Outline

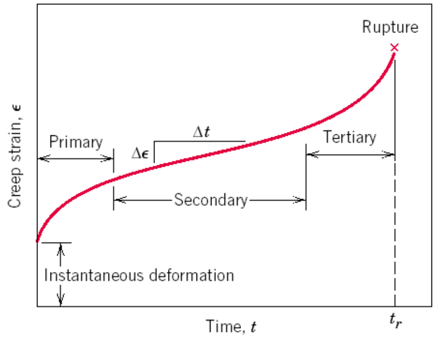
- Creep and high temperature failure
- Creep testing
- Factors affecting creep
- Stress rupture life time behaviour
- Creep mechanisms
- Example
- Materials for high creep resistance
  - *Refractory metals*
  - *Superalloys*

Creep and High Temperature Failure

- Materials are often placed in service at elevated temperatures and **static** mechanical stresses *(turbine rotors in jet engines and steam generators that experience centrifugal stresses, and high-pressure steam lines).*
- Such deformation is termed **creep.**
- Observed in ….. materials types;
- For metals, it becomes important at temperatures > ………
- Amorphous polymers, which include plastics and rubbers, **very sensitive** to creep deformation.
- Typical creep test: - subjecting a specimen to **…………** load/stress at **…………** temperature; - measure deformation or strain and - plot as function of elapsed time.
- Most tests are *constant load* type, which yield information of an engineering nature; *constant stress* tests are employed to provide a better understanding of the mechanisms of creep.

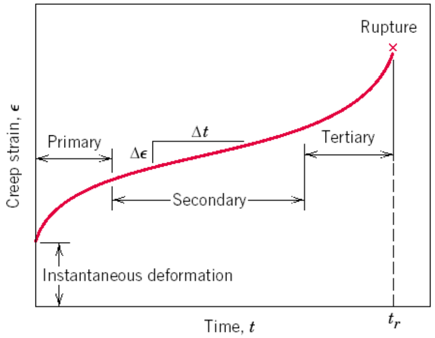
Creep and High Temperature Failure

- Constant load applied at constant "*high*" temperature
- Deformation as a function of time (ε vs. t)
- Three stages of creep:
- Stage I (primary creep)
  - *Continuously diminishing creep rate due to ……………………*



Creep Curve

- Stage II (secondary *steady-state creep)*
  - Constant rate or plot becomes ***linear***
  - Longest and ……………..…. stage
  - Balance between competing ***strain hardening*** and ***recovery*** (softening) of the material
- Stage III (tertiary creep)
  - Accelerated rate leading to *creep rupture* or failure
  - *Intergranular* cracking and/or formation of voids and cavities



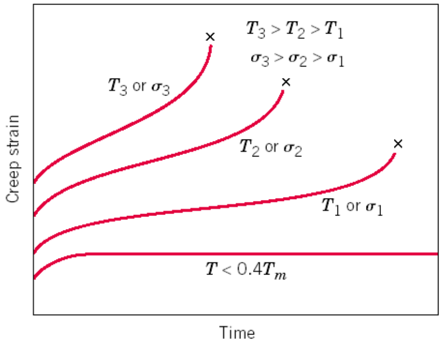
Creep Testing and Steady-State Creep Rate

- Performed in uniaxial ***tension*** with specimens of similar geometry to tensile testing
- Brittle materials: uniaxial ***compression*** with cylindrical samples (flaw effect minimized)

Creep Data

- Most important parameter is the *steady-state creep rate* $(\Delta\varepsilon/\Delta t)$
- Used as a *design parameter* in structures which are expected to last a long time (minimum strain) e.g. electric power and chemical plants
- Creep *rupture lifetime* (t_r) is more important in design for short lifetimes, e.g. gas turbine engine blades (F-18 turbine blade)
  - *creep test continues until failure* (creep rupture tests)

