



### HOMEWORK

Explain the influence of temperature on upper yield point formation in  $\text{Al}_2\text{O}_3$  or Si.

## Module #15

Dislocation Mobility, Stress-Strain Behavior  
and Yield Point Phenomena

### READING LIST

DIETER: Ch. 4, Page 132 and Ch. 6, pages 197-203



## Further implications of dislocation motion

- The implications of our discussions thus far indicate that plastic deformation at ambient temperatures results from the motion of dislocations and dislocation densities increase during plastic deformation.
- Previously, we showed that the *shear strain resulting from dislocation motion* could be represented as follows:

$$\gamma = \rho_{\perp} b \bar{x}$$

- Further, the *shear strain rate associated with* this type of deformation is:

$$\dot{\gamma} = \frac{d\gamma}{dt} = \rho_{\perp} b \frac{dx}{dt} + x b \frac{d\rho_{\perp}}{dt}$$

## Further implications of dislocation motion – cont'd

$$\dot{\gamma} = \frac{d\gamma}{dt} = \rho_{\perp} b \frac{dx}{dt} + xb \frac{d\rho_{\perp}}{dt}$$

- Term on the **right hand side** of this equation is very small relative to the term on the left side and **can be ignored**, which reduces the strain rate equation to:

$$\dot{\gamma} \cong \rho_{\perp} b v$$

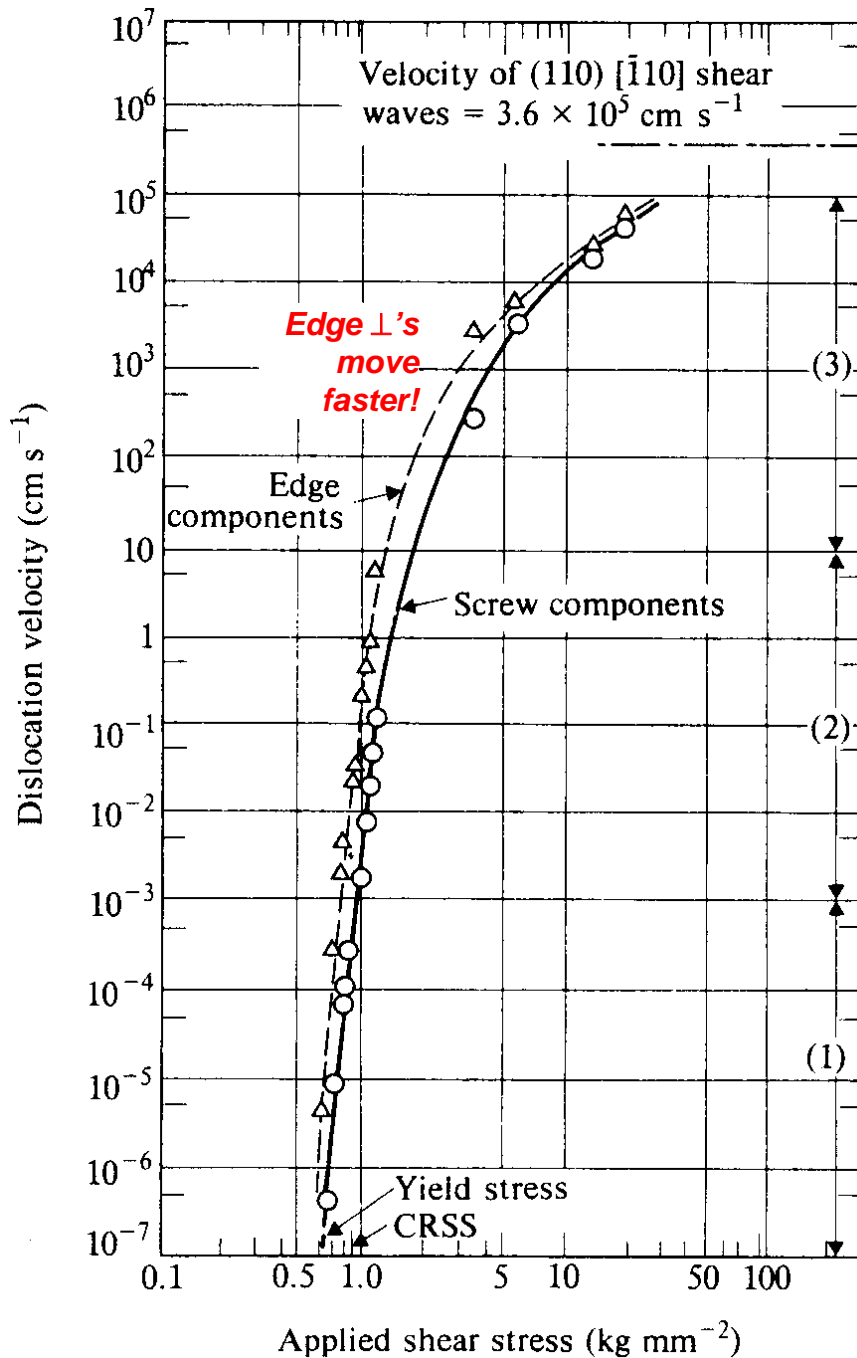
- This is the **Taylor - Orowan equation**. We can use it to describe macroscopic plastic deformation in terms of dislocation behavior.
- This equation defines deformation in terms of how fast dislocations move.

- This was investigated by Johnston and Gilman who showed that the dislocation velocity for a number of ionic crystals and metals is a strong function of the shear stress in the slip plane as follows:

$$v = A \left( \frac{\tau}{\tau_o} \right)^m$$

This equation is empirical in nature and applies for a specific velocity range:  $10^{-9}$  to  $10^{-3}$  m/s

- Where  $v$  is the dislocation velocity,  $\tau$  is the applied shear stress in the slip plane,  $\tau_o$  is the shear stress for  $v = 1$  m/s, and  $m$  is a constant.
- Dislocations glide velocities depend on:
  - Applied stress;
  - Purity of the crystal;
  - Temperature;
  - Type of dislocation.

