Temperature and Strain-Rate Dependence

Introduction

For most materials, an increase of strain rate raises flow stress. The effect of strain rate to the flow stress is mostly negligible near room temperature (e.g., ca. only 1 or 2% increase), but becomes pronounced at elevated temperatures (e.g., becomes 10-50% increase in flow stress).

Strain localization occurs in materials that have a high strain-rate dependence. For superplastic materials, tensile elongation can be as large as 1000% when coupling between strain rate and temperature can be fine tuned.

Strain rate

Strain rate $\dot{\varepsilon} = \frac{d\varepsilon}{dt}$

If in uniaxial tension test *displacement rate* of wedges 10 mm/sec.

And gauge length is 10 mm

Therefore strain rate = $\frac{10\ mm/sec}{10\ mm} = 1s^{-1}$

If gauge length 100 mm, strain rate= $\frac{10\ mm/sec}{100}$= $0.1s^{-1}$

Strain-Rate Dependence of Flow Stress

When temperature is held constant, stress and strain rate relation can be described by a *power-law* expression

$$\sigma = C\dot{\varepsilon}^{m} \quad \text{---- (1)}$$

where C is a strength constant that depends upon strain, temperature, and material, and m is the strain-rate sensitivity of the flow stress

Typical values of m is low at room temperature (0-0.03).

Table 7.1. Typical values of the strain-rate exponent, *m*, at room temperature

Material	*m*
low-carbon steels	0.010 to 0.015
HSLA steels	0.005 to 0.010
austenitic stainless steels	−0.005 to +0.005
ferritic stainless steels	0.010 to 0.015
copper	0.005
70/30 brass	−0.005 to 0
aluminum alloys	−0.005 to +0.005
α-titanium alloys	0.01 to 0.02
zinc alloys	0.05 to 0.08

Source: From various sources.

m can be obtained using either uniaxial testing at different strain rates or the strain rate jump test

