# Deformation Twinning and High Strain Rate Deformation of HCP metals -- Paper Reviews

Cindy Smith

Meyers, Vohringer, and Lubarda, "The Onset of Twinning in Metals: a Constitutive Description," Acta Mater. 49 (2001) 4025-4039.

Ramesh, "Effects of High Rates of Loading on the Deformation Behavior and Failure Mechanisms of Hexagonal Close-Packed Metals and Alloys," Met. and Mat. Trans. A, vol 33A, 2002, p 927-935.

# Background

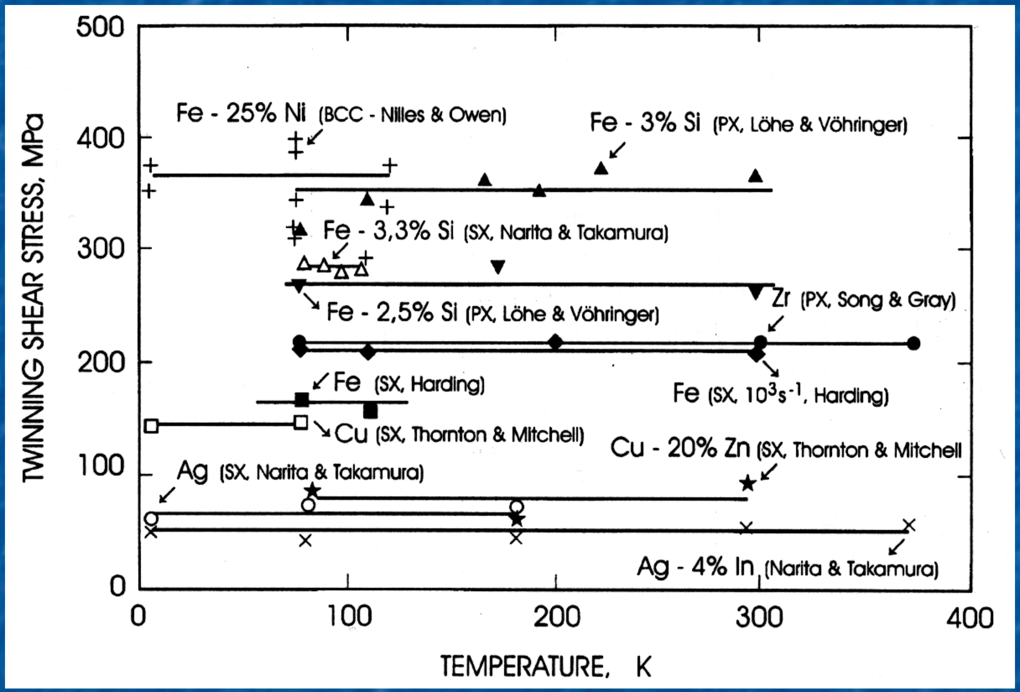
- Mechanical stresses can produce the following structural changes in metals:
  - Slip (dislocation motion)
  - Twinning (also requires dislocation activity)
  - Phase transformations (i.e. martensitic)
  - Fracture
- Twinning and phase transformations can be significant modes of deformation under certain conditions.
- Dislocation motion is highly sensitive to strain rate and temperature, while twinning has a much lower sensitivity.

# Mechanical Twinning

- Mechanical twinning has two effects on the evolution of plastic deformation:
  - Subdivides the grains, therefore increasing the barriers to slip, which increases the work hardening rate
  - Contributes to plastic deformation by twinning shear, which decreases the work hardening rate