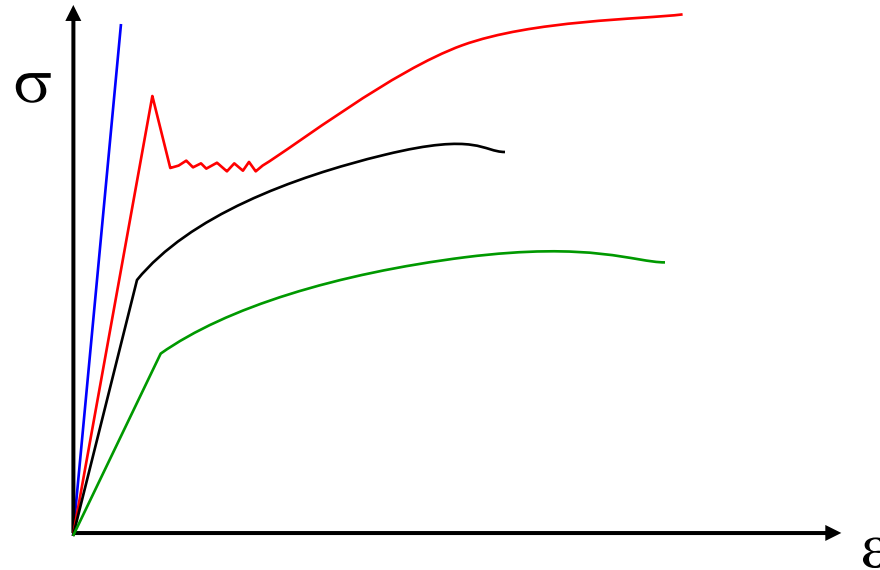


- Dislocation velocity increases rapidly at the critical resolved shear stress ( $\tau_{\text{CRSS}}$  or CRSS).
- This is where plastic deformation actually begins.

### Figure

Stress dependence of the velocity of edge and screw dislocations in LiF (after Johnston and Gilman, *J. Appl. Phys.* **30**, 129, 1959). Scanned from E.W. Billington and A. Tate, The Physics of Deformation and Flow, McGraw-Hill, New York, 1981, pages 418 and 420.

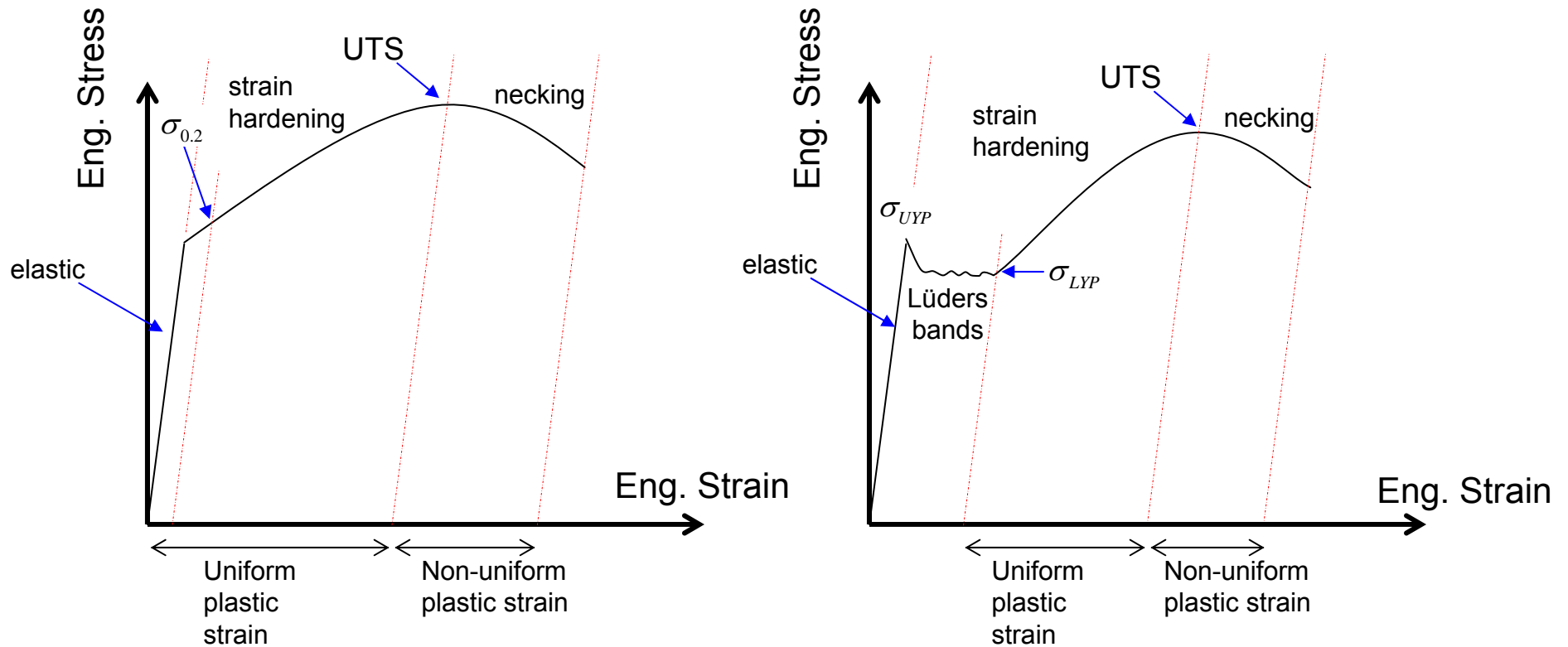
## What do stress-strain curves look like?



