재료의 기계적 거동
(Mechanical Behavior of Materials)

Lecture 15 – High Temperature Deformation of Crystalline Materials

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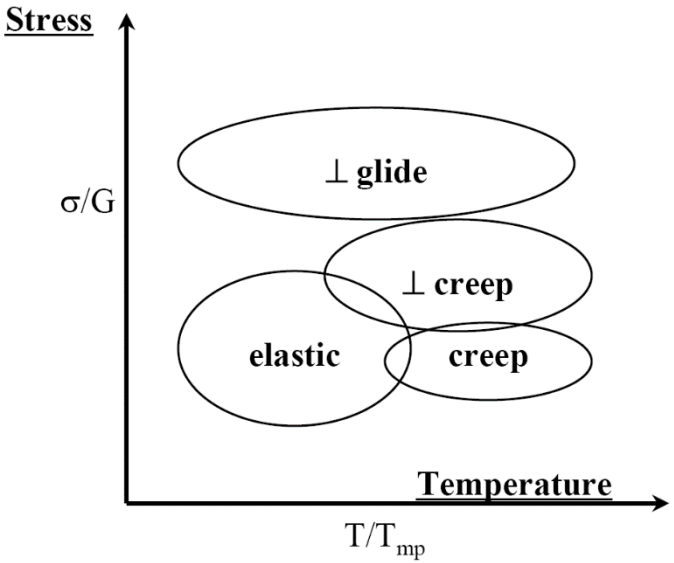
Introduction

- **$T > 0.5\ T_{mp}$: CREEP deformation occurs.**
  $\sigma < \sigma_{ys}$: Permanent deformation occurring by CREEP over long periods of time.

CREEP = time-dependent permanent deformation
YIELDING = time-independent permanent deformation

Deformation Mechanism Maps (DMM) [Ashby]



Steady-State Creep Rate

When long life is necessary and dimensional tolerances are critical (Ex. Jet engine turbine blade)

$$\dot{\varepsilon}_{ss} = A\sigma^{n} e^{-Q/RT}$$

A & n are material constants
Q is the creep activation energy

Dorn relation :
When $T \geq 0.5T_{mp}$, Q : activation energy for self-diffusion

Generalized form of the Creep Equation

$$\dot{\varepsilon} = \frac{ADGb}{kT}\left(\frac{\sigma}{G}\right)^n \left(\frac{b}{d}\right)^p, \text{ where } D = D_o \exp(-Q/kT)$$

D = diffusion coefficient
d = grain size
b = Burgers vector
k = Boltzmann's constant
T = the absolute temperature (degrees Kelvin)
G = the shear modulus
σ = applied stress
n = stress exponent
p = inverse grain size exponent
A = a dimensionless constant.

This form of the Dorn equation applies for all creep mechanisms.

