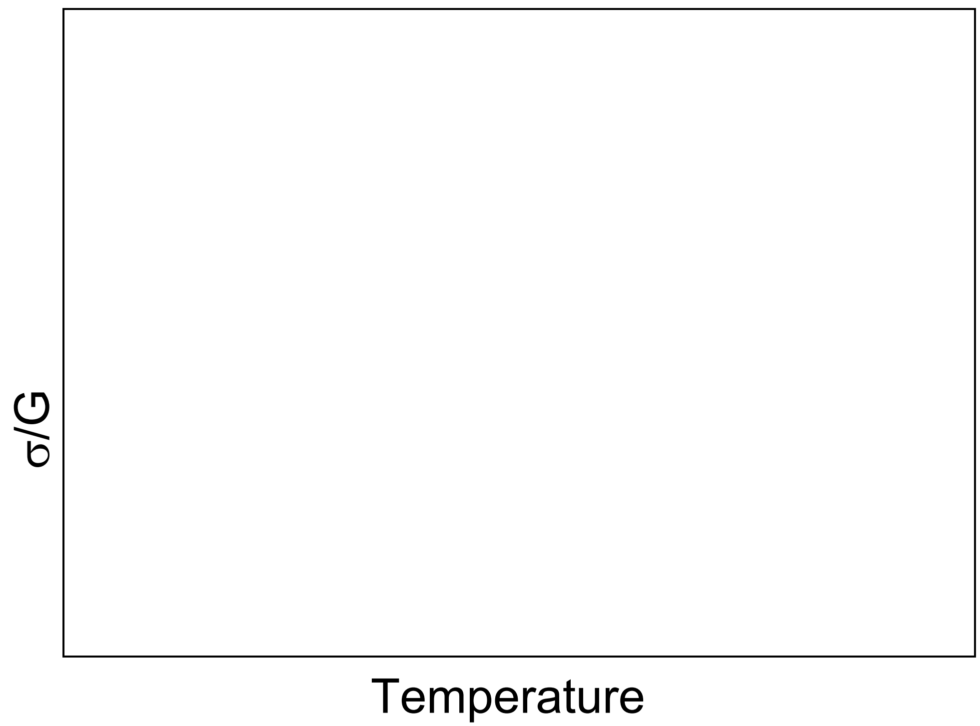
Plastic deformation via twinning (1)