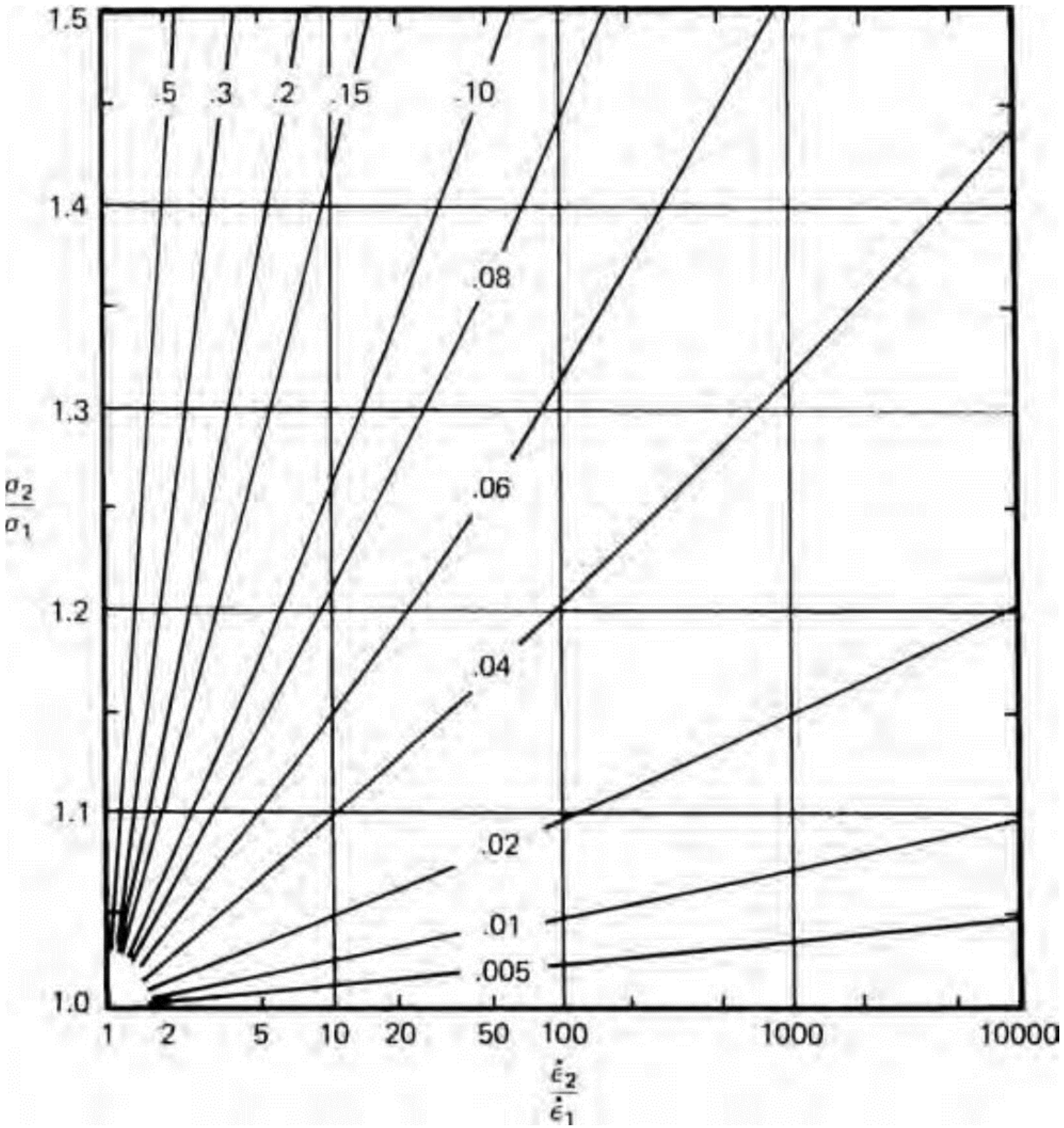
Determination of m

From (1) $\frac{\sigma_2}{\sigma_1} = \left(\frac{\dot{\varepsilon_2}}{\dot{\varepsilon_1}}\right)^m$

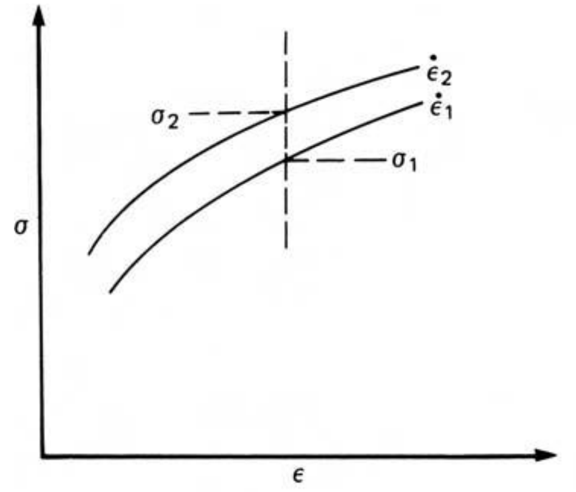
Or $\ln\frac{\sigma_2}{\sigma_1} = m\left(\frac{\dot{\varepsilon_2}}{\dot{\varepsilon_1}}\right)$ ------ (2)

at low temperatures, σ_2 is not much greater than σ_1, from (2)

$$\frac{\Delta\sigma}{\sigma} \simeq m \ln\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} = 2.3m\log\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}.$$

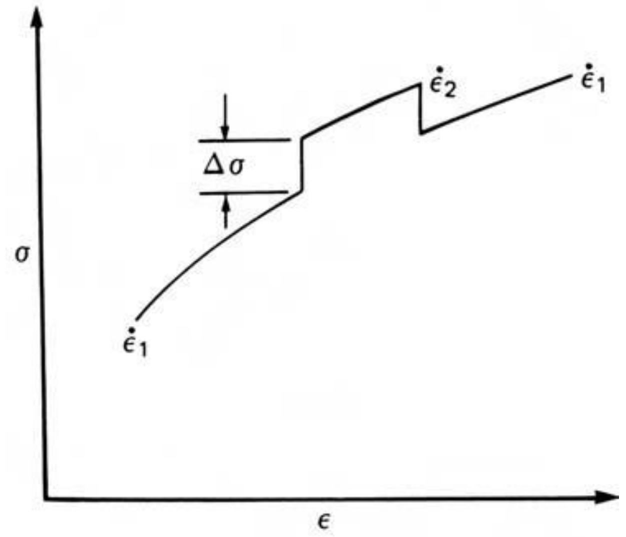


Determination of m



(a)