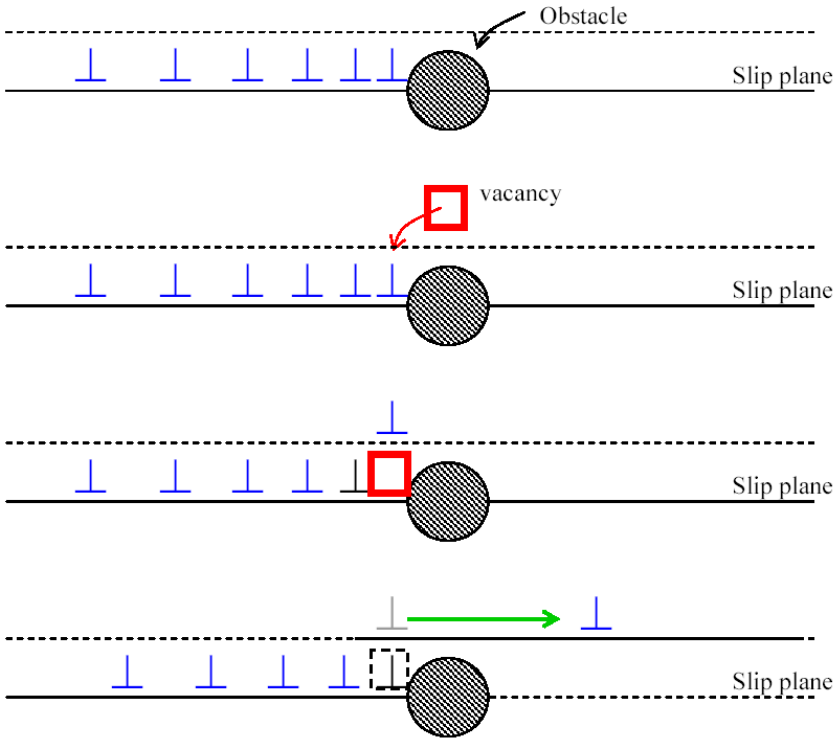
Dislocation Glide Creep

Low T or High σ

- ⊥ motion is assisted by thermal activation.

- Crystals always contain defects.

- Certain point defects, vacancies, can promote plastic deformation by helping ⊥'s overcome obstacles. This is "vacancy assisted climb".



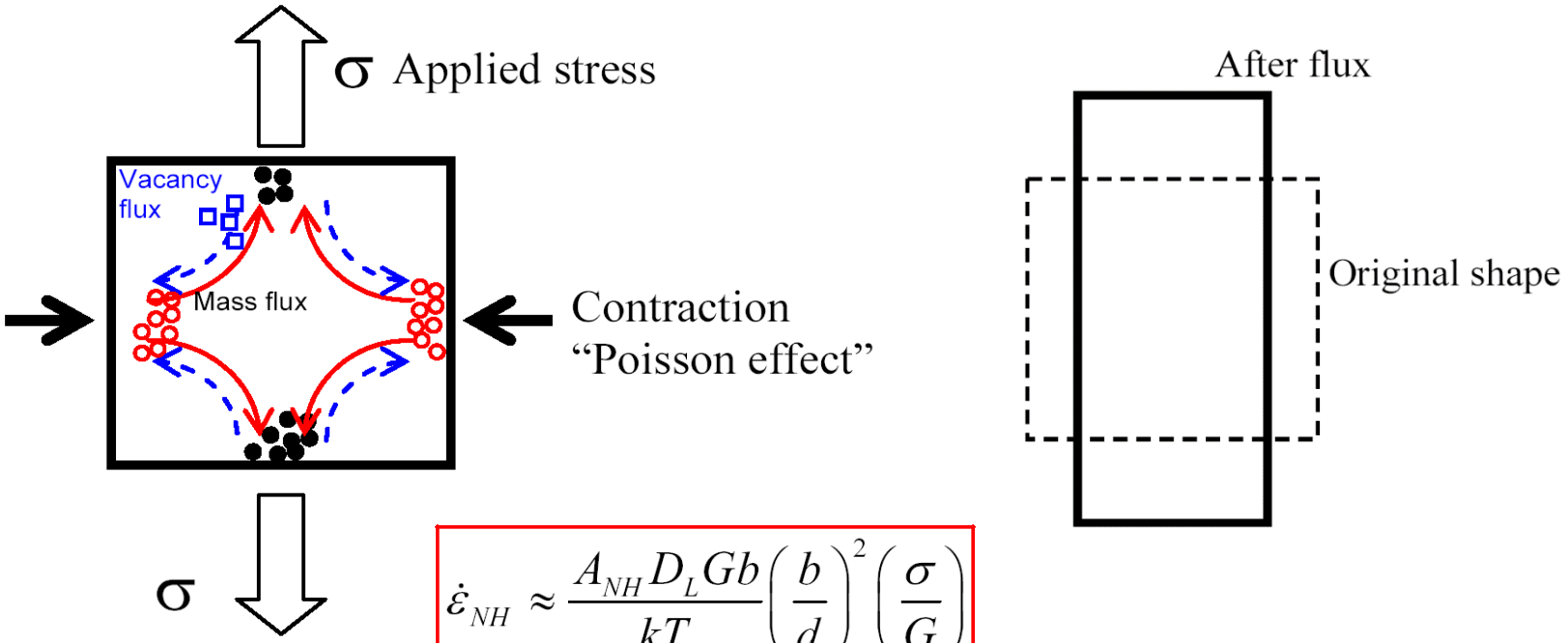
$$\dot{\varepsilon}_{dg} \approx \frac{ADGb}{kT}\left(\frac{\sigma}{G}\right)^5$$

Nabarro-Herring Creep

. Occurs solely by diffusional mass transport.

