



Module #11

Plastic Deformation in Crystalline Solids

READING LIST DIETER: Ch. 4, pp. 124-132, 135-137, and 139-144

> Hertzberg: Ch. 3 Courtney: Ch. 4



RECALL

- Consider SLIP in a single crystal oriented at the angle φ with respect to the tensile axis.
- NORMAL Force: $F_N = F \cos \phi$
- SHEAR Force: $F_S = F \cos \lambda$.
- Area of slip-plane: $A_s = A/COS\phi$ (check: A_s must have larger area than A.)

NORMAL Stress to the ϕ -plane: $\sigma_{\rm N} = F_{\rm N} / A_{\rm s} = (F\cos\phi)/(A_{\rm o}/\cos\phi) = \sigma \cos^2\phi$

SHEAR Stress in the ϕ -plane: $\tau_{\rm s} = F_{\rm s} / A_{\rm s} = (F\cos\lambda)/(A_{\rm o}/\cos\phi) = \sigma \cos\phi \cos\lambda$

The shear stress causes slip to occur. Slip is not in same direction as tilt of plane!



$$\tau_{RSS} = \sigma_{flow} \underbrace{\cos \phi \cos \lambda}_{\text{Schmid Factor}} = \sigma_{flow} m$$

- The active slip system will have the largest Schmid factor. We'll address this a little later.
- The critical resolved shear stress is:

$$\tau_{CRSS} = \sigma_y \cos\phi \cos = \sigma_y m$$



- τ_{CRSS} is the resolved shear stress needed for slip.
- It is a function of temperature, impurity level, strain rate, and dislocation density

Factors influencing σ_{ys} or τ_{CRSS}

► Temperature

– Increase $T \rightarrow$ decrease τ_{CRSS} .

► Strain rate

- Decrease $\dot{\varepsilon} \rightarrow$ decrease τ_{CRSS} .

• Defect content

- Impurity level
 - Decrease impurity content \rightarrow decrease τ_{CRSS} .
- Dislocation density
 - Decrease $\rho_{\perp} \rightarrow$ decrease τ_{CRSS} .
- Etc...

au_{CRSS} as a function of T and $\dot{\varepsilon}$



Figure 4.2:

Schematic illustrating the variation of τ_{CRSS} with temperature and strain rate. [Adapted from Courtney, p. 143].

Seeger, 1954

Flow stresses in crystals consist of two components, an athermal component τ_a which is proportional to the shear modulus, and a thermal component τ^* that is more sensitive to temperature and strain rate.

$$\tau_{CRSS} = \tau_{\mu} + \tau^*$$

 τ_{μ} is the athermal component of flow stress ($\tau_{\mu} \neq F(T)$) τ^* is the thermally dependent component of flow stress $(\tau^* \downarrow \text{ as } T \uparrow)$

The components of $T_{internal}$

- τ_{μ} (athermal)
 - Arises from the stress to move dislocations in the presence of long-range internal stress fields.
 - Long-range stresses are present over large distances in comparison to atomic dimensions. Examples of such barriers include the stress fields of other dislocations.

• τ^* (thermally dependent)

- Represents resistance to dislocation motion due to "short-range barriers" (i.e., atomic scale barriers). These barriers are so small that temperature induced thermal vibrations can affect the Peierls stress (i.e., lattice friction). Examples of such barriers include dislocation kinks and segregated/interacting impurity atoms.
- This component decreases as *T* increases and goes to zero at temperatures where short-range obstacles become ineffective in restriction dislocations.