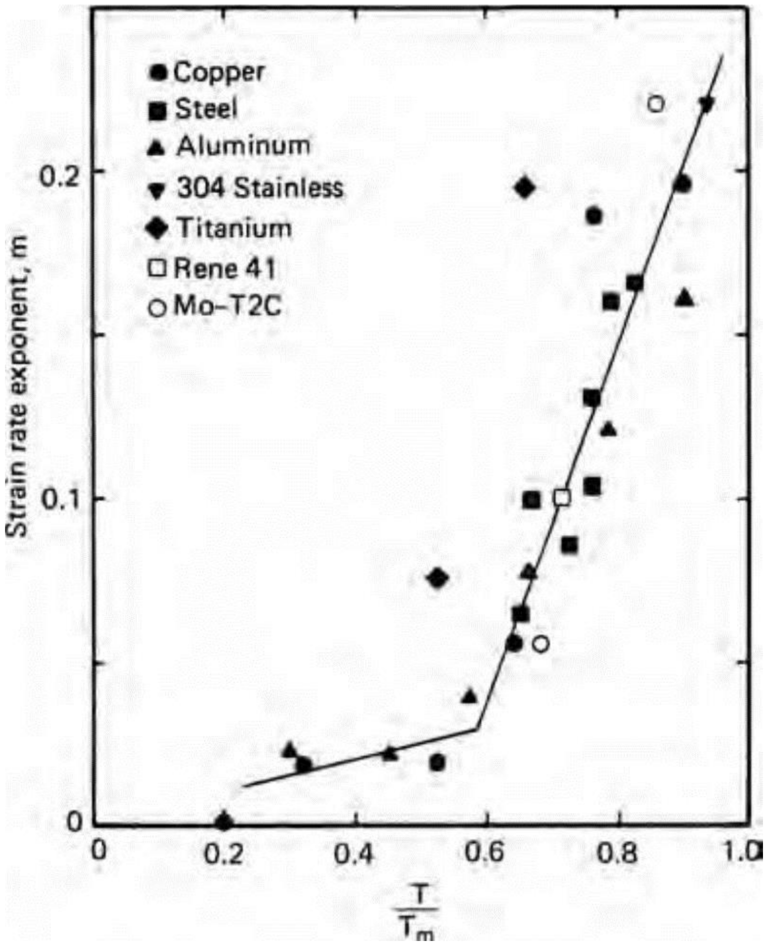
The strain-rate sensitivity, m, can be experimentally determined. One method is to run two continuous tensile tests at different strain rates and compares the levels of stress at the same strain. The other way is to change the strain rate suddenly during a test and compare the levels of stress immediately before and after the change. The two methods may give somewhat different values of m.