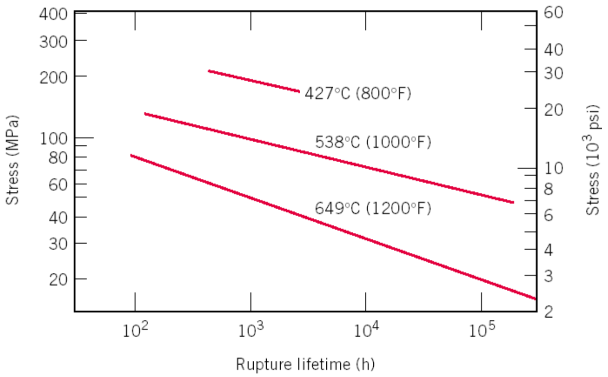
Stress and Temperature Effects



- Creep is observed > $0.4T_m$
  - *below 0.4Tm, no plastic strain with time.*
- If stress **OR** temperature is increased:
  - *the creep rate …………*
  - *instantaneous strain …………..*
  - *steady-state creep rate …………..*
  - *creep rupture lifetime …………*

Stress-Rupture Lifetime Behaviour

- Most common creep data representation is a plot of *log σ versus log t_r* (creep rupture lifetime)
- Linear relationship is found for data plotted at different temperatures
- These data can be used in design of components



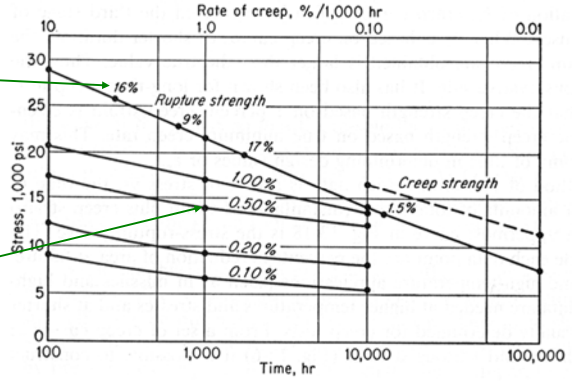
Note: Not all materials show such nice straight lines.

Stress vs. rupture lifetime for a nickel alloy at different temp.

Stress-Strain-Time

Creep Strength: stress at a given temperature which produces a certain steady state creep rate e.g 0.0001%/hr (0.1%/1,000hr)

Rupture Strength: stress at a given temperature to produce a certain life to rupture, usually 1,000, 10,000 or 100,000 hr.



Numbers are %Area Reduction at failure

What is the stress required to produce fixed strain?

(e.g. 0.5%) in fixed time (e.g. 1000 hrs)

Figure 13-18 (Dieter) *Deformation-time curves at 1300°F (700°C) for 16-25-6 alloy.*

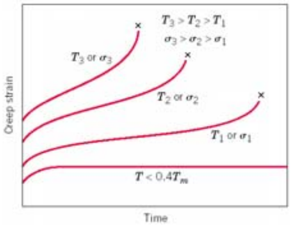
Stress-Steady State Creep Rate Behaviour

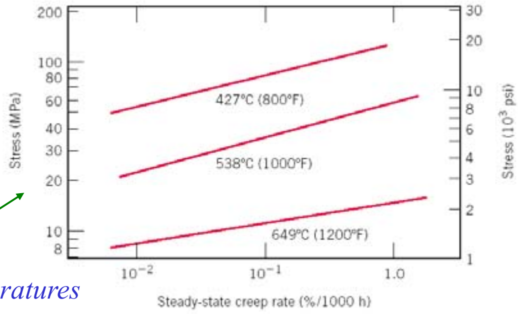
- Empirical relationship exists between steady-state creep rate and applied stress

$$\dot{\varepsilon}_s = K_1\sigma^n$$

Where K_1 and n are material constants

- $\dot{\varepsilon}_s$ versus σ (log-log scale) yields a linear curve
- Slope is *1/n*





nickel alloy at different temperatures

Influence of Temperature

- *Diffusion* is an exponential function of temperature (thermally activated process)
- Inclusion of temperature → *universal creep equation:*

$$\dot{\varepsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

Where K_2 is a constant and Q_c is the activation energy for creep

- Experimental value of n can be used to **predict** creep strain rate at different working conditions
- Activation energy for creep, Q_c, can be obtained from plots of log creep rate versus 1/T
- Can relate Q_c to the activation for diffusion and correlate it to ……….. processes
- This might be expected since creep involves *mass transfer or diffusion*

Influence of Temperature

- Line shows 1:1 correlation
- Activation energy for creep in metals at high temp. is equal to that for self-diffusion (*i.e. vacancy transport - dislocation climb*).
- **If vacancies move faster, metal creeps faster**.
- Other mechanisms are possible; grain boundary sliding …………………..

