

Module #23

CREEP & SUPERPLASTICITY

READING LIST

► DIETER: Ch. 13, all

- Chapter 13 in Meyers & Chawla
- T.G. Nieh, J. Wadsworth and O.D. Sherby, <u>Superplasticity in metals and ceramics</u>, (Cambridge University Press, Cambridge, 1997).



High Temperature Deformation of Crystalline Materials

- <u>T < 0.5 T_{mp</u></u>}
- <u> $T > 0.5 T_{mp}$ </u>

design so $\sigma < \sigma_{ys}$ design so $\sigma < \sigma_{ys}$

HIGH TEMPERATURE DEFORMATION <u>MODES</u> We must also consider permanent deformation occurring by <u>CREEP</u> over long periods of time.

<u>CREEP</u> = time-dependent plastic deformation <u>YIELDING</u> = time-independent plastic deformation

- We can incorporate these things into Deformation Mechanism Maps (DMM) [Frost and Ashby]
- They are useful in design applications – have DMM for each alloy – but to really know/predict high T useful life of alloy, still must do testing – usually accelerated!



Phenomenological Description of Creep





Stage II: $\dot{\varepsilon}$ = constant AND minimum, $\dot{\varepsilon}_{II}$

Difference between constant load and constant stress creep tests



STAGES OF CREEP

STAGE 0: Initial Strain on Loading ($\varepsilon_{\text{Elastic}}$???)

STAGE I:Transient (Primary) Creep $\dot{\varepsilon} \downarrow$ with \uparrow time & strain $\underline{\varepsilon} \downarrow$ with \uparrow time & strainCause $\left\{ \perp \rho \uparrow \text{ and subgrains form} \atop \text{to } \uparrow \text{ strength of material} \right\}$



STAGES **O**F **C**REEP – cont'd

STAGE III:Tertiary Creep $\dot{\mathcal{E}} \uparrow$ with \uparrow time & strain
fracture is soon to occur after Stage III beginsCause $\left\{ \begin{array}{c} recrystallization \\ coarsening of 2nd phase particles \\ formation of internal cracks & voids \end{array} \right.$

CREEP

Design Considerations

This parameter is usually addressed in scientific analyses as it is most readily correlated with microstructures and creep mechanisms.

 t_f : Use when failure must not occur but deformation/creep is tolerable.

Usually either $\dot{\mathcal{E}}_{II}$ or t_f

- Ex., Casing on rocket combustion chamber
- $\dot{\varepsilon}_{II}$: Use when long life is necessary and dimensional tolerances are critical.
 - Ex., Jet engine turbine blade

Steady-State Creep Rate (Monkman-Grant Relationship)

Where steady-state creep dominates creep life (some materials) $\dot{\mathcal{E}}_{\min} \times t_f = \text{constant}$

Sometimes it needs to be modified as follows:

$$\dot{\mathcal{E}}_{\min}^{\beta} \times t_f = \text{ constant; } \beta < 1$$

Steady-State Creep Rate (Dorn Relationship)

$$\dot{\varepsilon}_{II} = \dot{\varepsilon}_{ss} = A'\sigma^n \exp\left(\frac{-Q_c}{RT}\right)$$
$$= \dot{\varepsilon}_o \left(\frac{\sigma}{\sigma_o}\right)^n \exp\left(\frac{-Q_c}{RT}\right)$$

When $T \ge 0.5T_{mp}$ $Q_c \cong activation energy for self-diffusion$



This equation also holds for many materials and establishes the temperature and stress dependence of the creep rate.

Correlates with the activation energy for the mechanisms causing creep. We'll address the mechanisms shortly (in great detail).

$$\Rightarrow Q_c = R \frac{\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$





Activation Energy for Creep, Q_c (MJ/mole)

Activation energies for steady state creep and self diffusion for a select group of crystalline materials. Adapted from O.D. Sherby and A.K. Miller, <u>J. Eng. Mater. Technol.</u>, v. 101 (1979) p. 387.



Figure 4-6. Variation of the apparent activation energy for creep in aluminum with temperature (Sherby et al., 1957).

Acta Metall., v. 5, p. 219 (1957)

Generalized form of the Dorn 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 $\sigma = \text{applied stress}$ n = stress exponent p = inverse grain size exponentA = a dimensionless constant.

This form of the Dorn equation applies for <u>all</u> creep mechanisms.

CREEP MECHANISMS

It is convenient to discuss deformation (and creep) mechanisms in terms of temperature and/or applied stress.