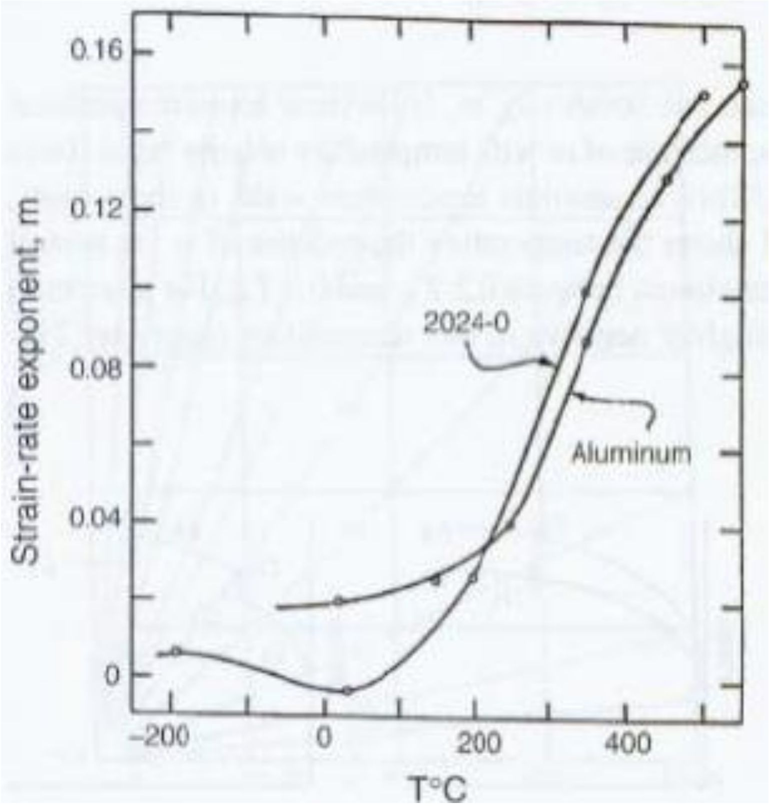


(b)

Two methods of determining m. (a) Two continuous stress–strain curves at different strain rates are compared at the same strain and $m = \ln(\sigma_2/\sigma_1)/\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)$. (b) Abrupt strain-rate changes are made during a tension test and $m = (\Delta\sigma/\sigma)/\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)$.

Effect of Temperature on m





The increase of m with temperature is quite rapid above half of the melting temperature (T >= Tm/2) on an absolute temperature scale.

Example problem 7.1: The strain-rate dependence of a zinc alloy can be represented by Equation (7.1) with $m = 0.07$. What is the ratio of the flow stress at $\varepsilon = 0.10$ for a strain rate of 10^3/s to that at $\varepsilon = 0.10$ for a strain rate of 10^{-3}/s? Repeat for a low carbon steel with $m = 0.01$.

SOLUTION: For zinc $(m = 0.07)$, $\sigma_2/\sigma_1 = (C\dot{\varepsilon}m_2)/(C\dot{\varepsilon}m_1) = (\dot{\varepsilon}_2/\dot{\varepsilon}_1)^m = (10^3/10^{-3})^{0.07} = (10^6)^{0.07} = 2.63$. For steel $(m = 0.01)$, $\sigma_2/\sigma_1 = (10^6)^{0.01} = 1.15$.

Example problem 7.2: The tensile stress in one region of an HSLA steel sheet $(m = 0.005)$ is 1% greater than that in another region. What is the ratio of the strain-rates in the two regions? Neglect strain-hardening. What would be the ratio of the strain rates in the two regions for a titanium alloy $(m = 0.02)$?

SOLUTION: Using Equation (7.2), $\dot{\varepsilon}_2/\dot{\varepsilon}_1 = (\sigma_2/\sigma_1)^{1/m} = (1.01)^{1/0.005} = 7.3$. If $m = 0.02$, $\dot{\varepsilon}_2/\dot{\varepsilon}_1 = 1.64$. The difference between the strain rates in differently stressed locations decreases with increasing values of m.