. Is important for much higher *T* and lower σ than was the case for dislocation glide creep.

. Can occur in crystalline and amorphous materials.



$$\dot{\varepsilon}_{NH} \approx \frac{A_{NH} D_L G b}{kT}\left(\frac{b}{d}\right)^2\left(\frac{\sigma}{G}\right)$$

$A_{NH} \cong$ 10-15

D_L = lattice diffusion coefficient

Coble Creep

- Also driven by stress-induced vacancy concentration gradient.
- Diffusion/mass transport occurs along:
  Grain boundaries in polycrystalline materials
  Surfaces in single crystals

$$\dot{\varepsilon}_C \approx \frac{A_C D_{GB} G b}{kT}\left(\frac{\delta}{b}\right)\left(\frac{b}{d}\right)^3\left(\frac{\sigma}{G}\right)$$

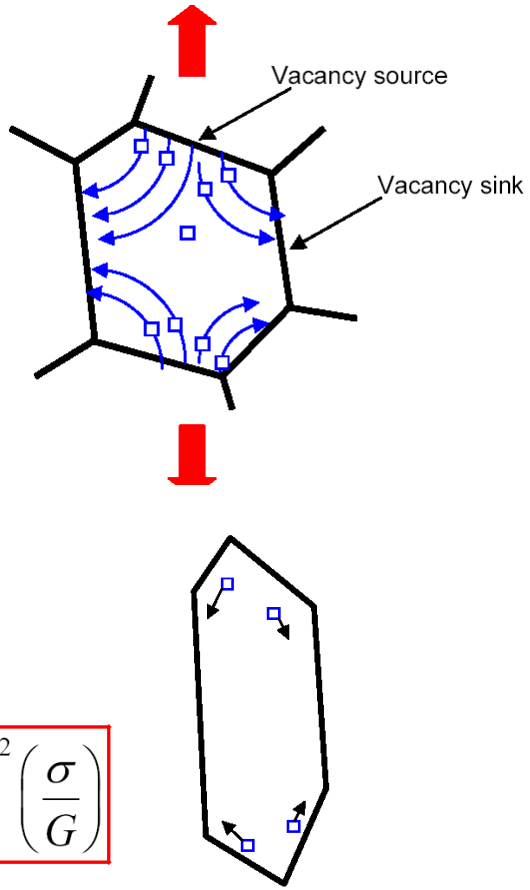
$A_C \cong 30\text{-}50$

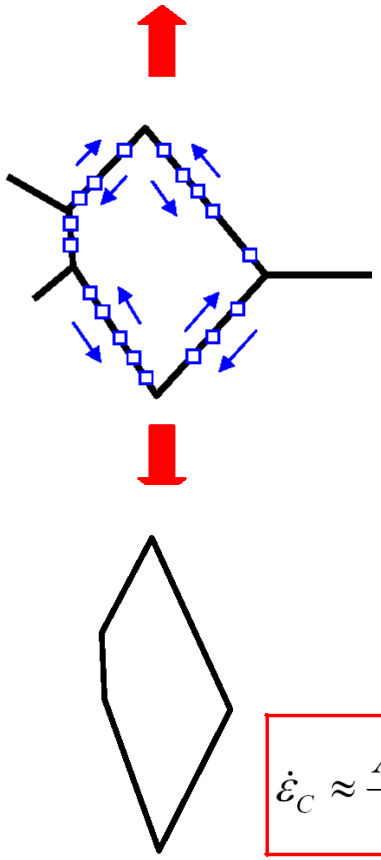
D_{GB} = grain boundary diffusion coefficient