Deformation mechanism maps $\frac{\sigma/G}{or}$ (DMMs) * τ/G

* Adapted from: M.F. Ashby, <u>Acta</u> <u>Metall.</u>, v. 20 (1972) p. 887-897.



 T/T_{mp}

WE'LL ADDRESS THE DETAILS IN A LITTLE WHILE

CREEP MECHANISMS

Low T or High σ : Dislocation Glide (DG) Creep

- Dislocation (\perp) motion is assisted by thermal activation.
- Does it involve diffusive processes?



• *E_o* is the activation that must be overcome by the dislocation to cause it to move from one lattice location to another.

• Thermal activation supplies energy (in absence of stress) which reduces the activation energy barrier by δE .

$$\dot{\varepsilon}_{dg} \cong \dot{\varepsilon}_{o} \exp\left(\frac{-E_{o}}{kT}\right) \exp\left(\frac{\delta E}{kT}\right) = \dot{\varepsilon}_{o} \exp\left(\frac{-E_{o}}{kT}\right) \exp\left(\frac{\tau ba_{s}}{kT}\right)$$

 NOTE: for BCC metals, T has a major influence on plastic deformation

Diffusional Flow Creep Mechanisms Nabarro-Herring (NH) Creep

- Occurs solely by diffusional mass transport (i.e., diffusion).
- Is important for much <u>higher *T*'s</u> and <u>lower σ 's than</u> was the case for <u>dislocation glide creep</u>.
- Can occur in crystalline and amorphous materials.



Diffusional Flow Creep Mechanisms – cont'd Nabarro-Herring (NH) Creep

- Applied stress creates tensile and compressive regions within a grain.
 - Concentration of vacancies in tensile regions is greater than that in compressive region.
 - Vacancy concentration gradient \rightarrow diffusion
 - Diffusion leads to shape change



$$\dot{\varepsilon}_{_{NH}} \approx \frac{A_{_{NH}}D_{_{L}}Gb}{kT} \left(\frac{b}{d}\right)^{2} \left(\frac{\sigma}{G}\right)$$
$$A_{_{NH}} \cong 10 - 16$$
$$D_{_{L}} = \text{ lattice diffusion coefficient}$$

NH creep is competitive with \perp glide creep NH creep \uparrow with \uparrow 7 and $\downarrow\sigma$

Diffusional Flow Creep Mechanisms

Coble Creep

- Also driven by stress-induced vacancy concentration gradient, <u>BUT</u>
- Diffusional mass transport occurs along:
 - Grain boundaries in polycrystalline materials
 - Surfaces in single crystal materials.

$$\dot{\varepsilon}_{C} \approx \frac{A_{C}D_{GB}Gb}{kT} \left(\frac{\delta}{b}\right) \left(\frac{b}{d}\right)^{3} \left(\frac{\sigma}{G}\right)$$
$$A_{C} \approx 30 - 50$$

 D_{GB} = grain boundary diffusion coefficient δ = effective width of grain boundary

• NH and Coble creep are really parallel processes (i.e., they operate in tandem).



Vacancy Flow Due to NH and Coble Creep Mechanisms





Nabarro-Herring







Coble



Grain Boundary Sliding



GB sliding occurs in conjunction with the NH & Coble creep mechanisms

GB sliding is also thought to be the mechanisms that allows a material to extend in length with no net change in grain size during superplastic forming operations

Dislocation Climb-Glide Creep

- RECALL: Crystals always contain defects
- Certain point defects, vacancies, can promote plastic deformation by helping $\perp\!$ s overcome obstacles. This is "vacancy assisted climb"



Solute Drag Creep

- Occurs in <u>some</u> metallic alloys (i.e. those that don't display short-time creep behavior).
- At low temperatures, solute atoms are immobile.
- At higher temperatures, solute atoms may diffuse, albeit slowly.
- From the Taylor-Orowan equation: $\dot{\varepsilon} = \rho b v$ dislocations move at a velocity *v*.
- Provided the dislocation velocity is near the velocity at which the solutes diffuse, the solutes can move along with the dislocations.

$$\dot{\varepsilon}_{SD} \sim \frac{D_{solute}\sigma^3}{\varepsilon_b^2 c_o} = \left(\frac{1}{64\varepsilon_b^2 c_o}\right) \left(\frac{D_{solute}}{b^2}\right) \left(\frac{kT}{G\Omega}\right) \left(\frac{\sigma\Omega}{kT}\right) \left(\frac{\sigma}{G}\right)^2$$
OR

 $(\Omega = atomic volume)$

$$\dot{\varepsilon}_{SD} = A_{SD} \left(\frac{D_{solute}}{b^2} \right) \left(\frac{\sigma \Omega}{kT} \right) \left(\frac{\sigma}{G} \right)^2$$

• This leads to serrated flow (i.e., the Portevin-Le Chatelier effect).