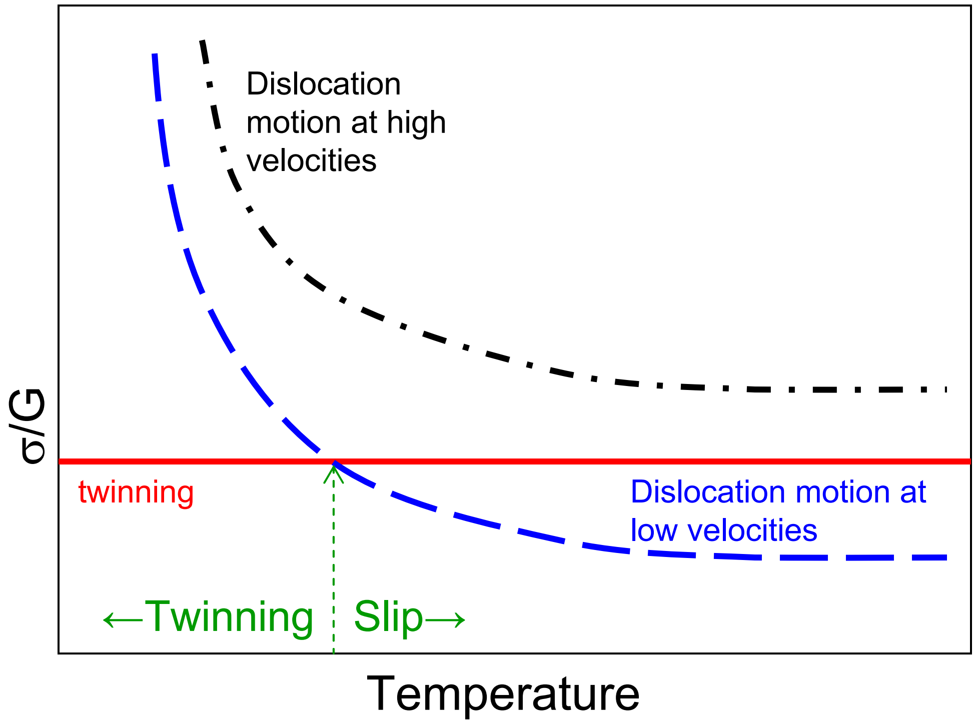
It is different from slip

- After twinning, the twinned region of a grain is a mirror image of the original lattice. After slip, the slipped region will have the same orientation as the original grain.
- Twinning consists of uniform shear strain while Slip consists of shear displacement of an entire block of a crystal.
- The twinning direction is always polar (i.e., in a single direction) while the slip direction can be positive or negative.
- Twinning causes a change of shape of a specific type and magnitude as determined by crystallography. This is not so with slip. The shape change varies with slip.

Plastic deformation via twinning (2)

- The stress required to form a twin is generally much larger than that required to cause slip. It is also less sensitive to temperature.





- Twinning tends to occur in instances where plastic deformation via slip (or diffusion) is hindered.
  - BCC metals at low temperatures
  - High strain-rate (ballistic) deformation
  - Etc…

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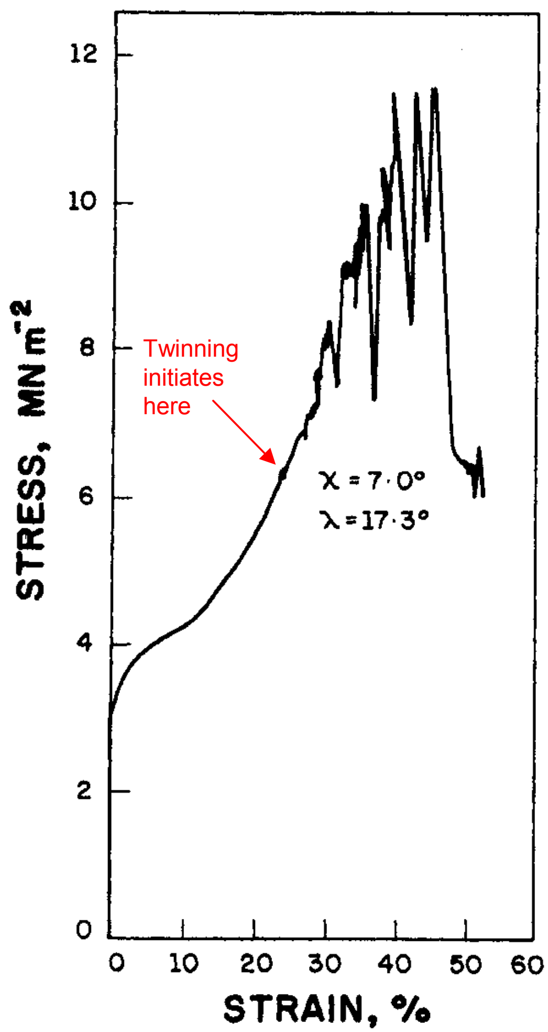


[Meyers & Chawla, 1st ed, p. 267]

- Twins form and move very quickly (near the speed of sound). This leads to the “cry” heard when polycrystalline Sn is bent plastically.

- The formation and motion of twins during straining can lead to serrated stress-strain curves as is shown for Cd on the left.

Influence of stacking-fault energy on twinning

- Recall: a reduction in stacking fault energy facilitates the formation of stacking faults.
- This also promotes twinning.
- WHY?

Anything else?

Influence of stacking-fault energy on twinning

- Recall: a reduction in stacking fault energy facilitates the formation of stacking faults.
- This also promotes twinning.
- WHY?

Cross-slip of dislocations is inhibited leading to planar slip.

Anything else?

B*

CAN TWINNING CONTRIBUTE TO PLASTIC DEFORMATION?

- Yes!

- Twinning can contribute due to the shear that it produces.

- This plastic strain however is very small.

► Twinning "may" also reorient part of a crystal such that its becomes favorable for slip to occur.

  – Remember, rotation or re-orientation of a crystal changes the Schmid factor.

This corresponds to case where the entire single crystal twins.