Thermally activated flow

- Very important in creep. Can play a significant role in deformation above 0 K. Can reduce stress necessary to overcome obstacles.
- Consider an effective stress which drives dislocation motion. The effective stress, τ_{eff} , is:

$$\tau_{eff} = \tau_{applied} - \tau_{internal}$$

- The internal stress, $\tau_{internal}$, is the stress that resists dislocation motion.
- $\tau_{internal}$ consists of two terms:
 - (1) a resistance to long-range obstacles (>10 atom diameters) that cannot be overcome by thermal fluctuation, τ_{μ} ;
 - (2) a resistance to short-range obstacles (~10 atom diameters) that can be overcome by thermal fluctuations, τ^* .

$$\begin{aligned} \tau_{internal} &= \tau_{\mu} + \tau^{*} \\ \vdots \\ \tau_{eff} &= \tau_{applied} - \left(\tau_{\mu} + \tau^{*}\right) \end{aligned}$$

$$\tau_{internal} = \tau_a + \tau^*$$
Rate
of ov
strong
obstato
top or
range
resistance
to flow
-

Rate limiting step consists of overcoming the strongest short-range obstacle situated near the top of the opposing longrange stress field.

Figure 8-20 Schematic representation of superimposed long-range and short-range stress fields. (Originally adapted from H. Conrad, *Materials Science and Engineering*, v. 6 (1970) pp. 265-273).



For thermal fluctuations to assist dislocation motion, enough energy (i.e., ΔH) must be supplied to overcome the short-range stress fields.

Figure 8-21 Thermal activation barrier.

[Figures copied from Dieter, p. 312]

Overcoming short-range barriers

• Apply a stress $\tau > \tau_a$. The force on this dislocation is:

$$F = \tau^* b L^*$$

where L^* is the length of dislocation segment involved in thermal fluctuation.

- Energy (ΔH) must be supplied to overcome the superimposed short-range barriers.
- The work done by the applied stress during thermal activation is:

$$W = \tau^* \left(x_o^* - x_o \right) b$$

Short-range barriers – cont'd

 The energy, ΔH, is the area beneath the forcedistance curve between x_o^{*} and x_o. It is designated as:

$$\Delta H = \int_{x_o}^{x_o^*} \left[F(x) - \tau^* b d^* \right] dx = \Delta H^* - v^* \tau^*$$

where ΔH^* is the activation energy at zero applied stress.

 v^{*} is known as the <u>activation volume</u>. It represents the average area swept out by the dislocation during some thermally activated event.

Activation Volume

- The <u>activation volume</u> $v^* = L^*bd^* = A^*b$. A^* is known as the activation area.
- The activation volume is important because it can be used to identify the mechanism controlling the thermally activated process.
- This is done by comparing the values of ΔH and v^* with values predicted from specific dislocation models.

Climb mechanism	$v^* = 1 b^3$
Peierls-Nabarro mechanism	$v^* = 10 - 10^2 b^3$
Cross slip mechanism	$v^* = 10 - 10^2 b^3$
\perp Intersection mechanism	$v^* = 10^2 - 10^4 b^3$
Non-conservative motion of jogs	$v^* = 10^2 - 10^4 b^3$

$\tau_{CRSS} = \tau_{\mu} + \tau^{*}$ $\tau_{CRSS} = \tau_{\mu} + \tau^{*}$

Figure 4.2:

Schematic illustrating the variation of τ_{CRSS} with temperature and strain rate. [Adapted from Courtney, p. 143].

[1]

- Region I ($T \le 0.25T_{mp}$)
 - τ_{CRSS} \uparrow with \downarrow *T*.
 - au_{CRSS} \uparrow with \uparrow $\dot{\epsilon}$.
 - Athermal component of flow stress is large. Difficult for dislocations to surmount short-range barriers.

au_{CRSS} as a function of T and $\dot{\varepsilon}$ $|\tau_{CRSS} = \tau_{\mu} + \tau$ au_{CRSS} П Ш I ~0.25 T_{mp} ~0.7 T_{mp} T

Figure 4.2:

Schematic illustrating the variation of τ_{CRSS} with temperature and strain rate. [Adapted from Courtney, p. 143].

[2]

- Region III $(T \ge 0.7T_{mp})$ •
 - In this temperature range, diffusive processes become important. Diffusion aids dislocation motion (i.e., makes it easier for dislocations to surmount barriers to their motion).
 - Both $\tau_{\mu} \& \tau^* \downarrow$ as $T \uparrow$.
 - $-\tau_{CRSS}\downarrow$ with \uparrow T.
 - τ_{CRSS} \uparrow with $\uparrow \dot{\epsilon}$.