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.



For grain 1 to slide relative to grain 2, there must be mass transport to "move" one portion of the particle relative to the other.

- Larger particles are more effective at inhibiting grain boundary sliding.
- ROLE OF PARTICLES: they inhibit recrystallization; they "pin" grain boundaries.

TABLERepresentative values of the parameters n, p and approximate
values of the constant A for $\dot{\varepsilon}_{ss}$

Mechanism	Favored by	Description	A	n	р
Nabarro-Herring Creep	High temperature, low stress and large grain size	Vacancy diffusion through the crystal lattice	10-15	1	2
Coble Creep	Low stress, fine grain sizes and temperatures less than those for which NH creep dominates	Vacancy diffusion along grain boundaries	30-50	1	3
Grain Boundary Sliding	Same range as NH and Coble creep	Sliding accommodated by vacancy diffusion through the crystal lattice (p=2) or along grain boundaries (p=3)		2	2 or 3
Dislocation creep	High stress, lower temperatures in comparison to Coble creep, and large grain sizes	Dislocation motion, with climb over microstructural obstacles.		3-8	0

$$\dot{\varepsilon} = \frac{ADGb}{kT} \left(\frac{\sigma}{G}\right)^n \left(\frac{b}{d}\right)^p$$

where $D = D_o \exp(-Q/kT)$

COMBINED CREEP MECHANISMS

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

Controlling parameters:

- A_{NH} vs. $A_C \underline{AND}$ grain size (d)
- NH: $\dot{\varepsilon} \propto d^{-2}$
- Coble: $\dot{\varepsilon} \propto d^{-3}$: grain size is more important here



Diffusion & Dislocation Creep

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



DEFORMATION MECHANISM MAPS

• Deformation mechanism maps (DMMs) show combinations of σ and T for specific creep mechanisms.



- DMMs have been developed from constitutive equations for alloys and are available for only a small fraction of engineering alloys.
- DMM: shows the dominant & active creep mechanism for a particular σ & T

<u>Visual aids</u>

*We can also superimpose strain rates onto DMM. Can see how this changes the dominant creep mechanism.

Deformation Mechanism Maps for AI, W, and MgO



- Does grain size influence DMMs?
- Why does Coble creep occur at low T relative to NH creep?



Incorporation of strain rate considerations and ignoring the elastic component modifies DMMs

Why does deformation rate shift the various regimes as illustrated?



FIGURE 7.18 (a) Schematic deformation mechanism map with isostrain-rate contours imposed on it. For example the strain rate $\dot{\epsilon}_2$ is obtained at the stress-temperature combination (σ_1, T_1) and the mechanism is Nabarro-Herring creep. The same strain rate is obtained by dislocation glide at the stress σ_2 and temperature T₂. (b) and (c) Deformation mechanism maps for W and MgO, both of 10 µm grain size, with strain-rate contours imposed on them. (Part (b) from M. F. Ashby, Acta Metall., 20, 887, 1972; (c) from A. G. Evans and T. G. Langdon, Prog. Matls. Sc., 21, 171, 1976.)



GRAIN SIZE EFFECT



- FIGURE 7.19 (a) A deformation mechanism map depends on grain size. Finer grain sizes expand the regions of Nabarro-Herring and, particularly, Coble creep. (b) An alternative formulation of a deformation mechanism map has axes of normalized stress and grain size at a specified temperature. In the figure, the dominant creep mechanisms are identified for various stress-grain size combinations. (*Part (a) from M. F. Ashby, Acta Metall.*, 20, 887, 1972.)
- How does grain size influence DMMs?

Effects of Structure & Properties on Creep Resistance

- $\dot{\varepsilon}_{II}$ \uparrow with: \uparrow applied stress
 - \uparrow diffusivity (\downarrow activation energy)

 \downarrow grain size

- For a given application *T*, use of higher T_{mp} material will \downarrow diffusivity and correspondingly $\downarrow \dot{\varepsilon}_{II}$.
- In general:
 - Diffusivities in bcc metals >> diffusivities in fcc metals
 - \therefore if we have a bcc metal and an fcc metal with the same T_{mp} ,