Table 17.1 Twinning Modes in Selected Metals

Crystal Structure	Metal	Twin Mode	Twinning Shear, S	Maximum Tensile Strain Single Crystal
Face-Centered Cubic	All	$\{111\}\langle 11\bar{2}\rangle$	0.707	0.40
Body-Centered Cubic	All	$\{112\}\langle 11\bar{1}\rangle$	0.707	0.40
Hexagonal Close-Packed	Be	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.19	0.095
	Ti	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.18	0.09
	Ti	$\{10\bar{1}1\}\langle 10\bar{1}\bar{2}\rangle$	0.10	0.05
	Ti	$\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$	0.22	0.11
	Ti	$\{11\bar{2}4\}\langle 22\bar{4}\bar{3}\rangle$	0.22	0.11
	Zr	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.17	0.085
	Zr	$\{11\bar{2}1\}\langle 11\bar{2}\bar{6}\rangle$	0.63	0.35
	Zr	$\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$	0.23	0.12
	Mg	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.13	0.065
	Mg	$\{10\bar{1}1\}\langle 10\bar{1}\bar{2}\rangle$	0.14	0.07
	Zn	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.14	0.07
	Cd	$\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$	0.17	0.085

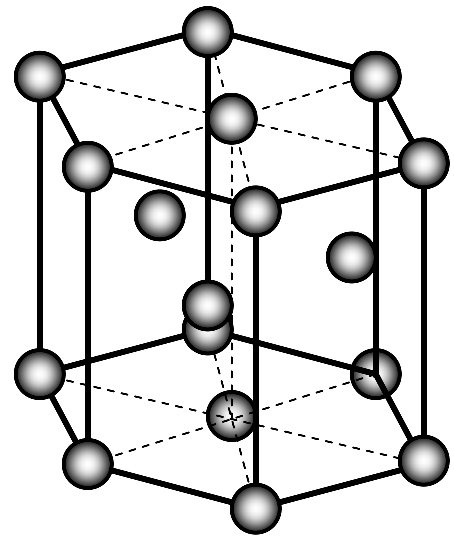
Twin strains <u>can be</u> large. Generally they are not.

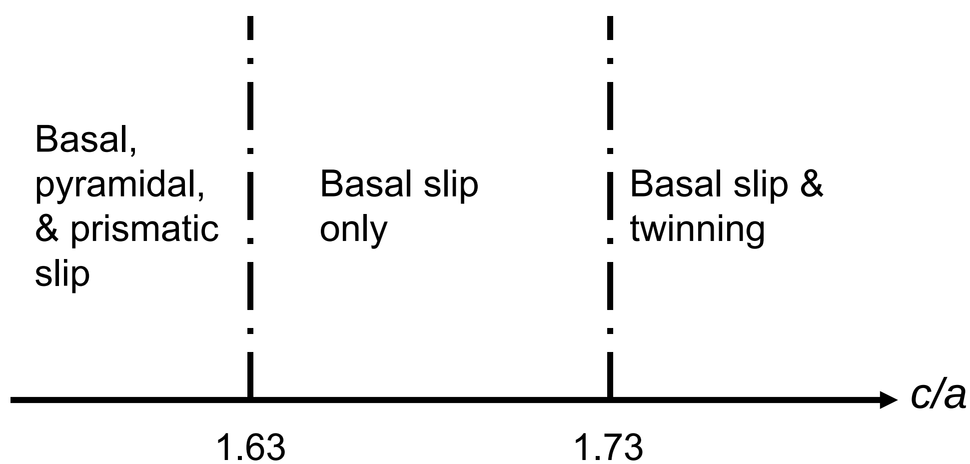
[Reed-Hill]

13. Schmid, E., and Boas, W., *Kristallplastizität*, p. 64. Julius Springer, Berlin, 1935.

For a more thorough explanation of deformation twinning, see your Physical Metallurgy textbook or one of the recommended references.

Influence of *c/a* ratio on twinning in hexagonal crystals





Contrasts between slip and twinning

SLIP	TWINNING
1.	1.
2.	2.
3.	3.
4.	4.
5.	5.
•	•

A*

Contrasts between slip and twinning

SLIP

1. Occurs in atomic distances
2. Shear strain is not uniform
3. Occurs in both directions
4. Preserves crystal orientation
5. Stress to cause yielding is lower than the stress to continue deformation
   - $\tau_{yield} < \tau_{flow}$

TWINNING

1. Occurs in fractions of atomic distances
2. Displacement is uniform from one plane to the next.
3. Unidirectional.
4. Changes crystal orientation (mirror)
5. Stress to nucleate a twin is greater than the stress to move a twin
   - $\tau_{nucleation} > \tau_{flow}$

B*

Kink Bands*

- Orowan (1942)

► Secondary deformation mode that is initiated by “localized” slip.