- We can use the Taylor-Orowan equation to predict what stress-strain curves will look like after yielding.
- Based on mobile dislocation density.
- We can also describe things in terms of solute locking of dislocations. This is related to solid solution hardening.

# Recap

- Concerning **yielding**, many studies have illustrated that when a consistent measure of yielding is used, large scale deformation in single crystals **will occur at** the CRSS on a specific slip (glide) plane, in a specific slip direction.
- CRSS  $\equiv$  critical value of the shear stress on a glide plane where large-scale deformation occurs.
- The CRSS is not the stress required to move a single dislocation on a slip plane. Rather *it is the stress required to move many dislocations!*
- By analogy, in a polycrystal, the yield stress is also the stress required to move many dislocations. As we shall see later, it reflects the collective CRSS values for a number of single crystals (in this case grains).



- Plastic deformation occurs when the applied stress exceeds the elastic limit.
- Plastic deformation occurs primarily via the motion of defects.
  - Point defects – diffusion aided flow (“creep”)
  - Line defects – “slip”
  - Surface/Planar defects – twins, APB’s, stacking faults, etc...
  - Volume defects? – not really. However, they do “influence” plastic deformation.



In general, multiple events occur at the  
same time

(slip+twinning+creep+etc.)

Most deformation occurs via slip or  
twinning

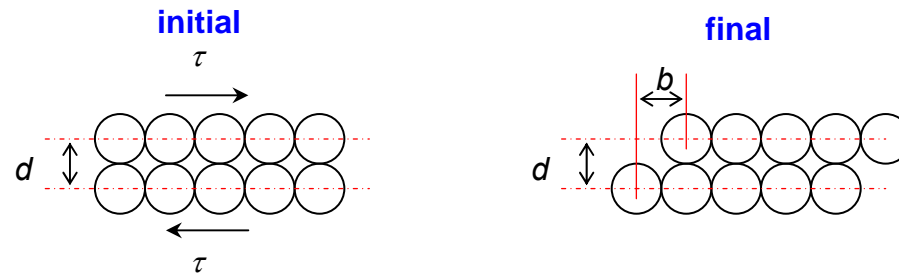
(at ambient temperatures)

however

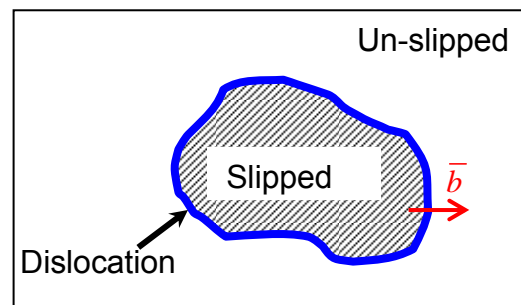
OUR CURRENT CONCERN IS **SLIP**

# Recall

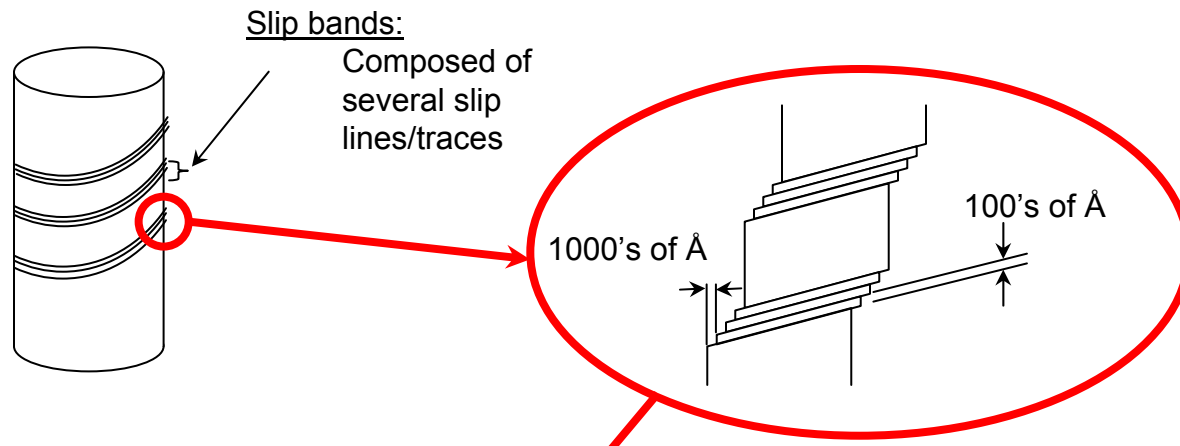
- Slip is the relative displacement of crystallographic planes by discrete distances.



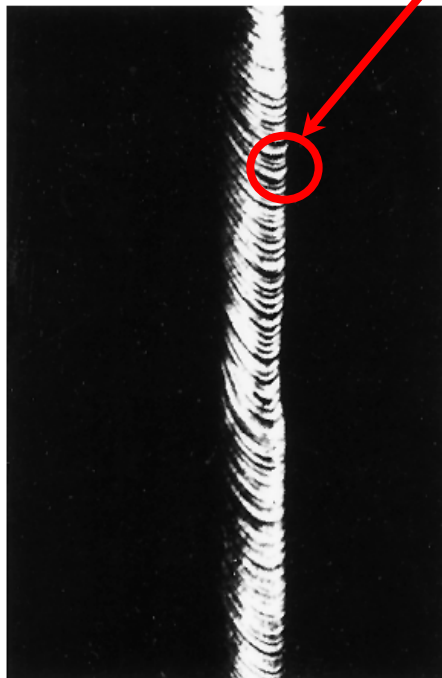
- Slip in crystals is a direct result of the motion of line defects, namely dislocations ( $\perp$ 's).