 $\dot{\mathcal{E}}_{bcc} > \dot{\mathcal{E}}_{fcc}$

- \uparrow grain size, $\downarrow \dot{\varepsilon}$ for diffusion controlled creep <u>but</u> does not have any influence on the **L** creep mechanism.
- For \bot glide <u>mechanism</u>: \uparrow grain size will $\uparrow \dot{\varepsilon}$

Grain Size Effect

• MarM 200 \rightarrow Ni-based superalloy used in turbine blades





$$\frac{\dot{\varepsilon} = 10^{-9} \text{ sec}^{-1}}{\tau / G} = 10^{-3}$$

$$T / T_{mp} = 0.5$$

$$d = 1 \text{ cm}$$

$$\tau / G = 10^{-3}$$

$$T / T_{mp} = 0.8$$

ċ is a Coble creep process∴ GS is very important

<u>A few important comments</u>

- Recall, that one way to engineer a material to exhibit higher creep resistance is to add second phase particles.
- If the particles restrict grain boundary sliding, they will decrease the steady state creep rate.
- Most creep resistant alloys utilize this technique. Single crystals are also used in conjunction with second phase particles.

Estimates of Creep Life

Have critical correlations between properties and performance



Design Lives:Jet turbine ------ 10,000 hr (1 year)Stationary turbine ------ ~10 yearsNuclear reactor ------ ~40 years

- <u>MUST</u>: be able to extrapolate properties measured over short (accelerated) time to predict performance over extended time.
- ONE
- WAY:Larson-Miller (L-M) MethodCorrelates temperature T (°R)with the time for failure t_r at aconstant engineering stress σ .

Larson-Miller (LM) Equation

 $T(\log t_r + c) = m$

c=constant, depends on alloy

m=parameter that depends on stress = LM parameter

- Known "*c*" for alloy, run a test at a specific *T* and measure *t_r* (time to rupture … previously I may have used *t_f* to denote the same thing).
- Now, if we keep stress constant,
 m = constant.
- We can change *T* and can calculate the time to rupture (failure).



Effects of creep on microstructure and fracture morphology

• <u>Microstructure:</u>

- During creep microstructural changes occur. Some are significant.
- Atomic scale
 - Dislocations are created and forced to move through the material leading to work hardening (Stage I).
 - Combined hardening and recovery processes can lead to the formation of subgrains or dislocation networks (Stage II).
- Micro-/Macro-structures:
 - Slip band formation
 - Grain boundary sliding
 - Cavity formation and growth
 - Cracking
 - Grain growth
 - Precipitate/second phase coarsening (Ostwald ripening)
 - Etc.

Effects of creep on microstructure and fracture morphology

Images from <u>ASM</u> <u>Specialty Handbook,</u> <u>Heat-Resistant</u> <u>Materials</u>, J.R. Davis editor, (ASM International, Materials Park, OH, 1997) p.24



Fig. 21 Comparison of microstructural changes in a γ'-strengthened nickel-base superalloy. (a) Cube-shaped γ' strengthening phase resulting from isothermal annealing (Ref 17). (b) Ostwald ripening of strengthening phase due to isothermal annealing (Ref 10). (c) and (d) Microstructural changes due to tensile creep and compressive creep, respectively (Ref 17). See test for details.

Effects of creep on microstructure and fracture morphology

• Fracture:

- Intergranular creep ruptures occur by (i) triple point cracking or (ii) grain boundary cavitation. Which process occurs depends upon strain rate and test temperature.



- Intermediate *T*, high strain rate:
 - Triple-point (or wedge) cracking
 - GBS can produce stress concentrations at grain boundary triple points to induce and propagate wedge cracks.
 - Etc.

Effects of creep on microstructure and fracture morphology

• Fracture (cont'd):



- High T, low strain rate:
 - GBS promotes cavity formation. This is a diffusion-controlled process which should not be confused with microvoid formation during slip.

Examples



Images from <u>ASM Specialty Handbook, Heat-Resistant Materials</u>, J.R. Davis editor, (ASM International, Materials Park, OH, 1997), p.25

Examples





Fig. 24 Microstructure and fracture appearance of type 316 stainless steel tested in creep to fracture ir air at 800 °C (1470 °F) at a load of 103 MPa (15 ksi). Time to rupture: 808 h. Light micrographs (a and b) illustrate spheroidal grain-boundary cavities that linked up to cause intergranular creep fracture. Both at 90×. The SEM frac tograph (c) illustrates the intergranular fracture morphology 1260×

Images from <u>ASM Specialty Handbook, Heat-Resistant Materials</u>, J.R. Davis editor, (ASM International, Materials Park, OH, 1997), p.25

 $7.7 \mu m$

Superplasticity

- It has been observed that some materials when heated above $0.5T_{mp}$ 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."