The creep rate of a material can be greatly reduced by the incorporation of a fine dispersion of nondeformable particles at grain boundaries.

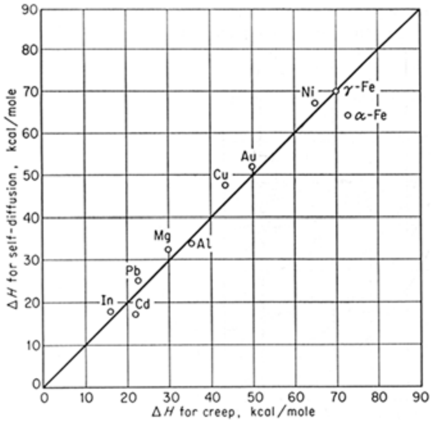
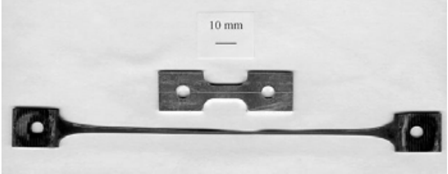


***Figure 13-13** (Dieter) Correlation between activation energies for high-temperature creep and self-diffusion.* Also see Fig 7.3 (Courtney)

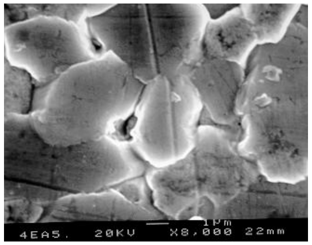
Superplasticity

Superplasticity is the ability of a material to withstand very large amounts of elongation without the occurrence of necking

- This property is related to a predominant mechanism of deformation : ……………….. sliding
- Consequently, it is promoted by a fine microstructure (*typically a mean grain size less than about twenty microns is required in the case of metallic alloys*).
- This property has been used for a long time as a forming technique for components with a particularly complex shape



Superplastic deformation of an Al alloy



Movement of grains during superplastic deformation of a Pb-Sn alloy

Superplasticity

Important elements in superplastic properties:

- Low strain rate (*so it is not ………..*)
- High temperature
- Small grain size
- Grain shape

$$\sigma = C\dot{\varepsilon}^m$$

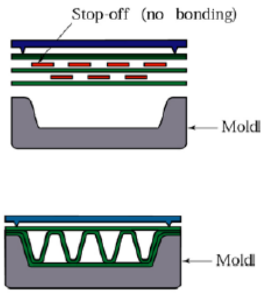
where
C = strength constant
m = strain-rate sensitivity exponent

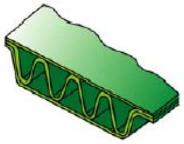
Common **titanium alloys** and several specially processed **aluminum alloys** are superplastic. **Inconel**, specialty stainless steels and several other alloys can also be made superplastic.

- Until recently, superplastic forming has only been available at relatively low strain rates, typically about 1% per min. At this strain rate, about 1 hr is needed to form an advanced structural component; too long to be economically effective.
- Superplasticity at higher strain rates, however, can be expected to stimulate broad commercial interest in superplastic forming.
- A strain rate higher than 100% per minute is considered economically practical. Such a strain rate would allow the forming of relatively complex structures in **less than three minutes**, including set-up time.