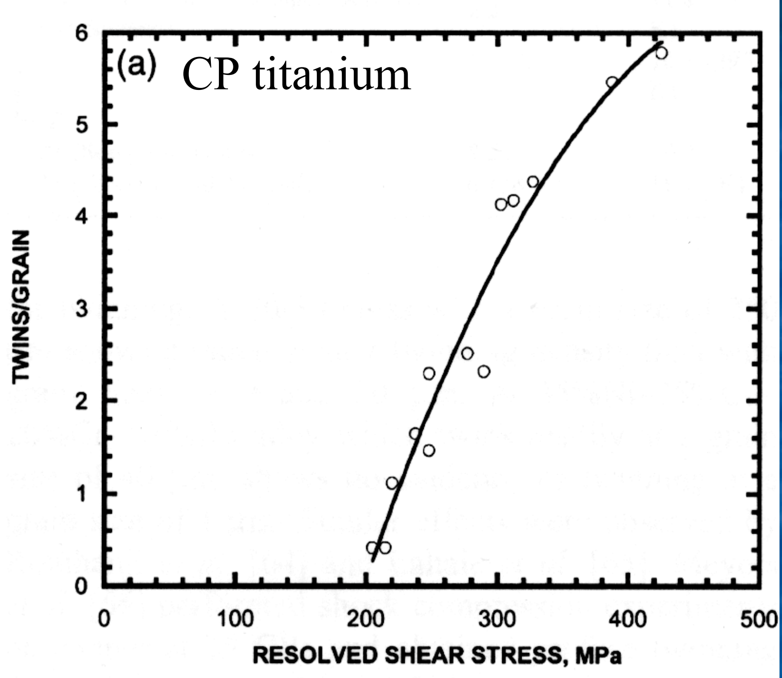
# Twinning Stress

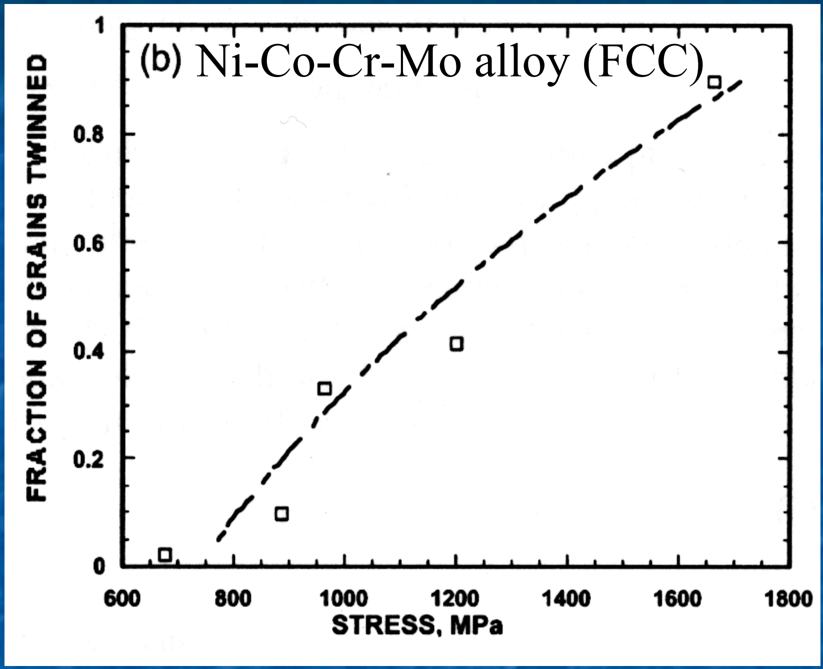
- The critical event for twinning is for most cases nucleation. Growth can occur at stresses that are a fraction of the nucleation stress.




A compilation of twinning stress vs. temperature for a variety of metals, including single crystals and polycrystals. Note the appearance of a critical stress that is temperature insensitive.

# Twinning Stress




- Twinning is an evolving process, increasing with stress, beyond its critical value.
- Results plotted were obtained at various temperatures and strain rates
- The increasing stress required for increasing amounts of twinning were explained by the unloading (and associated shielding) occurring in the surrounding of a twinned region.

# Grain Size Effect

- Twinning stress has been observed to depend more strongly on the grain size than the slip stress of a material.
- The Hall-Petch relationship is obeyed, but with a larger slope $k_T$ for the twinning stress than the $k_S$ for slip.

$$\sigma_T = \sigma_{T0} + k_T \, d^{-1/2}$$

| Material | H-P Slope for slip, $k_S$ (Mpa mm$^{1/2}$) | H-P Slope for twinning, $k_T$ (Mpa mm$^{1/2}$) |
|---|---|---|
| Zr (HCP) | 8.25 | 79.2 |
| Ti (HCP) | 6 (78K) | 18 (4K) |
| Cu (FCC) | 5.4 | 21.6 |

# Grain Size Effect

- The reason for the difference in the HP slope for slip and twinning has been suggested to be microplasticity
  - Microplasticity refers to dislocation activity occurring before the onset of the generalized plastic deformation
  - While yield stress is associated with generalized plastic deformation
- It is possible that microplasticity and overall deformation are controlled by different mechanisms,
  - i.e. elastic anisotropy, incompatibility stresses, and barriers to slip.
- Various researchers have seen a significantly greater twin density in materials such as copper and brass with grain sizes near 200 $\mu$m, than material with grain sizes near 10 $\mu$m.

# Effect of SFE and Texture

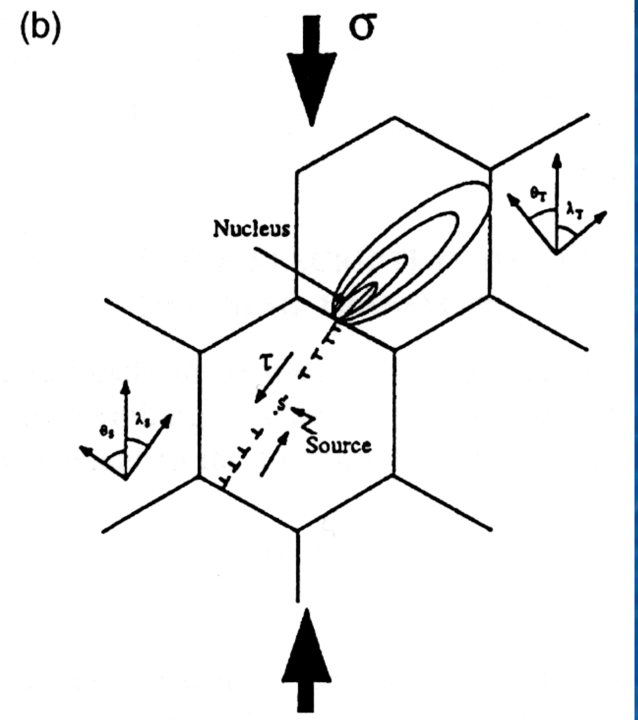
- Twinning stress is well known to increase with increasing stacking fault energy, especially for FCC materials.
- Texture has an important effect on twinning in low symmetry materials, i.e. HCP metals.
  - When a stress is reversed, a dislocation moves in the opposite sense along the same direction, while the critical resolved shear stress (CRSS) is independent of the direction of motion
  - A twin, however, has a definite sense along which it shears.
  - In the presence of texture, twinning stresses in compression and tension are different, while slip stresses remain the same.