- Dislocations represent boundaries between slipped and “unslipped” regions of a crystalline solid.



**FIGURE 7.9** Slip in a zinc single crystal. (From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

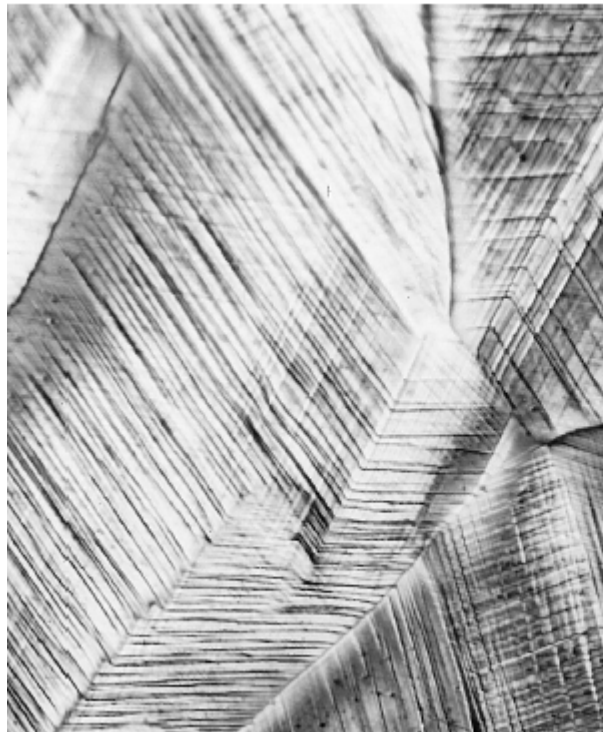


[Callister, p. 183]

- Slip leads to the appearance of slip traces on the surfaces of single crystal test specimens as is illustrated for Zn on the left.
- The slip traces correspond to the motion of many dislocations on specific slip planes.

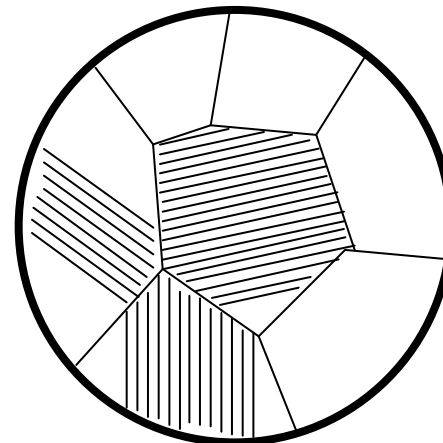
# In polycrystals, what happens after slip?

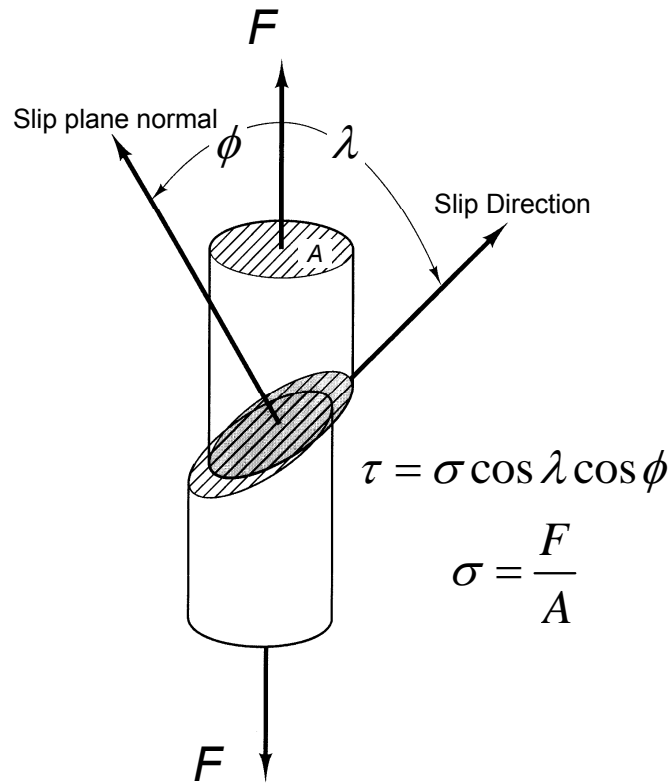
- The same thing happens in polycrystals, however, the slip lines will be different in each grain.
- Consider each grain to be a single crystal that is rotated relative to the others.



[Callister, p. 186]

**FIGURE 7.10** Slip lines on the surface of a polycrystalline specimen of copper that was polished and subsequently deformed. 173 $\times$ . (Photomicrograph courtesy of C. Brady, National Bureau of Standards.)