• The ability of a material to deform superplastically is related to its resistance to necking during deformation. This resistance is defined by the strain rate sensitivity exponent, m.



[Meyers & Chawla]

Figure 13.32 Superplastic tensile deformation in Pb–62%Sn eutectic alloy tested at 415 K and a strain rate of 1.33×10^{-4} s⁻¹; total strain of 48.5. (From M. M. I. Ahmed and T. G. Langdon, *Met. Trans. A*, 8 (1977) 1832)

Superplasticity – cont'd

- <u>Microstructural Requirements</u>:
 - 1. Grain size \leq 10 µm
 - This grain size must not change during straining!
 - Explains why we see superplasticity so frequently in two-phase alloys that are resistant to grain growth.
 - 2. Grain shape remains equiaxed during superplastic deformation
 - Grains "slide" and "tilt" under stress.
- <u>Strain Rate Sensitivity:</u>

$$\sigma_{flow} = F(\dot{\varepsilon}); \quad \Delta \dot{\varepsilon} \to \Delta \sigma_{flow}$$

$$\sigma_{flow} \neq F(\dot{\varepsilon}); \quad \Delta \dot{\varepsilon} \to \Delta \sigma_{flow} \equiv \text{constant}$$

$$\sigma_{flow} = k' (\dot{\varepsilon})^{m} \quad \text{Strain rate exponent}$$
Depends on strain rate



Figure 13.33 (a) Schematic representation of plastic deformation in tension with formation and inhibition of necking. (b) Engineering-stress– engineering-strain curves.

Determination of Strain Rate Sensitivity

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

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

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

(1) and (2) are a result of strain rate hardening





The amount of superplastic deformation tends to increase as *T* increases and *d* decreases.



FIGURE 15.40 (a) Low-stress-strain rate behavior of a material manifesting superplasticity. In regions I and III, the strain rate sensitivity (b) is fairly small, whereas it is high in Region II where superplasticity is observed. As indicated in (a), increases in temperature or decreases in grain size shift the σ - $\dot{\epsilon}$ curve downward and to the right. The same changes produce a somewhat higher value on *m* as shown in (b).

Grain switching mechanism

M.F. Ashby and R.A. Verall, "Diffusion-accommodated flow and superplasticity," Acta Metallurgica, V. 21, n. 2 (1973), p. 149-163.

- The primary mechanism contributing to superplasticity is argued to be grain boundary sliding (GBS).
- Grain shapes don't change; grain locations change.
- Diffusion is required to allow grains to "switch" positions.
 - Region I: low $\dot{\varepsilon}$ -- diffusional flow & grain switching
 - Region III: high $\dot{\varepsilon}$ -- \perp creep

- Region II: where superplasticity occurs. A mixture of I and III.
- * *m* is maximum where you have both diffusional flow and creep!



Acta Metallurgica, V. 21, n. 2 (1973), p. 149-163.

FIG. 7. The accommodation strains required when grains move from the initial to the intermediate states. These may be obtained by bulk diffusion and by boundary diffusion. Note that the flow, particularly in grain 2, is local, confined to the surface regions of the grain.

DIFFUSIVE FLUX

What types of materials deform superplastically?

- Al alloys
 - 7075, 2095
 - AI-6Cu-0.5Zr (1200% strain)
 - Al(6061)-20% SiC(whiskers) (1400% strain)
 - Etc...
- Ti alloys
 - Ti-6Al-4V (1000% strain)
- Ni alloys
 - Alloy 718
- Others
 - Bi-44%Sn eutectic (1950% strain)
 - Mg-33%Al eutectic (2100% strain)
 - Pb-62%Sn eutectic (4850% strain)
- Ceramics
 - Zirconia (350% strain)
 - Zirconia + SiO_2 (1000% strain)

Types of superplasticity

- Fine-structure superplasticity (FSS)
 - Occurs at low rates (i.e., 10⁻⁴ to 10⁻³ s⁻¹. Fine grain size is required along with second phase particles at grain boundaries to retain grain size.
- Internal-stress superplasticity (ISS)
 - Occurs when internal stresses can develop in a material allowing tensile plasticity to occur under low, externally applied stresses. Fine grain size is not required here.
- High strain-rate superplasticity (HSRS)
 - An extension of FSS. Occurs at higher rates (i.e., 10⁻¹ to 10¹ s⁻¹, which is close to the strain rates for forging. Fine grain size is necessary along with the presence of liquid phases at grain boundaries.