SUPERPLASTICITY---Class lecture

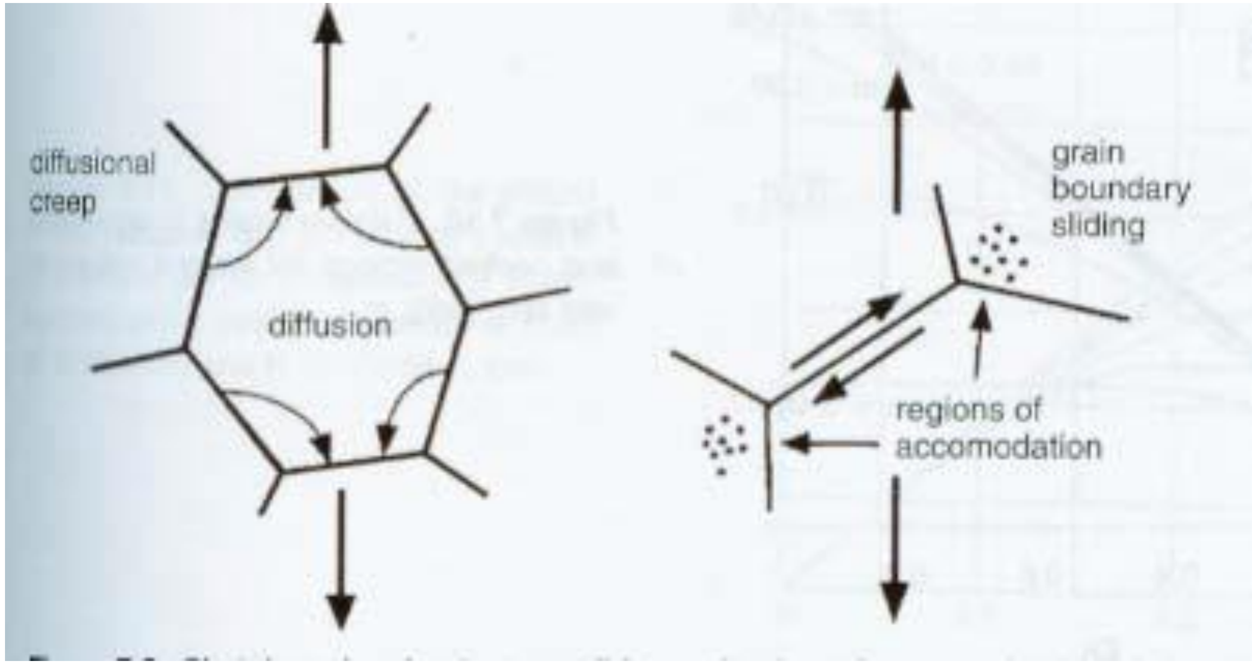
Activation volume– class lecture

$$v^* = 3\sqrt{3}\,\frac{k_B T}{mH}$$

Superplasticity Mechanisms

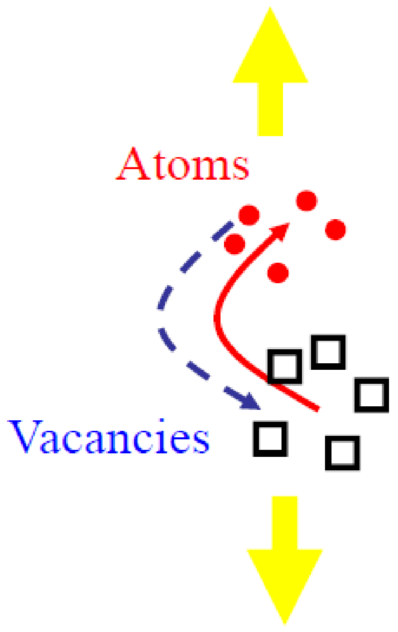
Two main mechanisms contributing to the superplasticity. One is a net diffusional flux under stress of atoms from grain boundaries parallel to the tensile axis to grain boundaries normal to the tensile axis, causing a tensile elongation (i.e., diffusional creep).