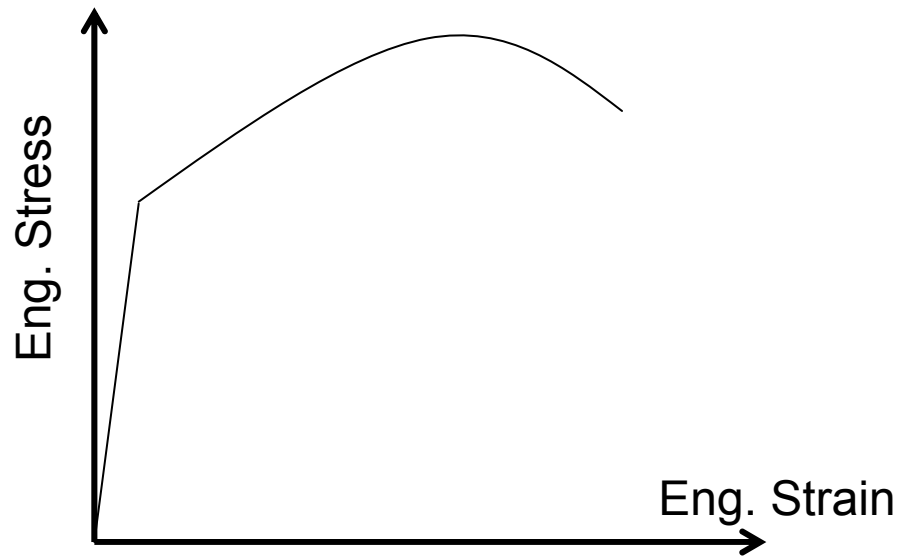


Dislocations move on specific planes and in specific directions

*slip systems*

This is what leads to slip traces in single crystals and polycrystals

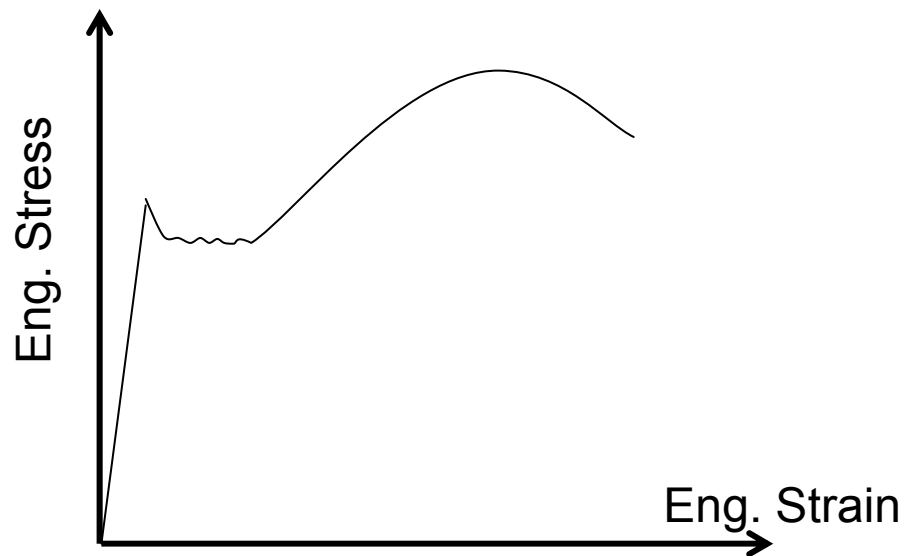
- Slip bands/traces always correspond to specific crystallographic planes and directions.
- Usually the close packed planes and close packed directions.
- Each step on the surface of a tensile specimen is proportional to  $nb$ , where  $n$  is an integer and  $b$  is the Burgers vector.



- Some stress strain curves exhibit upper yield points. Some don't.
- WHY?
- Can be considered 2 ways:

1) In terms of dislocation velocity and density

2) In terms of solute diffusion (strain aging\*).




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\* Strain aging is related to solid solution hardening which will be addressed later.

# Recall

- Dislocation induced strain can be equated as:

$$\boxed{\gamma = \rho_{\perp} b \bar{x}} \text{ or } \varepsilon = \rho_{\perp} b \bar{x}$$

- The shear strain rate associated with this type of deformation can be equated as:

$$\dot{\gamma} = \frac{d\gamma}{dt} = \rho_{\perp} b \frac{d\bar{x}}{dt} + b \bar{x} \frac{d\rho_{\perp}}{dt} \rightarrow \boxed{\dot{\gamma} \cong \rho_{\perp} b \bar{v}} \text{ or } \dot{\varepsilon} \cong \rho_{\perp} b \bar{v}$$

(very small)

this is the **Taylor-Orowan equation**.

- This equation is dominated by two terms ( $\rho_{\perp}$  and  $v$ ), both of which depend upon a series of testing and materials parameters as indicated below:

$$\rho_{\perp} = Fcn(\varepsilon_p, \sigma, T, Structure)$$

$$\bar{v} = Fcn(\sigma, T, Structure)$$

Now, the Orowan equation can be re-written as:

$$\dot{\gamma} \cong b \times \rho_{\perp} (\varepsilon_p, \sigma, T, Structure) \times \bar{v} (\sigma, T, Structure)$$

- In a general tensile test, the strain rate consists of an elastic component and a plastic component (elastic-plastic deformation).

$$\dot{\gamma} = \dot{\gamma}_{Elastic} + \dot{\gamma}_{Plastic}$$

where

$$\dot{\gamma}_{Elastic} = \frac{\dot{\tau}}{G} = \dot{\tau} \left( \frac{1}{G_{machine}} + \frac{1}{G_{specimen}} \right)$$

and

$$\dot{\gamma}_{Plastic} = \rho_{\perp} b \bar{v}$$



- After substitution, the strain rate equation can be re-written as:

$$\dot{\gamma} = \frac{\dot{\tau}}{G} + \rho_{\perp} b \bar{v}$$

- In this equation, the **dislocation density** and the **dislocation velocity** are dependent on  $\sigma$ - $\varepsilon$  (or  $\tau$ - $\gamma$ ) behavior.