# Twinning Stress

- Mechanical twinning in BCC and HCP metals is most common at high strain rates and low temperatures, because this effectively raises the flow stress up to the level required for twin formation.
  - Twinning usually occurs before macro-yielding and in many cases is inhibited by significant plastic deformation.
- FCC metals have a lower strain-rate sensitivity and a higher work hardening ability, which leads to twinning occurring after significant plastic deformation.

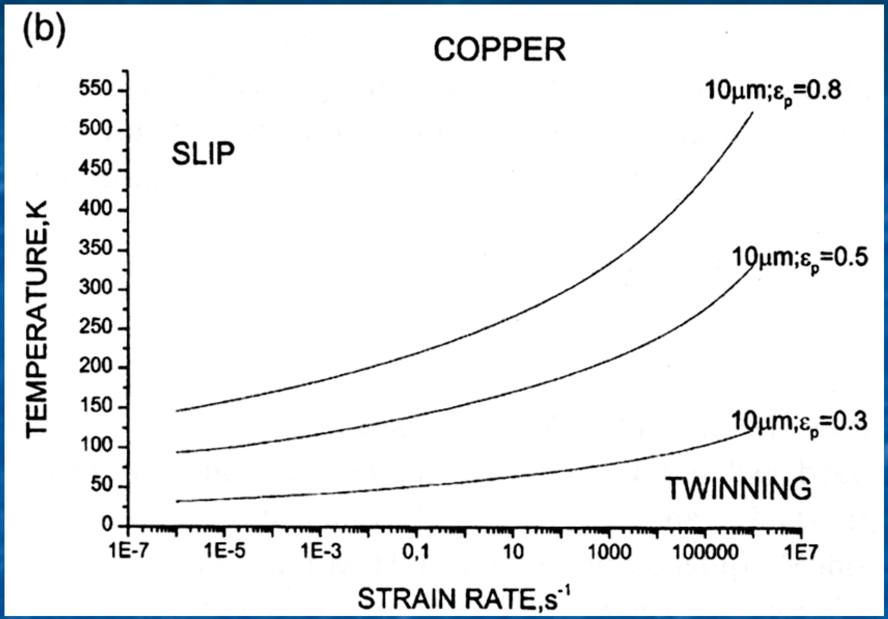
# Constitutive Model by Meyers, et. al.

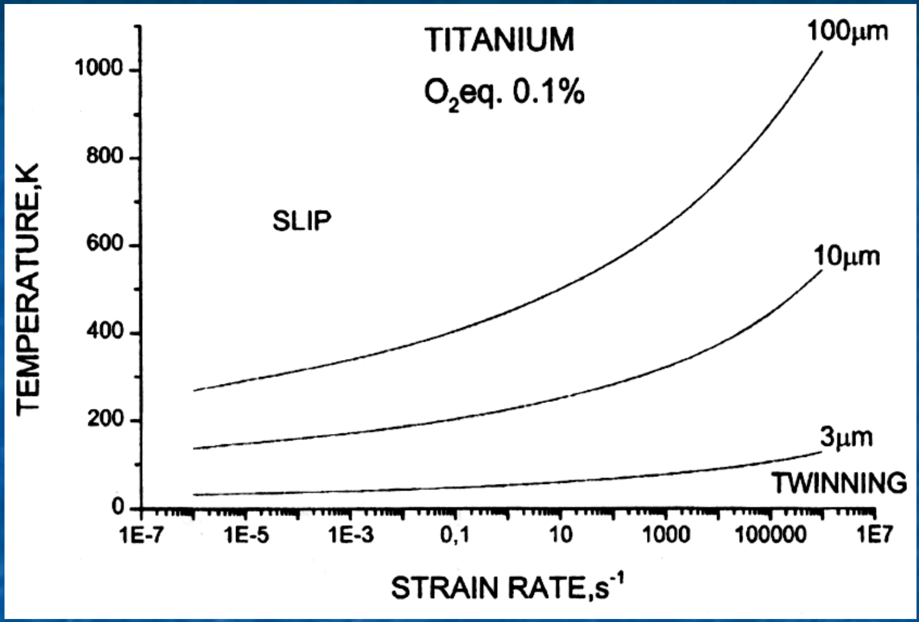
- Assumptions made:
  - Pile-ups play a key role in creating the stress concentration for the twin nucleation.
  - No two dislocations are simultaneously traveling to the barrier.
  - Microslip occurs at the elastic stage.
  - Twinning occurs when the slip stress becomes equal to the twinning stress.
  - CRSS for twinning is independent of the stress state




- Nearly all of the constants are then found by curve fitting the equations to experimental results.
- No attempt was made to compare the calculated slip-twinning transitions with experimental results on the initiation.