δ = effective width of grain boundary

DIFFUSIONAL FLOW CREEP MECHANISMS

Vacancy Flow According to NH and Coble Creep Mechanisms





$$\dot{\varepsilon}_{NH} \approx \frac{A_{NH} D_L G b}{kT} \left(\frac{b}{d}\right)^2 \left(\frac{\sigma}{G}\right)$$

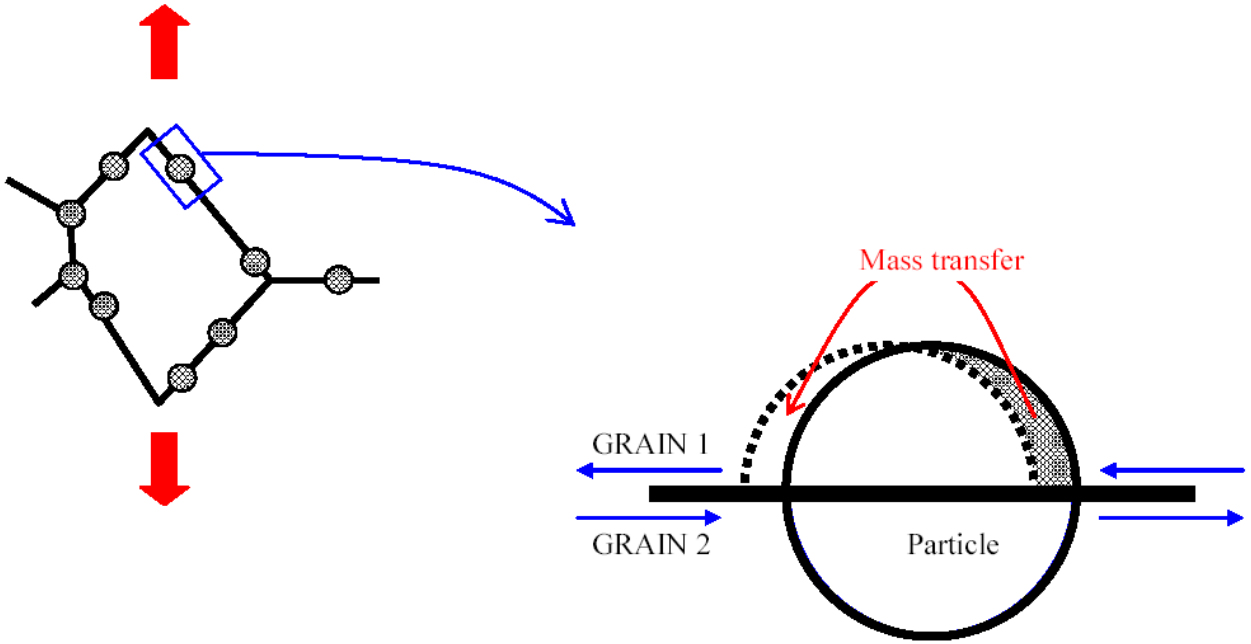
Nabarro-Herring

$$\dot{\varepsilon}_{C} \approx \frac{A_{C} D_{GB} G b}{kT} \left(\frac{\delta}{b}\right) \left(\frac{b}{d}\right)^3 \left(\frac{\sigma}{G}\right)$$

Coble

CREEP IN TWO PHASE ALLOYS

. The creep rate of a material can be greatly reduced by the incorporation of a fine dispersion of non-deforming particles at grain boundaries.
. The particles effectively inhibit grain boundary sliding.