- Macroscopic mechanism. Not to be confused with kinking of dislocations.

► Kink bands correspond to localized and symmetric bending of the structure about an axis that lies in the slip plane and perpendicular to the slip direction.

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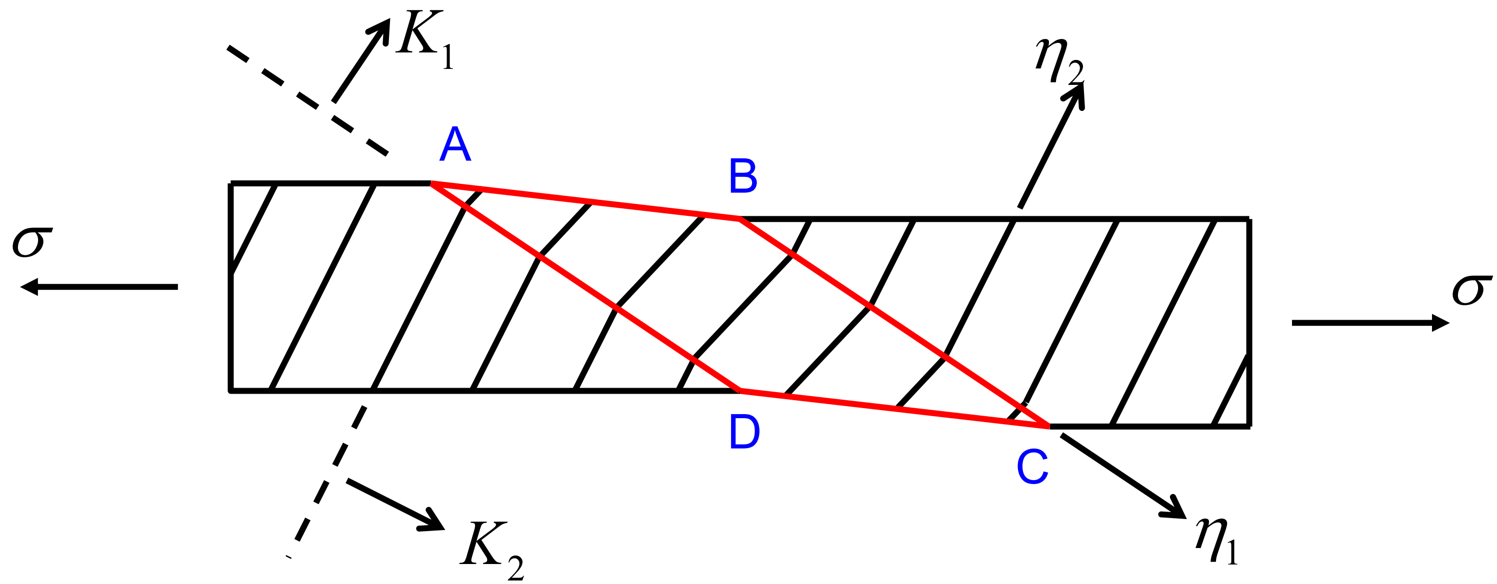
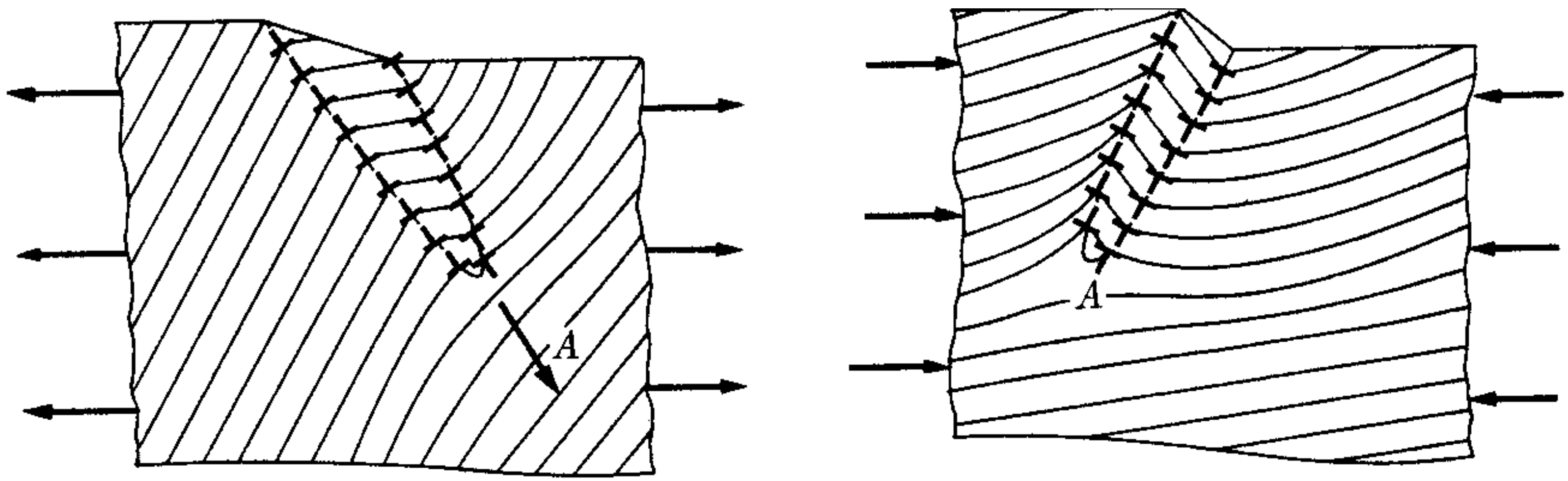
* A.G. Crocker and J.S. Abell, “The crystallography of deformation kinking,” *Philosophical Magazine* 33 (1976) 305-310.
* J.B. Hess and C.S. Barrett, “Structure and nature of kink bands in zinc,” *Trans. Metall. Soc. AIME* 185 (1949) 599-606.