# Constitutive Model by Meyers, et. al.




$$\sigma = \sigma_G + C_1\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^{C_3 T} + C_2\epsilon^n \exp(C_4 T) + k_S d^{-1/2} \quad (15)$$

The term $\exp(C_4T)$ decreases the work hardening as $T$ increases. The twinning stress is represented by

$$\sigma_T = \sigma_{T0} + k_T d^{-1/2}. \quad (16)$$

- Work hardening as a function of temperature, and twinning stress as a function of the HP grain size effect were also included in the equations used to calculate the slip-twinning transitions.

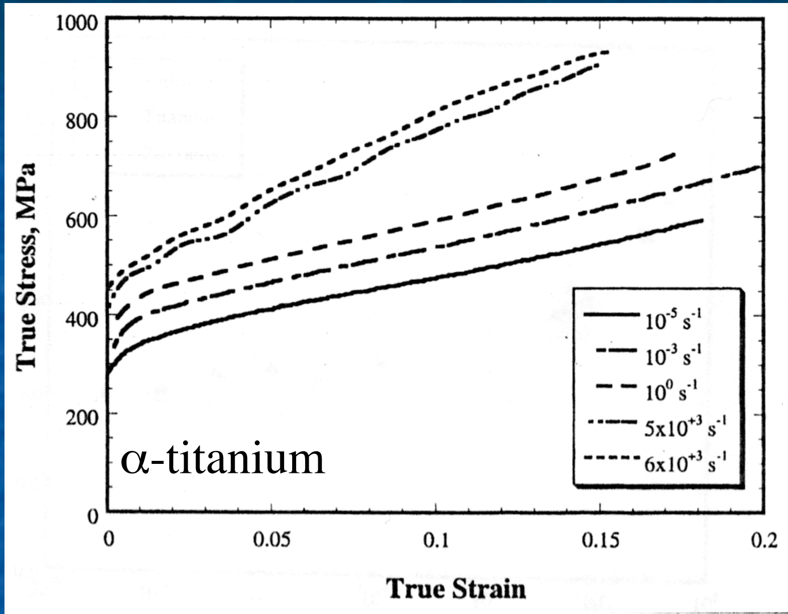
# Strain Rate Dependence in HCP Deformation Behavior

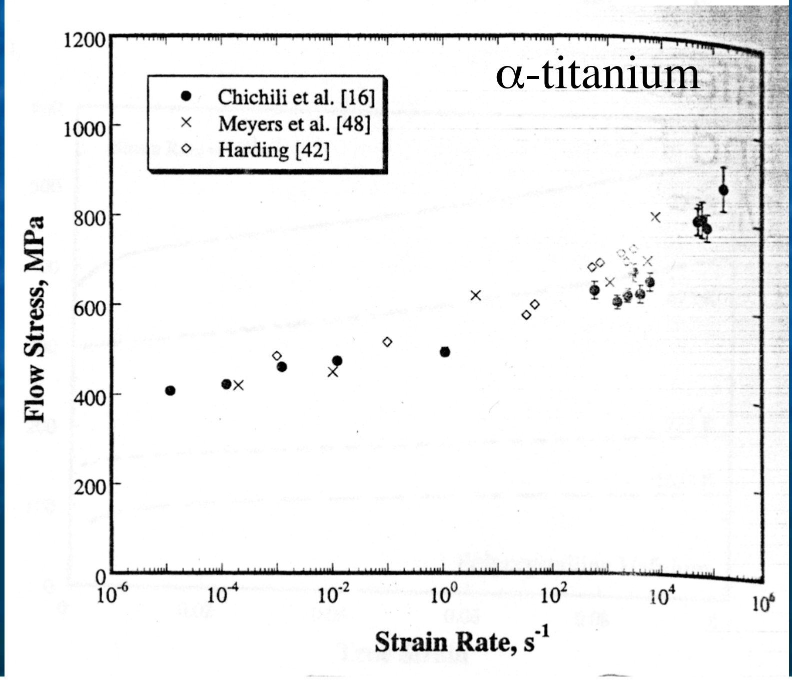
- Most studies have focused on FCC and BCC metals and alloys, which show three features:
  - Increasing flow stress with increasing strain rate.
  - A strain rate dependence on the strain hardening of FCC metals, but not BCC metals
  - Development of a variety of dislocation substructures after high-rate loading, which can lead to strong rate-history effects

Ramesh, "Effects of High Rates of Loading on the Deformation Behavior and Failure Mechanisms of Hexagonal Close-Packed Metals and Alloys," Met. and Mat. Trans. A, vol 33A, 2002, p 927-935.