$\tau_{CRSS} = \tau_{\mu} + \tau^{*}$ $\tau_{\mu} = \tau_{\mu} + \tau^{*}$

Figure 4.2:

Schematic illustrating the variation of τ_{CRSS} with temperature and strain rate. [Adapted from Courtney, p. 143].

- Region II $(0.25T_{mp} < T < 0.7T_{mp})$
 - In this temperature range, $\tau_{\mu} \neq F(T) \& \tau^* \cong 0$; $\therefore \tau_{CRSS} = constant$.
 - Temperature is too low for diffusion to influence permanent deformation, thus $\tau \cong \tau_{\mu} \neq F(T)$.
 - Does crystal structure play a role?

au_{CRSS} as a function of T and $\dot{\varepsilon}$

Full caption from Figure 4.2

Figure 4.2:

Schematic illustrating the variation of τ_{CRSS} with temperature and strain rate. At high temperatures (Region III), τ_{CRSS} is a strong function of both variables. At intermediate temperatures τ_{CRSS} is independent of strain rate and temperature and is given by τ_{μ} . At lower temperatures, τ_{CRSS} again increases with decreasing temperature and increasing strain rate. Thus, for example, at temperature T_1 , τ_{CRSS} can be considered to be the sum of the athermal stress τ_{μ} and a thermally dependent stress τ^* . At the transition from Region I to Region II, τ^* effectively becomes zero. [Adapted from Courtney, p. 143].

Temperature variation of $\tau_{\rm CRSS}$ for various materials



Figure 4.3:

The temperature variation of τ_{CRSS} for materials with different structures and bonding characteristics. [Adapted from Courtney, p. 144]

KEY POINTS:

- <u>FCC metals</u> have low resistance to plastic deformation (i.e., they are weaker)
- <u>BCC metals</u> have much higher resistances to plastic deformation (i.e., they are generally stronger)
- *T* dependence of τ_{CRSS} :

-BCC - high; FCC - lower

- Impurities $\uparrow \tau_{\rm CRSS}$, sometimes greatly (principle behind solid solution hardening)
- <u>lonically bonded</u> materials have low τ_{CRSS} (Ex., NaCl, CsCl, etc.)
- <u>Covalently bonded</u> materials have high τ_{CRSS} (Ex., TiC, diamond, etc.)



- There are also temperature effects.
- Yield stress (and CRSS) increases as *T* decreases.

Figure

Stress dependence of the velocity of edge dislocations in 3.25% silicon iron at four temperatures (after Stein and Low, *J. Appl. Phys.* **31**, 362, 1960). Scanned from E.W. Billington and A. Tate, <u>The Physics of Deformation and Flow</u>, McGraw-Hill, New York, 1981, pages 418 and 420.

The dependence of dislocation velocity on applied shear stress for a variety of materials.

Figure scanned from D. Hull and D.J. Bacon, <u>Introduction to</u> <u>Dislocations, 4th Edition,</u> (Butterworth-Heinemann, Oxford, 2001) p. 51; originally adapted from Haasen, <u>Physical</u> <u>Metallurgy, 3rd Edition,</u> (Cambridge University Press, Cambridge, 1996) p. 283.



- Dislocation velocity also varies from material to material.
- Could there also be some relationship to crystal structure, elastic properties, and/or melting temperature?
- Think about it!

Characteristic tensile stress-strain curve for a single crystal



3 stages of work hardening for single crystals

Stage I	Stage II	Stage III
Easy	Linear	Parabolic
Glide	Hardening	Hardening

Deformation of single crystals (1)



Stage I:

- After yielding, the shear stress for plastic deformation is essentially constant. There is little or no work hardening.
- This is typical when there is a single slip system operative. Dislocations do not interact much with each other. "Easy glide"
- Active slip system is one with maximum Schmid factor (i.e., $m = \cos\phi \cos\lambda$)

Deformation of single crystals (2)



Stage II:

- The shear stress needed to continue plastic deformation begins to increase in an almost linear fashion. There is extensive work hardening ($\theta \cong G/300$).
- This stage begins when slip is initiated on multiple slip systems.
- Work hardening is caused by interactions between dislocations moving on intersecting slip planes.