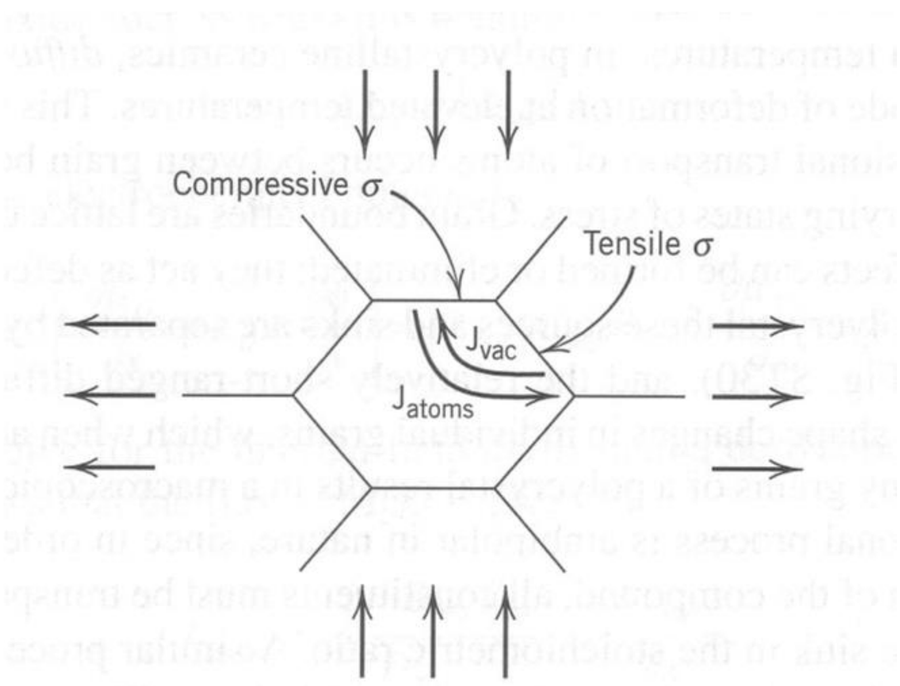
The other is grain boundary sliding. Accommodation of the triple junction of the grain structure needs to occur either by slip or by diffusion.

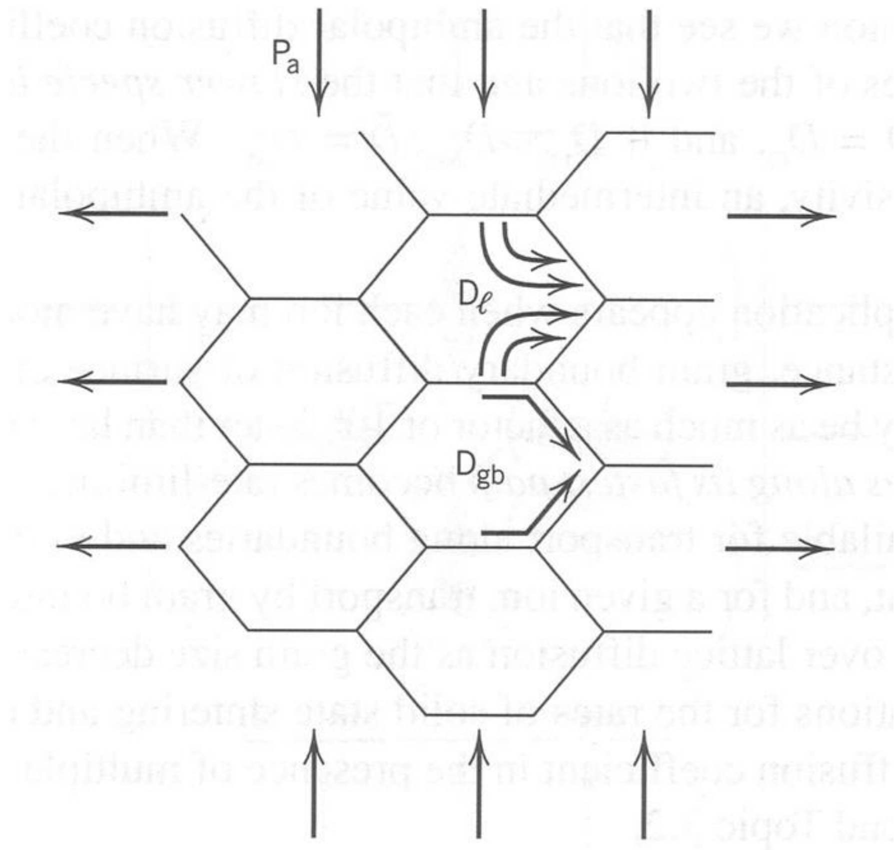


Superplasticity Mechanisms

For the creep model, creep occurs by diffusion between grain boundaries. As atoms diffuse from lateral boundaries to boundaries normal to the tensile stress, the grain elongates and contracts laterally (since vacancies move at a direction counter to that of the atomic diffusion)