# Rate dependence of flow stress

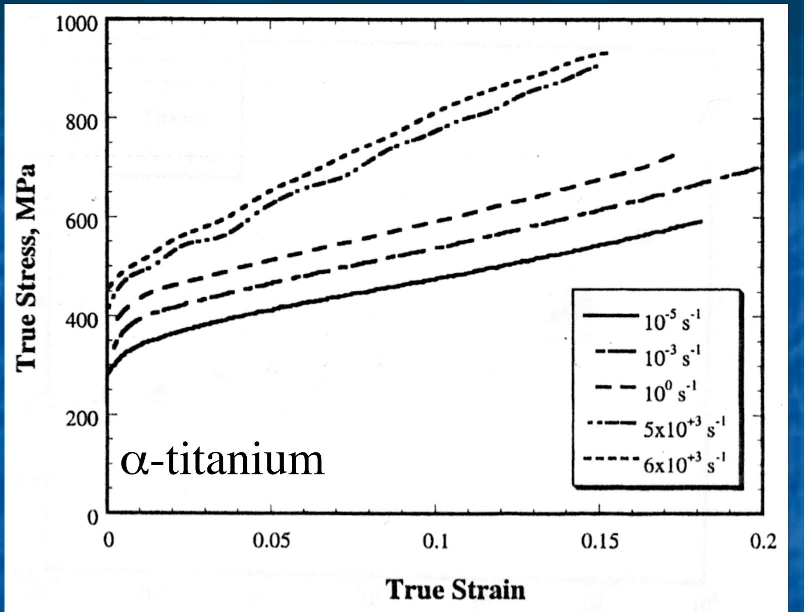
- For most cubic metals there appears a strong increase in the apparent rate sensitivity at strain rates on the order of $10^2$ to $10^3$ $s^{-1}$.
- This can be attributed, at least in part, to the substantial microstructure evolution that occurs.
- Since this microstructural evolution occurs in the same timescales as most applications involving high rate loading, most constitutive models are based on the apparent rate sensitivity of the flow stress.