Deformation of single crystals (3)



Stage III:

- There is a decreasing rate of work hardening.
- This decrease is caused by an increase in the degree of cross slip resulting in a parabolic shape to the curve.

Deformation of single crystals (4)



Effect of Temperature:

- Increasing 7 results in a decrease in the extent of Stage I and Stage II and in a decrease in $\tau_{\text{CRSS}}.$
- Stage I:
 - Initiation of secondary slip systems is easier
- Stage II:
 - Cross slip is easier

Deformation of single crystals (5)



Stacking Fault Energy (SFE):

- FCC metals
 - Decrease SFE, decrease cross slip (faults get wider).
 - This increases the stress level needed to have a transition from Stage II to Stage III.
- Example:
 - Cu-Zn: Cu-30 at.% Zn has low SFE, extends Stage II to high stress levels.

Outline for Discussions of

Plastic Deformation in Single Crystals and Polycrystals

1. Deformation of single crystals

- a. Crystallography of slip
- b. Stress-strain curves
- c. Influence of # of slip systems
- d. Crystal rotation during deformation
- e. Temperature dependence of stress

2. Deformation of polycrystals

- a. Implications of grain boundaries
- b. Stress-strain curves
- c. Influence of # of slip systems
- d. Influence of # of deformation modes

Orientation of slip plane and slip direction relative to the loading axis



 $\phi + \chi = 90^{\circ}$ $\phi + \lambda$ is not necessarily 90°

 Stress normal to slip plane:

$$\sigma_N = \sigma \cos^2 \phi$$

 Shear stress acting on slip plane:

 $\tau_{RSS} = \sigma \cos \phi \cos \chi$

• Shear stress acting on slip plane, in slip direction

$$\tau_{CRSS} = \sigma \cos \phi \cos \lambda$$

What happens to a single crystal during a tensile test?



Orientation of crystal slip plane during tensile deformation. (a) before deformation; (b) after deformation w/o grip constraint; (c) after deformation with grip constraint [Scanned from R.W. <u>Hertzberg, Deformation & Fracture</u> <u>Mechanics of Engineering Materials, 4th ed.</u>, (John Wiley & Sons, New York, 1996) p. 95].

- (a) Consider a single crystal oriented for slip on planes oriented χ degrees from the tensile axis.
- (b) Ideally, crystal planes will "glide" over one another without changing their relative orientation to the load axis..
- (c) However, during tensile testing, the ends of the tensile bar are constrained.
- Thus the *crystal* planes *cannot glide freely*. They are forced to rotate towards the tensile axis $(\chi_i < \chi_o)$.

- The slip plane re-orients as the length of the specimen changes.
- The glide shear stress and shear strain can be determined from the initial orientation of the slip plane (χ_o) and slip direction (λ_o) and the extension of the specimen (L_i/L_o).

$$\gamma = \frac{1}{\sin \chi_o} \left\{ \left[\left(\frac{L_i}{L_o} \right)^2 - \sin^2 \lambda_o \right]^{1/2} - \cos \lambda_o \right\}$$

$$\tau = \frac{P}{A} \sin \chi_o \left[1 - \frac{\sin^2 \lambda_o}{\left(L_i / L_o \right)} \right]^{1/2}$$

• Crystal rotation can be traced with the aid of a stereographic projection.



Crystal Orientation:

• Determines how many slip systems are active (through the Schmid factor).

Why does the number of active slip systems change?



Orientation of crystal slip plane during tensile deformation. (a) before deformation; (b) after deformation w/o grip constraint; (c) after deformation with grip constraint. Note rotation in gage to χ_i . [Scanned from R.W. <u>Hertzberg, Deformation &</u> <u>Fracture Mechanics of Engineering Materials, 4th ed.,</u> (John Wiley & Sons, New York, 1996) p. 95]

- During plastic deformation, the single crystal will either:
 - Undergo a translation of the upper and lower sections relative to each other due to slip

OR

- When (as is usual) testing constrains the upper and lower ends keeping them aligned, the crystal will rotate such that the angle between the stress axis and the slip direction decreases.
- THUS the Schmid factor changes! This can lead to the initiation of slip on a different system.