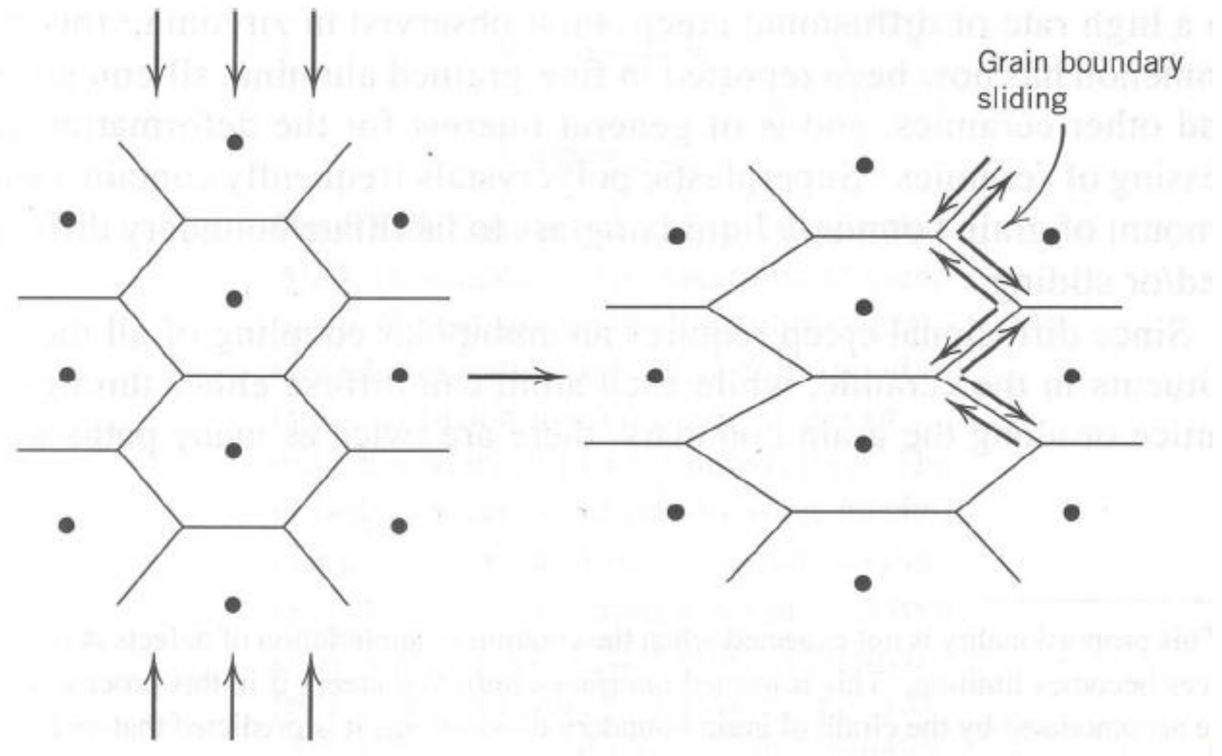






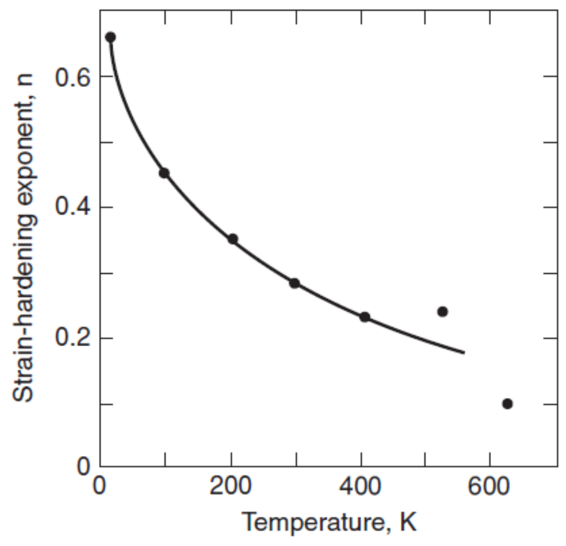
Superplasticity Mechanisms

By observing the relative positions of grain centers as grains deform, it is apparent that in order to accommodate the shape change without opening up voids at the grain junctions (i.e., causing cavitation) the grains must slide with respect to one another.