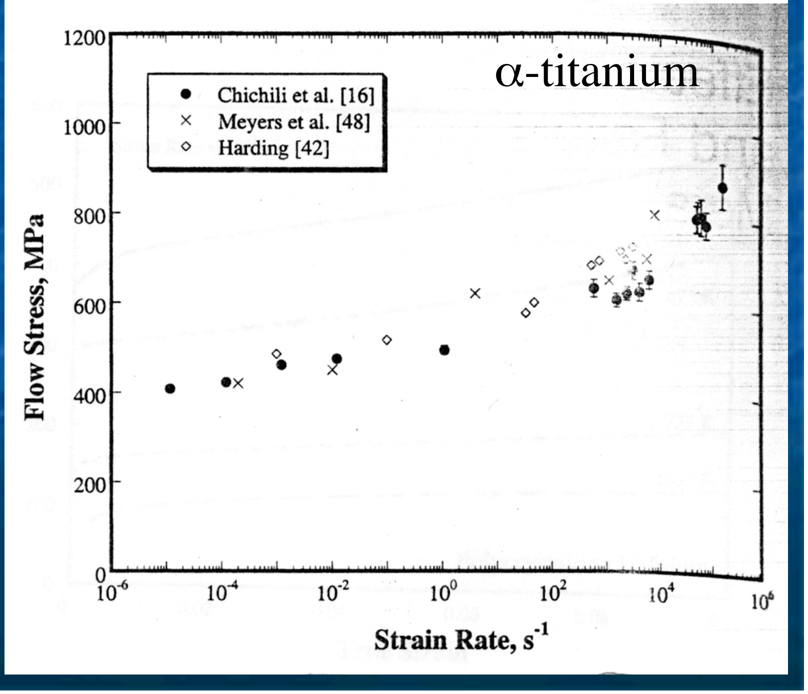


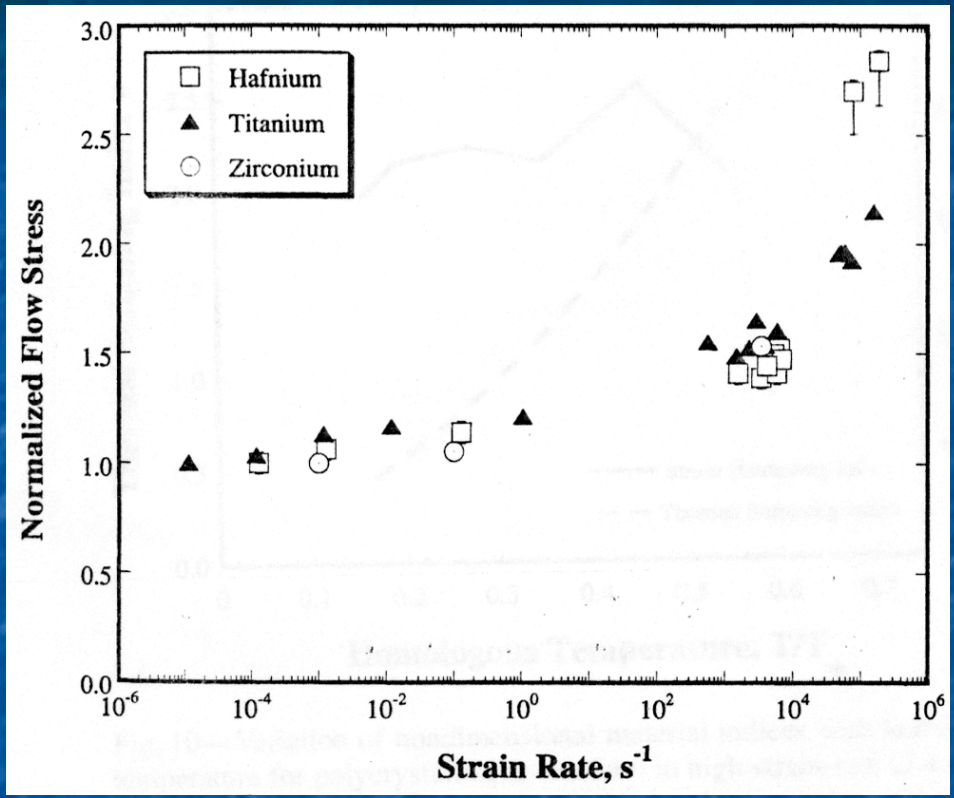
# Strain Rate dependence of HCP metals

- Note the change in:
  - Apparent yield stress with strain rate
  - Flow stress with strain rate
  - Apparent strain-hardening rate with strain rate
- The increased strain hardening at higher strain rates is very different from the behavior of typical FCC metals.
- Also note the slight upward curvature of the stress-strain curves in the quasi-static data region.
  - This may be indicative of the development of deformation twinning, or it may be tied to texture.



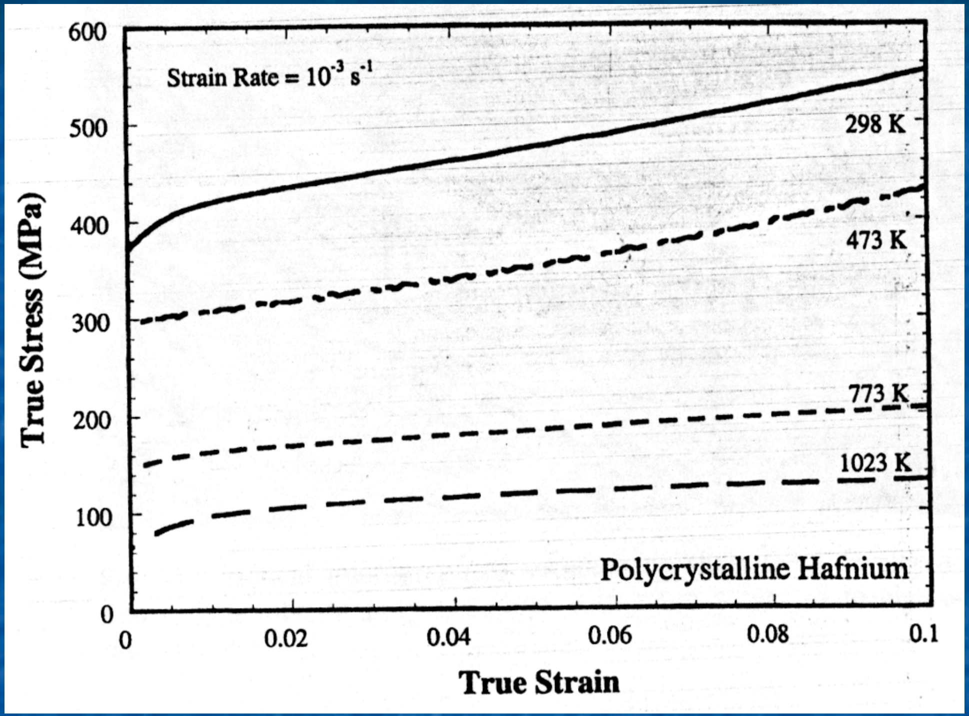
# Strain Rate dependence of HCP metals




- Flow stress has been normalized by the flow stress at quasi-static strain rates. The behavior of the three materials is in excellent agreement.
  - To the knowledge of Ramesh, as of 2002 there was no data on Zr above the strain rate of $10^4$.