- Recall:

$$\bar{v} = A \left( \frac{\tau}{\tau_o} \right)^m$$

which can be re-written as:

$$\bar{v} = A \left( \frac{\sigma}{\sigma_o} \right)^m$$

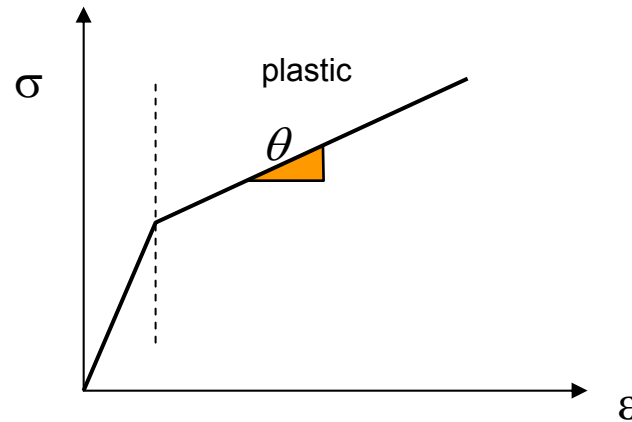
- If we consider a single crystal, when the crystal yields, there is the possibility of work hardening.
- As we will discuss in detail later, work hardening occurs when normally mobile dislocations intersect, thus tying each other up.
- During work hardening, dislocations continue moving. This will result a *back stress* that *reduces the effective stress* required *to establish a critical dislocation velocity* to the *applied stress minus the back stress* or:

$$\sigma = \sigma_{\text{applied}} - (\text{back stress})$$

where  $\sigma$  is in this case the total stress applied on the dislocations (i.e., *the effective stress*).

- This *back stress* is often called the internal stress.

- We can say something definitive about yield behavior by first assuming linear work hardening.



- In this case, the internal stress then becomes:  $(\theta \epsilon_p)$

- Thus:  $\sigma = \sigma_{applied} - (\theta \epsilon_p)$

- If we substitute this expression into:  $\bar{v} = A \left( \frac{\sigma}{\sigma_o} \right)^m$

we get:  $\bar{v} = A \left( \frac{\sigma_{applied} - \theta \epsilon_p}{\sigma_o} \right)^m$

This equation accurately ties the dislocation velocity to stress and strain.

- Dislocation density depends on plastic strain in the following way:

$$\rho_{\perp} = \rho_m = \rho_o + C\varepsilon_p^a$$

$\rho_m$  = mobile dislocation density

$\rho_o$  = grown in dislocation density

- If we incorporate this dependence into the Taylor-Orowan relationship we get the following expression:

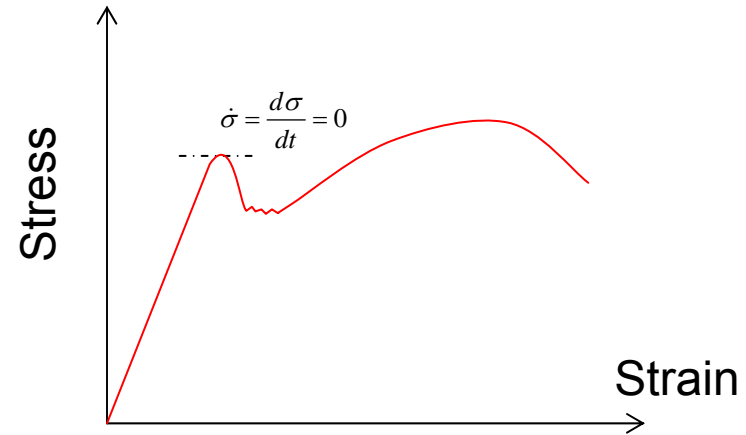
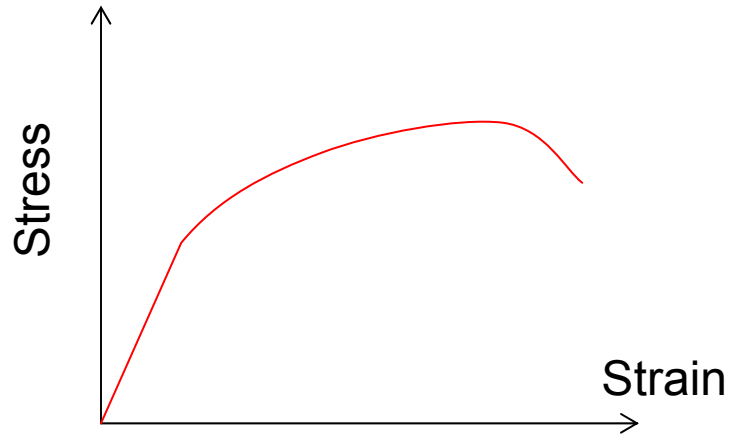
$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + A' [\rho_o + C\varepsilon_p^a] \left[ \frac{\sigma_{\text{applied}} - \theta\varepsilon_p}{\sigma_o} \right]^m b$$

$$= (1) + (2)$$

This expression describes in full the stress-strain behavior of a solid.

- Below the elastic limit, there is no plastic strain. Thus **term (1) dominates this expression up to the elastic limit.**
- Beyond the elastic limit, there is significant dislocation multiplication AND significant plastic strain. Thus (2) will begin to dominate.

- Getting back to the actual  $\sigma$ - $\varepsilon$  curves, some have sharp upper yield points and some don't. **WHY?**



- Many reasons. **One explanation can be provided in terms of dislocation density** using the equation that was derived on the preceding page.

$$\dot{\sigma} = \frac{d\sigma}{dt} = 0$$

- In materials that exhibit upper yield points (UYP), the slope of the stress-strain (and thus stress-time) curve at that UYP is equal to zero.