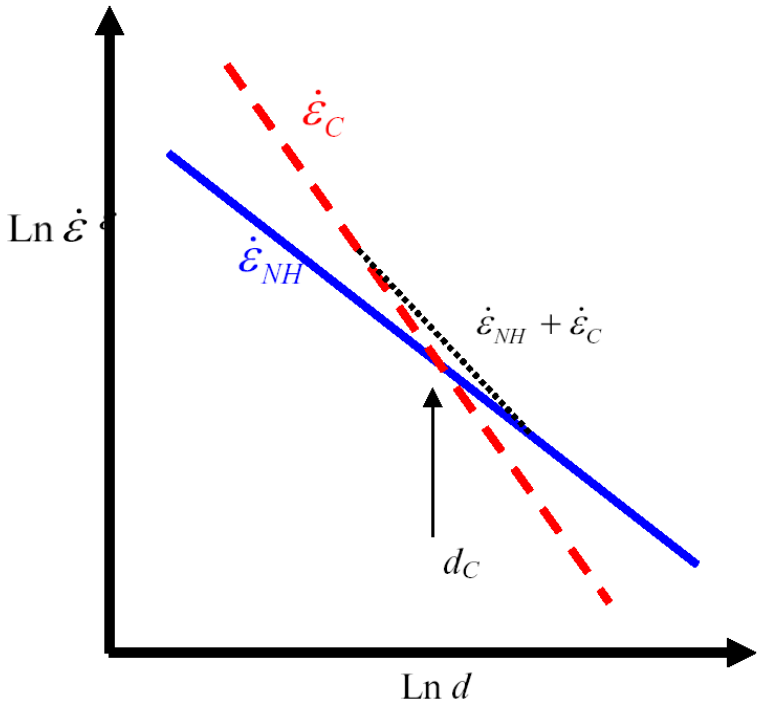


ROLE OF PARTICLES: they "pin" grain boundaries.

COMBINED CREEP MECHANISMS

DIFFUSION CREEPS

$$\dot{\varepsilon}_{diffusion} = \dot{\varepsilon}_{NH} + \dot{\varepsilon}_{C}$$



- NH: $\dot{\varepsilon} \propto d^{-2}$
- Coble: $\dot{\varepsilon} \propto d^{-3}$

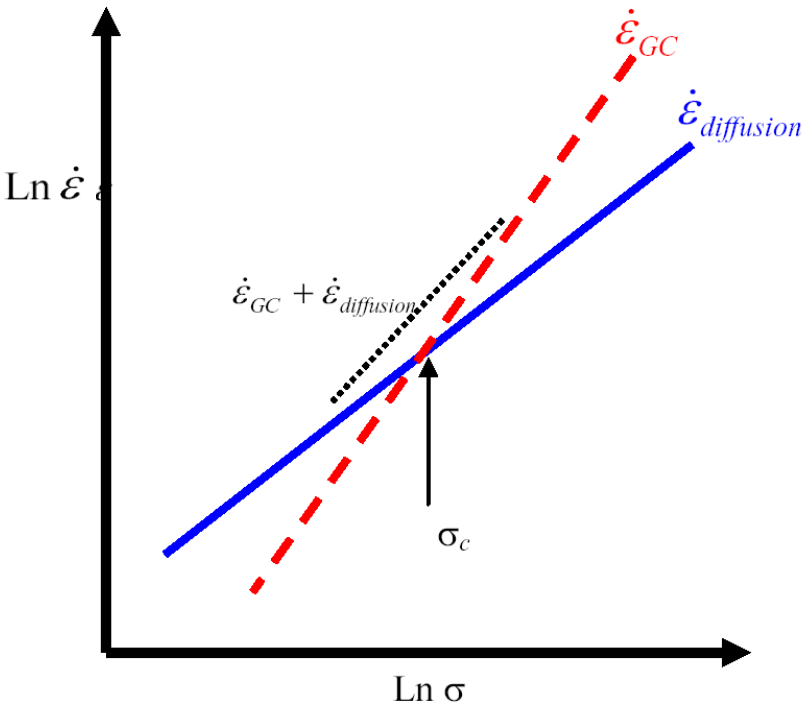
$\therefore$ grain size is more important.