# Temperature Dependence

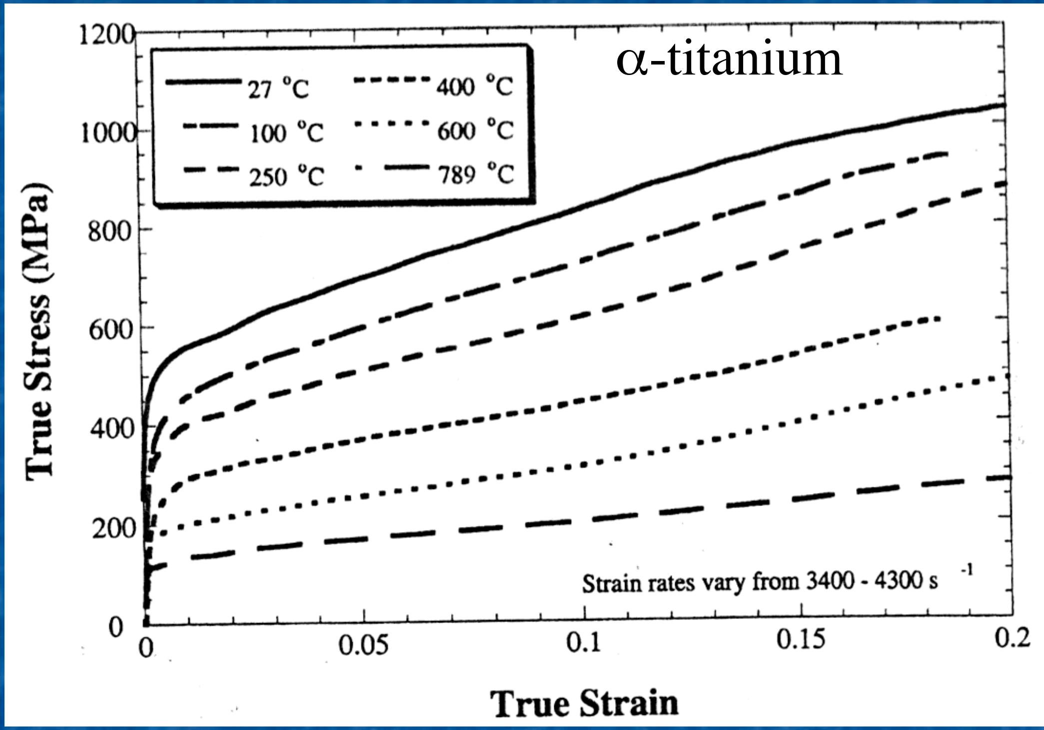
- Temperature dependence of the mechanical response of HCP metals at low strain rates has been studied extensively.
- Softening occurs with increasing temperatures in HCP metals, which is associated with dislocation-interstitial and dislocation-dislocation interactions.




- Note the upward curvature of the stress-strain curve at room temperature, and the more conventional shape at higher temperatures.
  - Zirconium is known to have a relatively sharp change in the strain hardening rate.

# Temperature Dependence

- There is little data for high-temperature, high-strain-rate deformation of HCP materials, largely due to the difficulty of running the experiments.
  - Evolution of microstructure during heating needs to be considered




- Note the reduction in the apparent yield strength and apparent work hardening rate with increasing temperature.

# Modeling high strain rate deformation of HCP

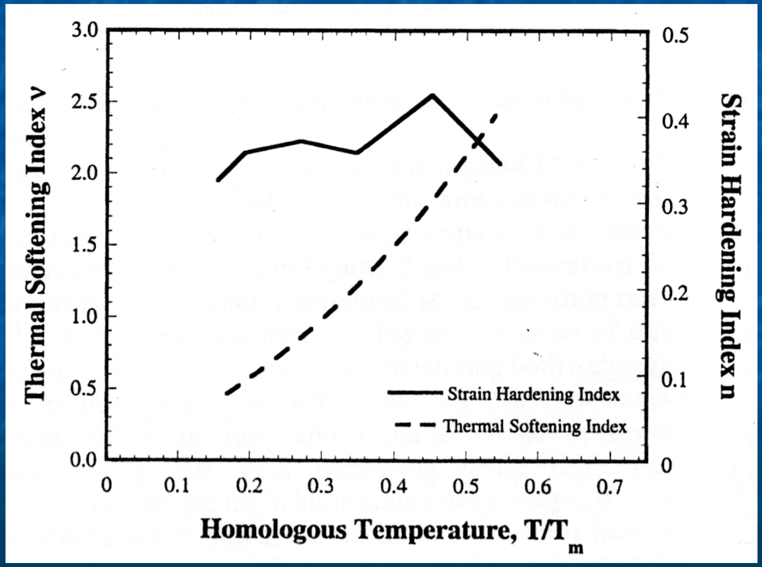
- Power-law formulations are often used for determining the flow stress ($\sigma$) in terms of the strain ($\varepsilon$), strain rate, and temperature ($\theta$).
- However, the power-law model does not necessarily work for HCP metals.
- These nondimensional indices are normalized quantities, and they will vary with homologous temperature and possibly with strain rate for HCP metals.