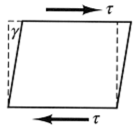
Superplastic Forming with Diffusion Bonding

- Superplastic Forming can be combined with Diffusion Bonding to produce a number of ……….. SPF/DB structures.
- SPF/DB parts are produced by joining several sheets in a specific pattern and then superplastically expanding the sheets to produce an integrally-stiffened structure.





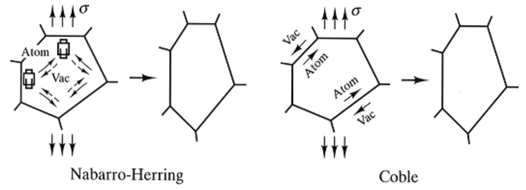
Suggested creep mechanisms



(a) Viscous creep

(a) Viscous creep for amorphous solids.

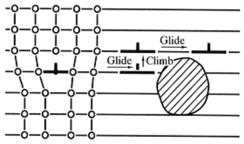
Diffusional and dislocation creeps (b and c) in crystalline solids.



Nabarro-Herring Coble

(b) Diffusional creep

Vacancy diffusion through bulk (Nabarro-Herring Creep) or along grain boundaries (Coble creep). Hence larger grains or single grain/crystal is ………



(c) Dislocation creep

(c) Dislocation creep still relies on vacancy diffusion.

Creep and Dislocation Movements

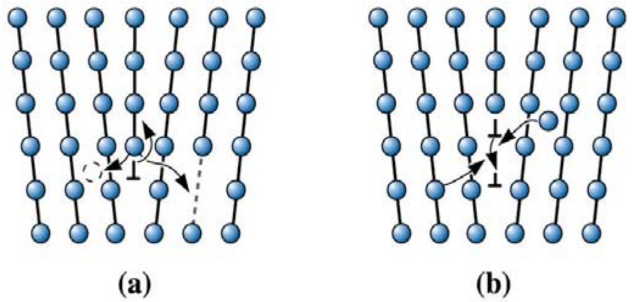


Figure 6.57 Dislocations can ……… (a) when atoms leave the dislocation line to create interstitials or to fill vacancies or (b) when atoms are attached to the dislocation line by creating vacancies or eliminating interstitials. From *"The science and Engineering of Materials" 4th edition by D.R. Askeland and P.P. Phule.*

When vacancies move faster → metal creeps faster

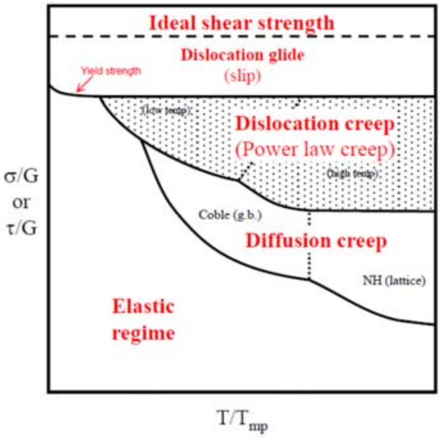
Creep Mechanisms

Diffusion Creep

- Nabarro-Herring:
  - *bulk diffusion (from one side of a grain to another)*
  - *at higher T's and lower σ's*
  - *occurs in crystalline and amorphous materials.*
- Coble:
  - *diffusion of atoms along the grain boundaries, which produces sliding of the grain boundaries.*

Dislocation (Power-Law) Creep

- Solute drag: *Solutes migrate towards distorted regions around ⊥'s to ……… lattice strain ………..*
- Dislocation climb-glide
- There are others …



Deformation mechanism maps (DMMs)
See figure 7.14 (Courtney)

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
σ = applied stress
n = stress exponent
p = inverse grain size exponent
A = a dimensionless constant.