- Thus, at the upper yield point:

$$\dot{\varepsilon} = A' [\rho_o + C\varepsilon_p^a] \left[ \frac{\sigma_{applied} - \theta\varepsilon_p}{\sigma_o} \right]^m b$$

which can be re-written as:

$$\sigma_{applied} = \sigma_{ys} = \theta\varepsilon_p + \sigma_o \left[ \frac{\dot{\varepsilon}}{A' [\rho_o + C\varepsilon_p^a] b} \right]^{1/m}$$

- At the yield point:  $\varepsilon_p \cong 0$

thus:

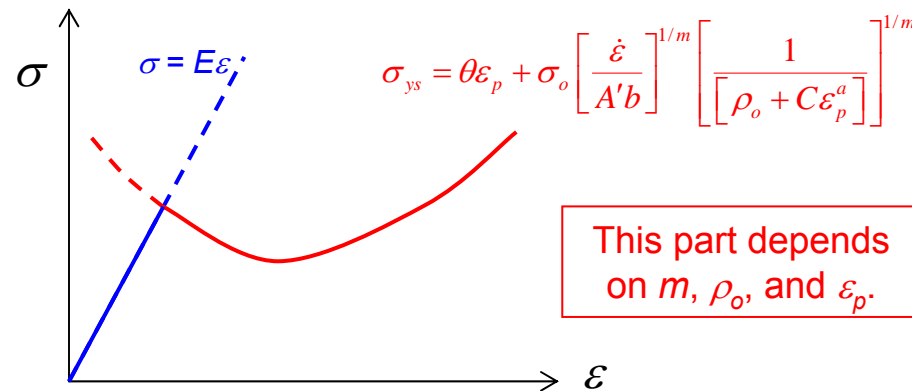
$$\sigma_{UYP} = \sigma_o \left[ \frac{\dot{\varepsilon}}{A' [\rho_o] b} \right]^{1/m}$$

- The flow stress will decrease from this value until work hardening is significant.
- When the lower yield point (LYP) is reached, the work hardening rate ( $d\sigma/d\varepsilon$ ) equals zero.
- Once the LYP is exceeded,  $d\sigma/d\varepsilon$  increases due to work hardening.

- At the lower yield point:

$$\sigma_{ys} = \theta \varepsilon_p + \sigma_o \left[ \frac{\dot{\varepsilon}}{A'b} \right]^{1/m} \left[ \frac{1}{[\rho_o + C\varepsilon_p^a]} \right]^{1/m}$$

- Do you recognize this equation?
- If we combine it on a graph with the expression for elastic strain we get the plot that follows.



- Using this model, it is possible to explain the occurrence of UYPs and LYPs in tensile tests. This model does not work for all materials.



- If we remove all constants from the derived equation, we can observe a general trend:

$$\sigma_{ys} \propto (\dot{\epsilon})^{1/m}$$

- This expression tells us that at higher strain rates, the yield stress (and flow stress) should be higher.
- Generally, it has been observed that as strain rate increases:
  1. The work hardening rate increases
  2. Ductility decreases
  3. Yield drops, if they are present at all, get larger. This is illustrated on the next slide.

Effects of temperature and strain rate on size of UYP in  $\text{Al}_2\text{O}_3$ .