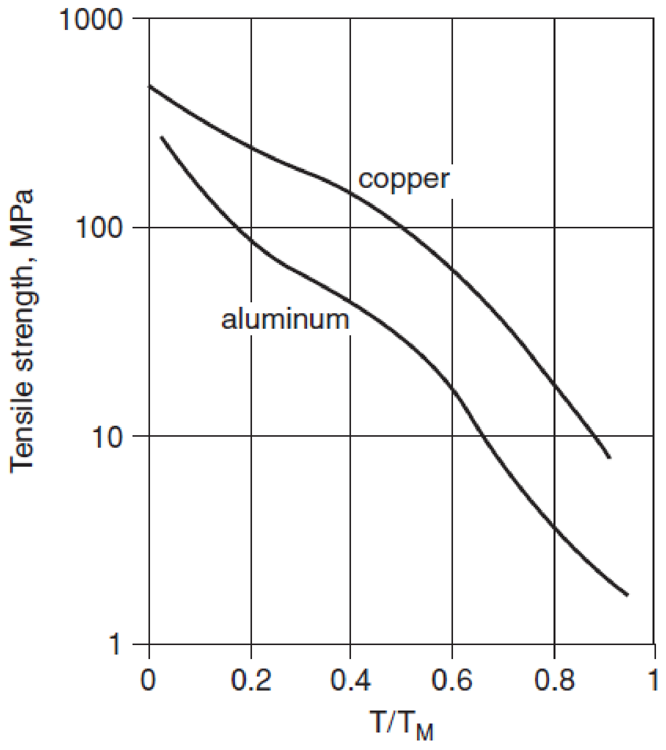


TEMPERATURE DEPENDENCE OF FLOW STRESS

Effect of T



Decrease of the strain-hardening exponent, n, of pure aluminum with temperature



Decrease of tensile strength of pure copper and aluminum with homologous temperature.

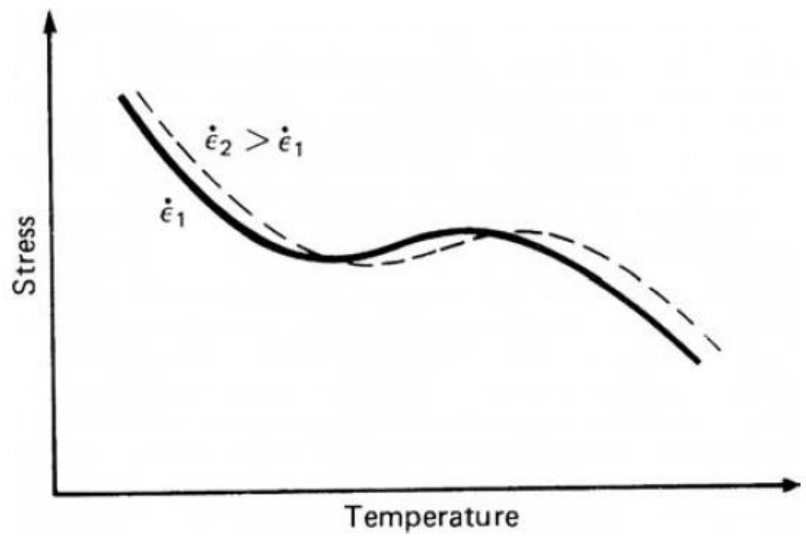


Fig. shows σ ↑ with T

Schematic plot showing the temperature dependence of flow stress for some alloys.
In the temperature region where flow stress increases with temperature, the strain-rate sensitivity (m) is negative.

Effect of T

Temp. dependence of flow stress at const. strain and strain rate

$$\sigma = C_2 e^{Q/_{RT}}$$

Q= activation energy of plastic flow (J/mol.)

R= universal gas constant (8.314 J/mol/K)

T= test temp(K)

Adiabatic shear fracture????

Combined effect

Combined effect

- Class lecture