Why does the number of active slip systems change?



(001) Stereographic projection showing lattice rotation for an FCC crystal during tensile elongation. [Adapted from R.W. <u>Hertzberg, Deformation</u> <u>& Fracture Mechanics of</u> <u>Engineering Materials, 4th ed.,</u> (John Wiley & Sons, New York, 1996) p. 98]

- This figure illustrates lattice rotation for a crystal oriented for single slip (orientation *P*).
- This figure is explained on the next page.

Why does the number of active slip systems change?

- As the crystal rotates, the angle between the slip plane and the tensile axis decreases. "The orientation of the tensile axis changes."
- When the rotation causes the tensile orientation to change to P', the Schmid becomes equal for two slip systems. Slip will occur on two slip systems (i.e., dislocations will move on both systems).



 The crystal will continue to rotate with deformation occurring on alternating slip systems. This will continue until the load axis reaches [112] where the crystal will neck down until failure without changing orientation.

Figure Lattice rotation of an FCC crystal involving "overshoot" of primary and conjugate slip systems. [Adapted from R.W. Hertzberg, <u>Deformation & Fracture Mechanics of</u> <u>Engineering Materials, 4th ed.</u>, (John Wiley & Sons, New York, 1996) p. 99]

What about compression?



- In a compression test, the compression axis rotates towards the slipplane normal.
- The viewgraph on the next page shows the rotations on a stereogram.



Lattice Rotation:

- Compression axis rotates towards [111] until it reaches the [001]-[011] boundary.
- Duplex slip begins there which induces a net rotation towards [011].

RECALL

Characteristic tensile stress-strain curve for a single crystal



3 stages of work hardening for single crystals

Stage I	Stage II	Stage III
Easy	Linear	Parabolic
Glide	Hardening	Hardening

Influence of stress axis orientation



Why is crystallographic orientation so important?

- The stress axis orientation controls the number of active slip systems.
- Recall: Slip occurs when the Schmid factor is maximum.
- More slip systems means a "harder" material.

Implications for polycrystalline materials

- Plastic deformation within an individual grain is *constrained by the neighboring grains*.
- Because strains along grain boundaries must be the same for each grain, the grains will deform in a cooperative manner. If this is not the case, catastrophic failure occurs.



 Since plastic deformation of a single grain is restrained by its neighboring grain, a polycrystalline material will have an intrinsically greater resistance to plastic flow than would a single crystal.

What does it all mean?

• Since in general one grain (either A or B) will have a higher resolved shear stress (τ_{RSS}), the plastic deformation of that grain will be restricted.

THUS:

- Higher yield stress for polycrystal versus single crystal.
- Greater work hardening for polycrystal versus single crystal.
- This is the basis for *"texture" hardening*.



Figure 4.15

Room-temperature tensile (force/stress)-strain curves of single crystal, bicrystals and polycrystals of (a) Nb and (b) NaCl. Higher stress levels and lower ductilities of polycrystals compared to single crystals are due to the restraints that adjacent crystals in a polycrystal place on the deformation of each other. The level of the flow stress of a bicrystal depends on the relative misorientation of the two crystals comprising it. (*Data from C.S. Pande and Y.T. Chou, Treat. Matls. Sc. Tech., ed., H. Herman,* 8, 43, 1975; for NaCl from R.J. Stokes, Proc. Br. Cer. Soc., 6, 189, 1966.). [Adapted from Courtney]

Grains rotate and elongate during plastic deformation.



Has implications on strength. What about elastic modulus?

[Figure copied from W.D. Callister, Jr, <u>Materials Science and Engineering: An Introduction, 7th Edition</u>, (Wi]ley, New York, 2007) p.186.