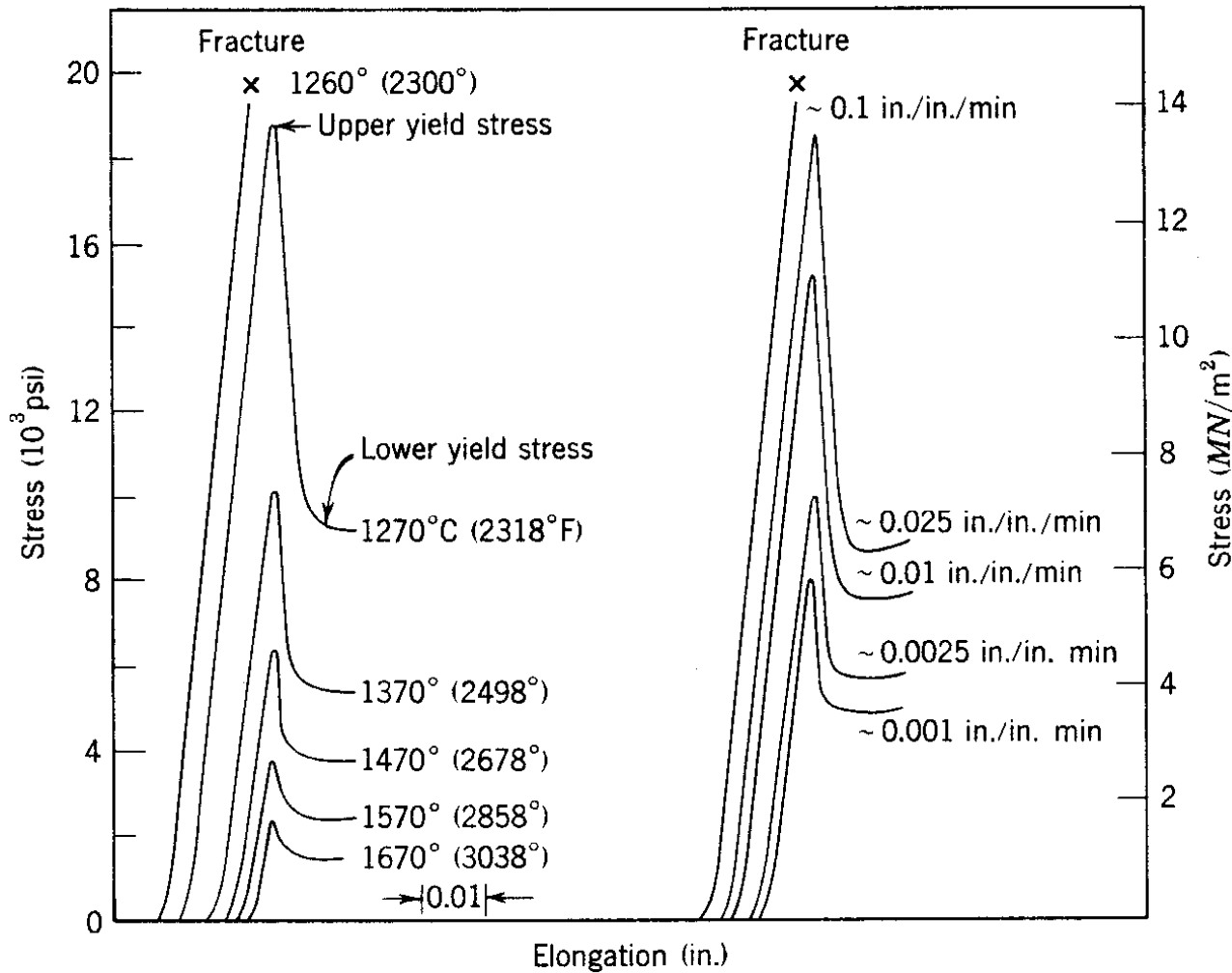
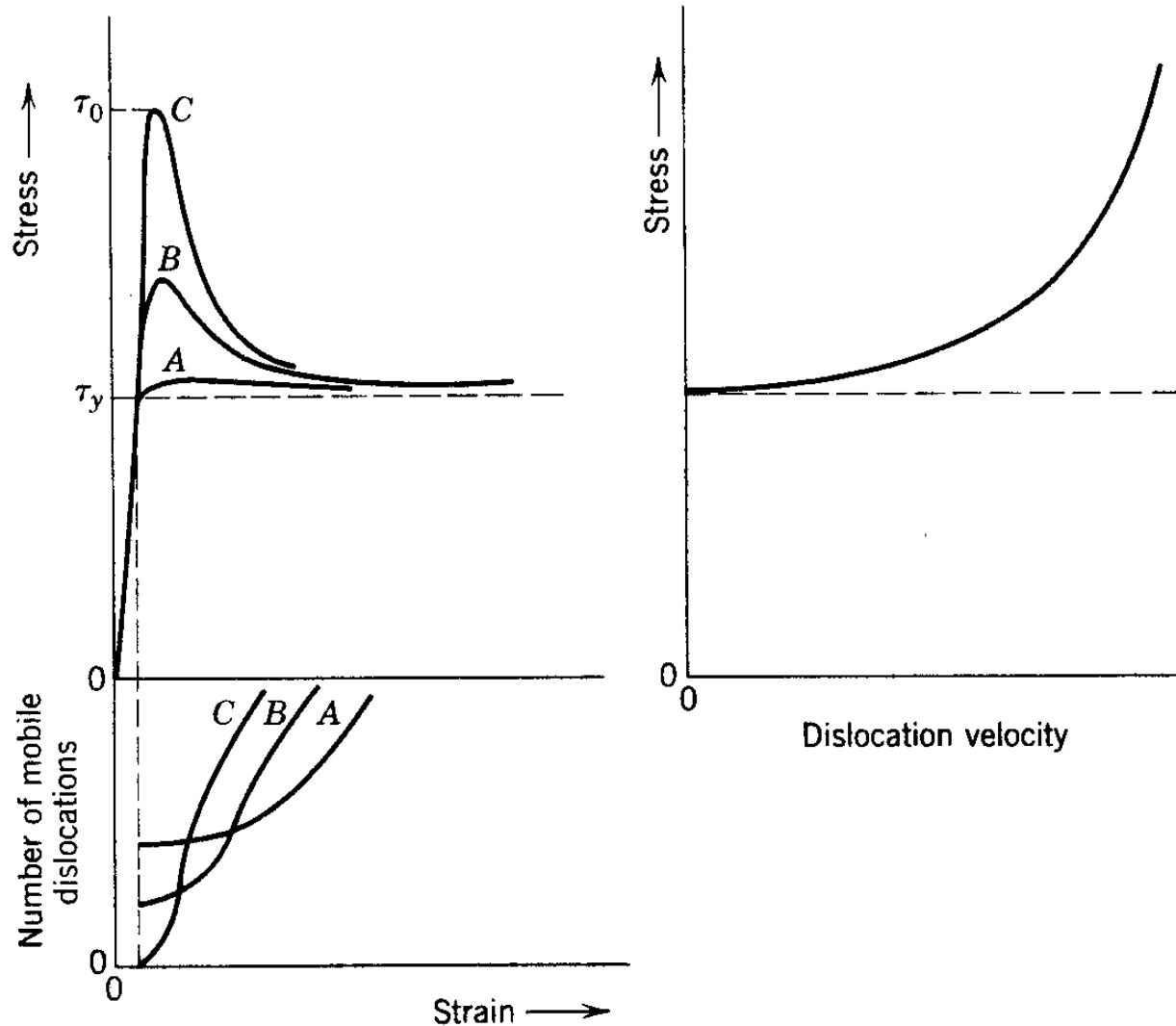


Fig. 14.26. (a) Deformation behavior of single-crystal  $\text{Al}_2\text{O}_3$ . On the left the effect of temperature and on the right the effect of strain rate. A sharp yield stress and a sharp yield drop are observed. [Figure adapted from Kingery et al., Introduction to Ceramics, 2<sup>nd</sup> Edition, (Wiley, New York, 1976) p. 730.]



- Illustrates the relationships between mobile dislocation density and strain rate.
- Also, when  $m$  is small, UYPs are more pronounced than when  $m$  is large.
- Why do FCC materials not generally exhibit UYPs while BCC materials often do?

Fig. 14.18. Differential shapes of stress-strain curves at yielding as interpreted in terms of dislocation density. [Figure adapted from Kingery et al., Introduction to Ceramics, 2<sup>nd</sup> Edition, (Wiley, New York, 1976) p. 721. This figure was originally adapted from the classical work of Gilman.]