This form of the Dorn equation applies to all creep mechanisms

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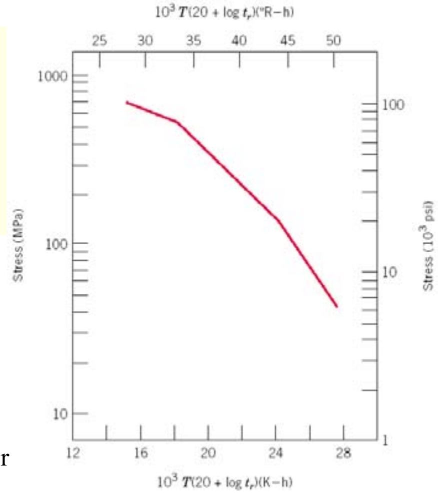
Creep Mechanisms

Mechanism	Favored by	Description	A	n	p
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 (Power-law)	High stress, lower temperatures in comparison to Coble creep, and large grain sizes	Dislocation motion, with climb over microstructural obstacles.		3-8	0

Representative values of the parameters n, p and approximate values of the constant A

Data Extrapolation-Larson-Miller parameter

- Impractical to collect data over long times, e.g several years
- solution: perform creep rupture tests at *higher temperatures* under same stress for shorter times
- extrapolate for service conditions



- *Larson-Miller parameter:*

  $P_1 = T(C + \log t_r)$

  - C is a constant (~20)
  - T is temperature (K)
  - t_r is the creep rupture life (hours)
- plot log σ versus log L-M parameter

i.e. for a given material at some specific stress level, the time-to-rupture will vary with temperature such that P_1 remains …..…….. Often plotted as Log stress vs Log P_1.

Data Extrapolation-Larson-Miller parameter

Table 13.3 (Dieter) Time compression operating conditions based on Larson-Miller parameter. C = 20

Operating conditions	Larson-Miller test conditions
10,000 h at 1000° F	13 h at 1200° F
1,000 h at 1200° F	12 h at 1350° F
1,000 h at 1350°	17 h at 1500° F

long times at low temperatures.

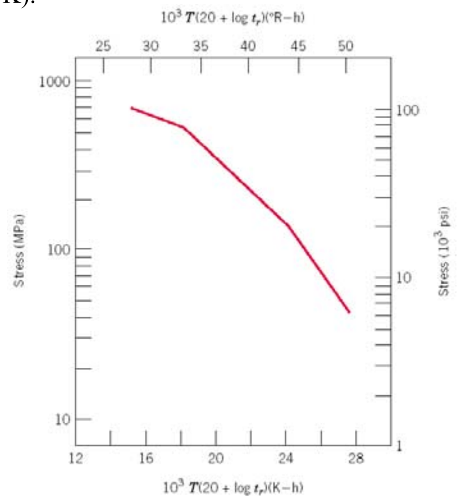
much shorter times at higher temperatures.

As long as still the same creep mechanism!

Note: not all materials have good L-M Parameter plots. Other extrapolation methods can be used (e.g. *Sherby-Dorn parameter, Monkman-Grant method,*).

Example

Using the Larson–Miller data for S-590 iron shown in the figure below, predict the time to rupture for a component that is subjected to a stress of 140 MPa (20,000 psi) at 800°C (1073 K).



Materials for High Temperature Creep Resistance

- Generally, factors for better creep resistance include:

✓ ……. melting temperature

✓ ……. elastic modulus

✓ ……. grain size (small grains allow more grain boundary sliding)

Also, **………** particles are more effective at inhibiting grain boundary sliding.
Particles inhibit recrystallization by "pinning" grain boundaries

- Metallic materials commonly used for high temperature service include:

➢ **Stainless steels -** Alloys based on Fe + carbon + Chromium (+ Nickel/Manganese…etc)

- *Chromium provides oxidation resistance (1000°C) - gas turbines, steam boilers …etc*

➢ **Refractory metals**

➢ **Superalloys**

Refractory metals

- They have extremely high melting temperatures

niobium (Nb)	2468°C
molybdenum (Mo)	2617
tungsten (W)	3410°C ………. melting metal
tantalum (Ta)	2996°C

- This is due to very strong interatomic bonding and also have
  - large elastic moduli
  - high strength & hardness, (ambient & elevated temperatures).

✓ Tantalum and molybdenum are often alloyed with stainless steel to improve its corrosion resistance.