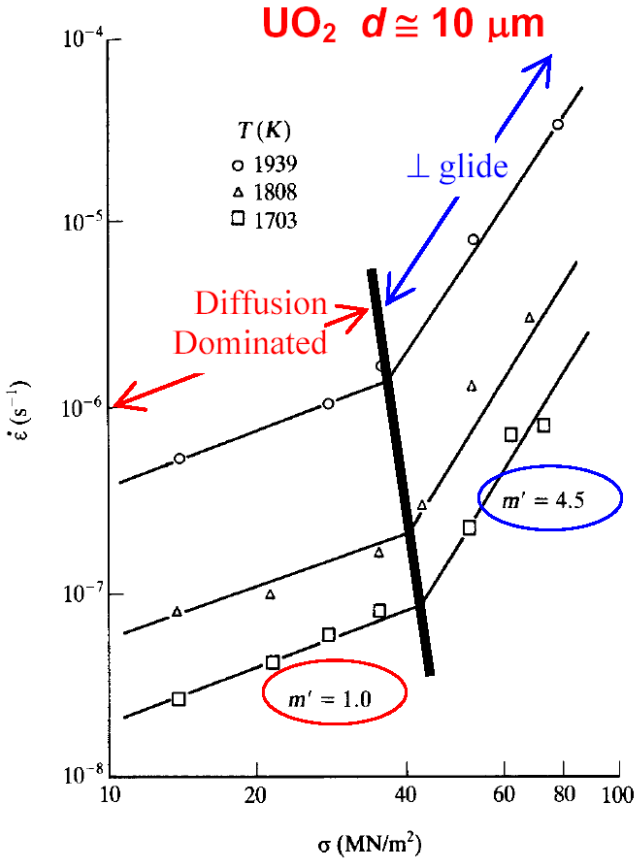
COMBINED CREEP MECHANISMS

DIFFUSION & DISLOCATION CREEP

In this case, σ is critical for determining the relative proportion that each mechanism contributes to the overall creep rate.

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{diffusion} + \dot{\varepsilon}_{GC}$$





ESTIMATES OF CREEP LIFE

Design Lives:

Jet turbine ..... 10,000 hr (1 year)
Stationary turbine .....~10 years
Nuclear reactor .....~40 years

MUST: be able to extrapolate properties measured over short (accelerated) time to predict performance over extended time.