For the purposes of constitutive modeling, it is useful to define the following nondimensional material indices:

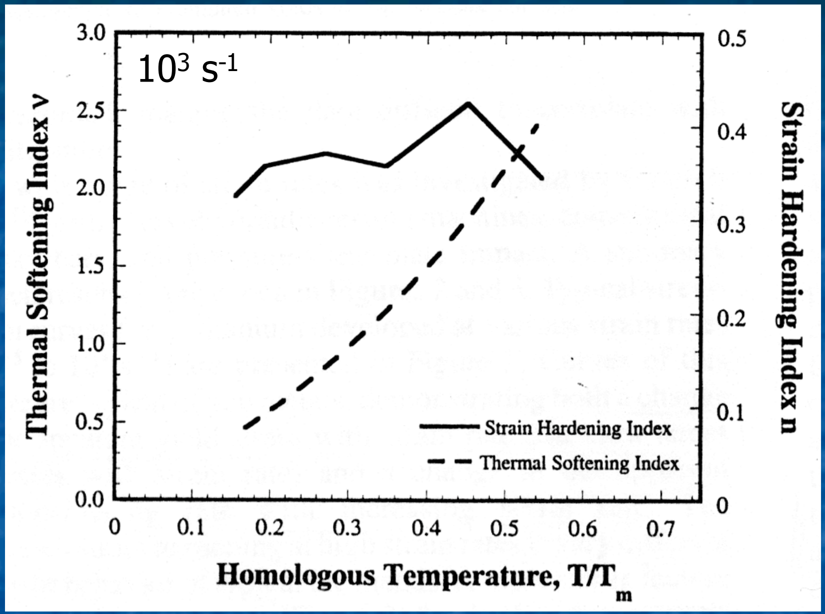
The strain-hardening index $n$: $n = \frac{\varepsilon}{\sigma}\left(\frac{\partial \sigma}{\partial \varepsilon}\right)$

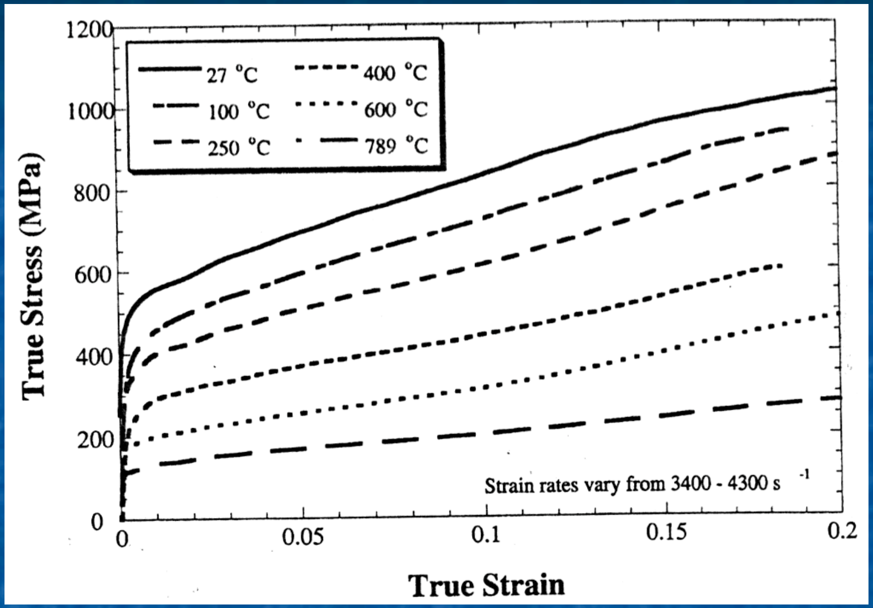
The strain-rate-hardening index $m$: $m = \frac{\dot{\varepsilon}}{\sigma}\left(\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right)$

The thermal-softening index $\nu$: $\nu = \frac{\theta}{\sigma}\left(\frac{\partial \sigma}{\partial \theta}\right)$



# Modeling HCP




- Note at high strain rates:
  - n varies weakly with homologous temperature,
  - v increases strongly with homologous temperature
- The strain rate hardening index (m) increases strongly with increasing strain rate
- Although the apparent strain hardening decreases strongly with temperature, the strain hardening index n varies only weakly with temperature.

# Conclusions

- Twinning stress is temperature insensitive.
- Twinning is an evolving process, increasing with increasing stress.
- Twinning stress depends more strongly on the grain size than the slip stress.
- Texture has an important effect on twinning in low symmetry materials, i.e. HCP metals
- A Constitutive Model of the slip-twinning transitions by Meyers, et. al., incorporated these ideas, but did not compare their results with experimental results.

# Conclusions (cont.)

- There is an apparent rate sensitivity of:
  - The flow stress
  - The yield stress
  - The strain hardening rate
- Softening occurs with increasing temperatures in HCP metals at low strain rates
  - There is little data on HCP metals at high strain rates and high temperatures
- The power-law model does not necessarily work for HCP metals, as the nondimensional indices are normalized quantities, and they will vary with homologous temperature