✓ Molybdenum alloys - extrusion dies and structural parts in space vehicles;

✓ Tungsten alloys - incandescent light filaments, x-ray tubes, and welding electrodes.

✓ Tantalum is immune to ………………… by virtually all environments at temperatures below 150°C, and is frequently used in applications requiring such a corrosion-resistant material.

Superalloys

Superlative combinations of properties.

Most are used in aircraft turbine components, (*exposure to severely* ***oxidizing*** *environments and* ***high temperatures*** *for* ***reasonable time*** *periods*).

Mechanical integrity under these conditions is critical; density is important - *centrifugal stresses are diminished in rotating members when the density is ………….*

Classified according to predominant metal in the alloy,

- ✓ **Cobalt** + *alloying elements*
- ✓ **Iron** + *alloying elements*
- ✓ **Nickel** + *alloying elements*

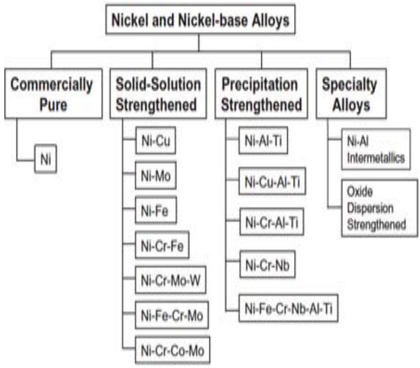
Although they are age hardenable, they retain remarkably high strengths at elevated temp. ➔ hence called superalloys!

Alloying elements include the refractory metals (Nb, Mo, W, Ta), Cr and Ti.

In addition to turbine applications, these alloys are utilized in nuclear reactors and petrochemical equipment.

<u>E.g. Alloy X</u> : (bal Ni) + Cr 20.5-23.0, Fe 17.0-20.0, Co 0.5-2.5, Mo 8.0-10.0, W 0.2-1.0, Ti 0.15, Al 0.50, C 0.05-0.15, Mn 1.0, Si 1.0, B 0.008, Cu 0.5
high temperature petro-chemical alloy

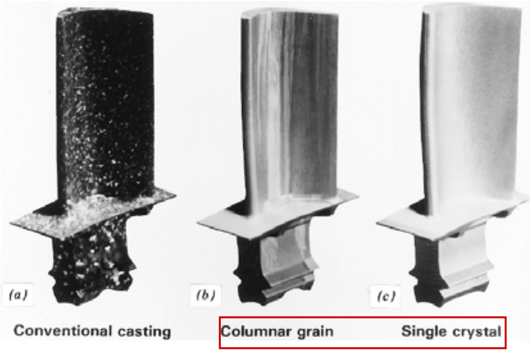
Superalloys



Element	Composition (Weight %)	Alloying Effect
Ni	50-55	• Solid solution base
Cr	17-21	• Strengthens solid solution • Enhances oxidation resistance • Forms Carbides: MC,M_7C_3, $M_{23}C_6$ • Enhances sulfidation resistance
Nb	4.75-5.5	• Forms Carbides: MC, $M_{23}C_6$, M_6C • Intermetallic and hardening precipitate former
Mo	2.8-3.3	• Forms Carbides: MC, $M_{23}C_6$, M_6C • Improves creep strength
Ti	0.65-1.15	• Forms Carbides: MC, $M_{23}C_6$ • Forms γ' • Intermetallic and hardening precipitate former
Al	0.2-0.8	• Forms γ' • Intermetallic and hardening precipitate former • Oxidation resistance enhancer
Co	$\leq$ 1.0	• Strengthens solid solution • Raises γ' solvus temperature • Sulfidation resistance enhancer
Cu	$\leq$ 0.3	• Strengthens solid solution
C	$\leq$ 0.08	• Forms Carbides: M_6C • Grain boundary refiner
Fe	Balanced	• Strengthens solid solution

Superalloys

- nickel and cobalt superalloys are ………………… and ………… *strengthened* to maximise their creep resistance
- superalloys are also grown as single crystals to eliminate ……… ……………thus improving the creep behaviour.



produced by directional solidification

Next time:

Creep