LARSON-MILLER METHOD

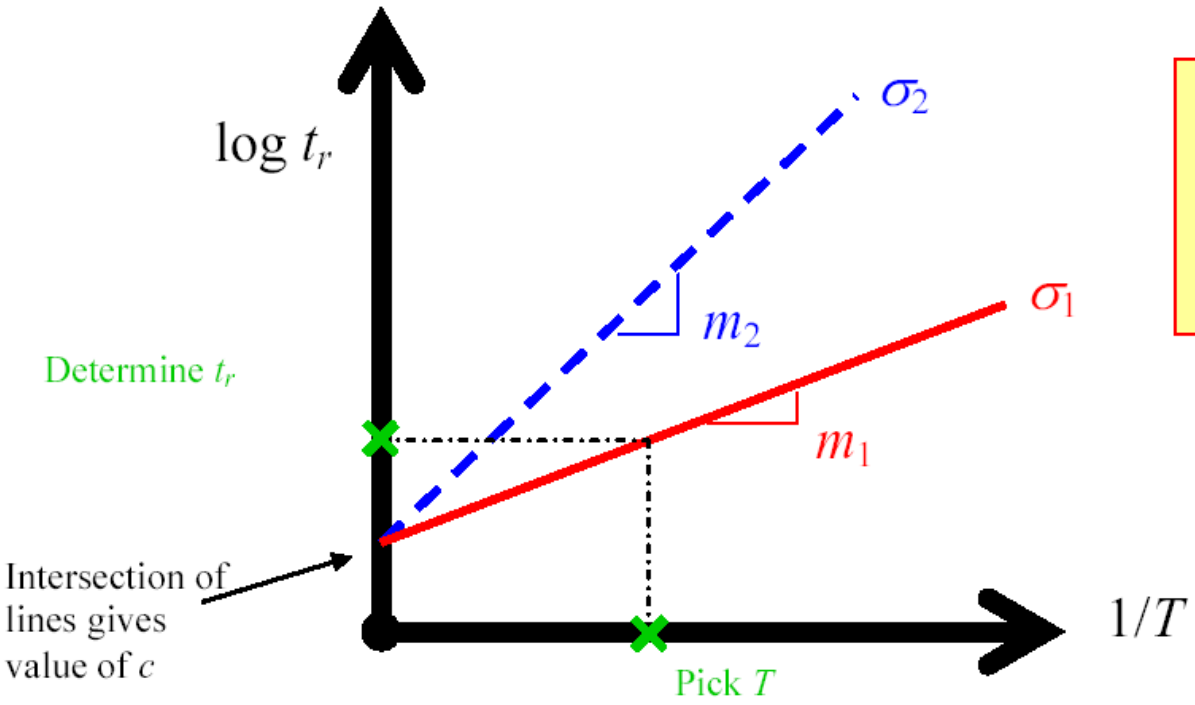
$$m=LM=T(\log t_f + C)$$

LM or m : Larson-Miller constant varied with stress
C : Material constant
t_f : Time to rupture

ESTIMATES OF CREEP LIFE

Now, if we keep stress constant, m = constant.

We can change T and can calculate the time to rupture (failure).



Experimentally, the LM approach gives optimistic life predictions

SUPERPLASTICITY

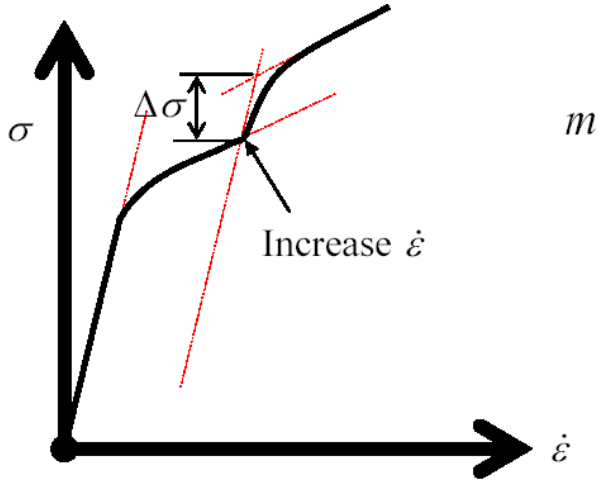
It has been observed that some materials when heated above 0.5Tmp can elongate to extremely large strains (e.g., ~5000%).
We take advantage of this phenomenon to form complex shapes that cannot normally be obtained by forging, extrusion, or other metalworking processes.
This is called "superplasticity".

Microstructural Requirements:

1. **Grain size ≤ 10 μm**
   This grain size must not change during straining!
2. **Grain shape remains equiaxed during superplastic forming.**
   Grains "slide" under stress.

SUPERPLASTICITY

Strain Rate Sensitivity:

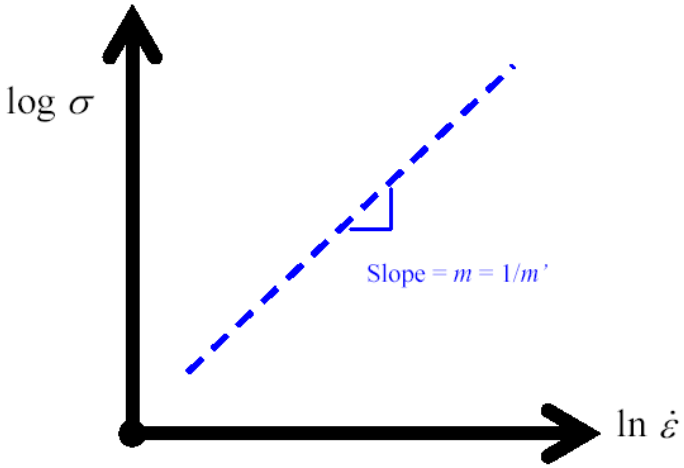


$$m = \frac{d \ln \sigma}{d \ln \dot{\varepsilon}}$$

As *m* increases, the material becomes more resistant to necking.

In the neck, $\dot{\varepsilon}_{neck} > \dot{\varepsilon}_{non-neck}$

We can determine *m* from strain rate change and/or stress relaxation tests.



∴ flow stress of the neck > flow stress in non-necked region

∴ deformation stops in the neck.