Crystallography of kink bands



- Slip occurs on planes K_2 in the direction η_1.
- Due to an enhanced local change in the specimen axis, slip becomes concentrated in region ABCD.
- Boundaries AD and BD orient themselves so as to become symmetric with respect to the structure. The deformation is in essence a simple shear on the plane K_1 in the direction η_1.
- [Adapted from A.G. Crocker and J.S. Abell, "The crystallography of deformation kinking," *Philosophical Magazine* 33 (1976) 305-310].



[McClintock and Argon, p. 135]

- When crystals with only one set of easy slip planes nearly normal to the tensile axis are extended.
- When crystals with their slip systems nearly parallel to the compression axis are compressed.
- Has been observed in FCC, BCC, HCP, and ionic crystals.

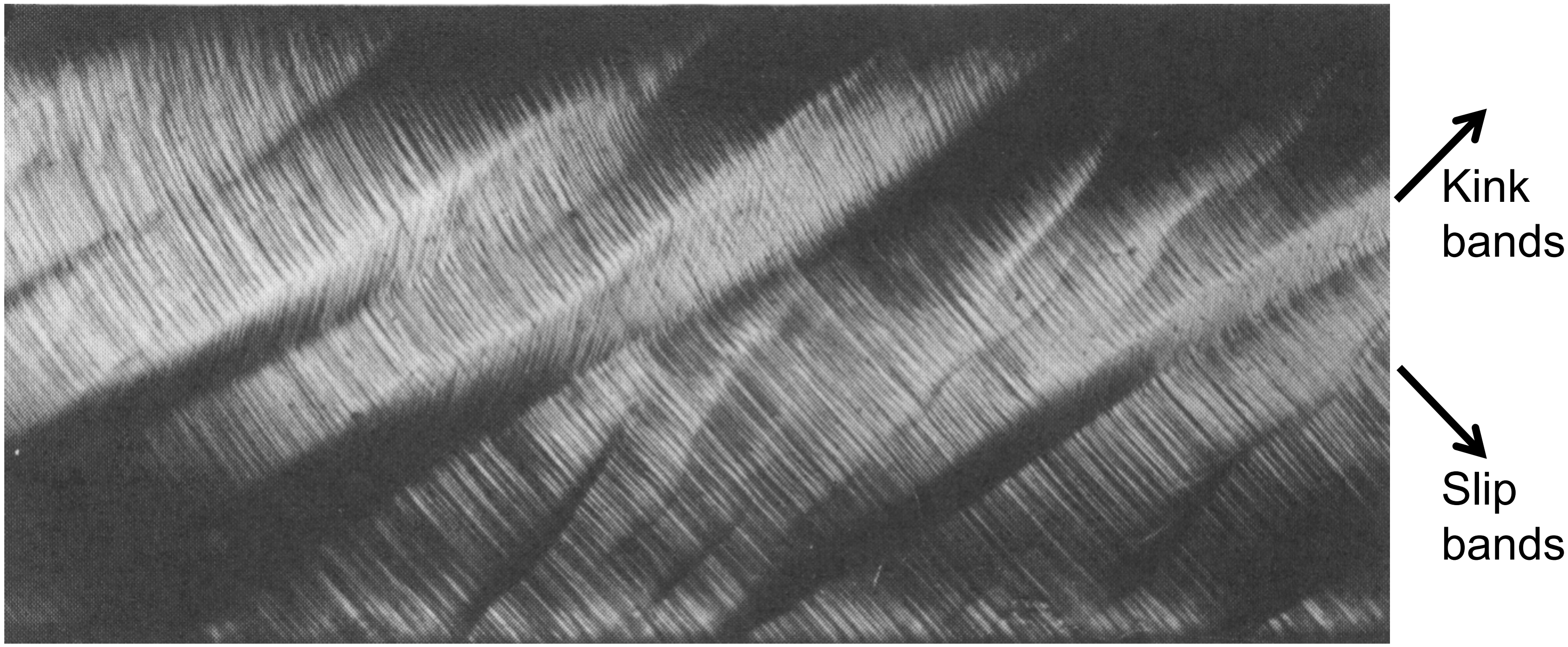


Fig. 8.4. Kink bands in an Al single crystal deformed 17.5% in tension. 100X. [Copied from R.W.K. Honeycombe, The Plastic Deformation of Metals, 2nd Edition (American Society for Metals, 1984) p. 203.]

Kink bands often occur:

1. When there is no resolved shear stress for slip (compression or tension).

2. In layered structures such as the so-called $M_{n+1}AX_n$ (MAX) phases.

3. When twin re-orientation inhibits slip or induces buckling stresses.

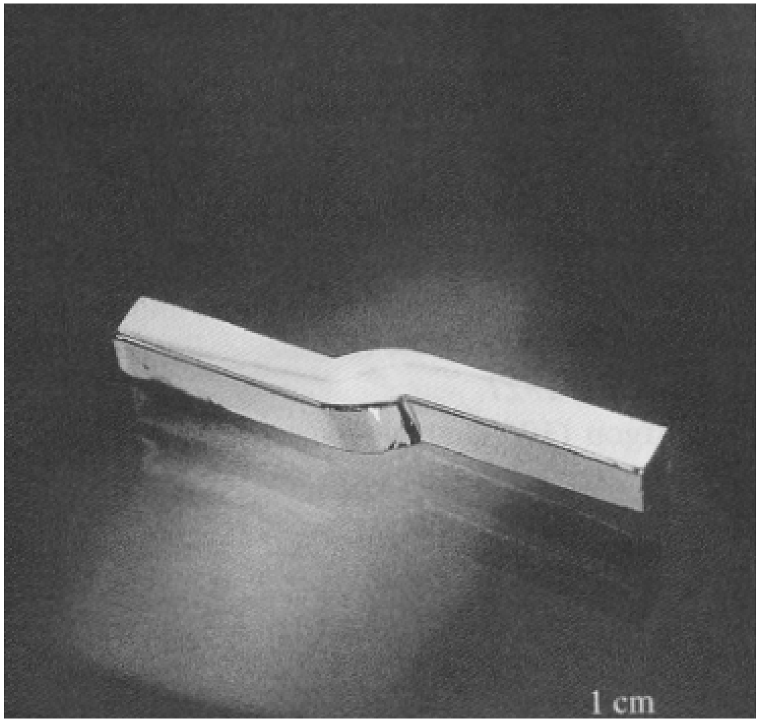


Fig. 2.21. A macroscopic kink in a Cd crystal (courtesy of J. J. Gilman, private communication, 1961). Figure adapted from A.S. Argon, Strengthening Mechanisms in Crystal Plasticity, (Oxford University Press, Oxford, 2008).