خزش
Creep

منابع درسی

1- Fundamental of creep in metals and alloys
By M. Kassner

2- Mechanical metallurgy
By G. Dieter

3-Mechanical properties and working of metals and alloys
By A. Bhaduri

4-Creep-resistant steels
By F. Abe, T.-Ulf Kern and R. Viswanathan

بارم بندی کلاس

۱- فعالیت کلاسی

۲- تمارین کلاسی

۳- سمینار

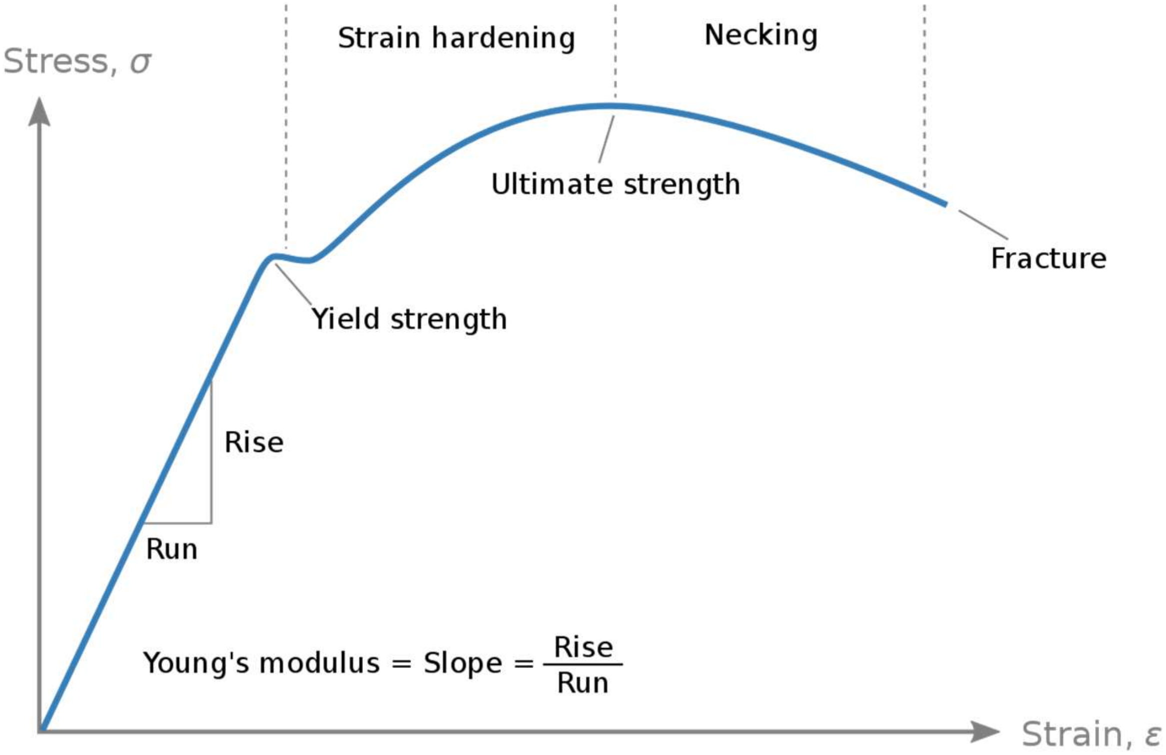
۴- پایان ترم

مباحث مقدماتی

- استحکام
- مدول یانگ
- چقرمگی
- برجهندگی

استحکام در دمای پایین و تست کشش

آزمون کشش در دمای محیط



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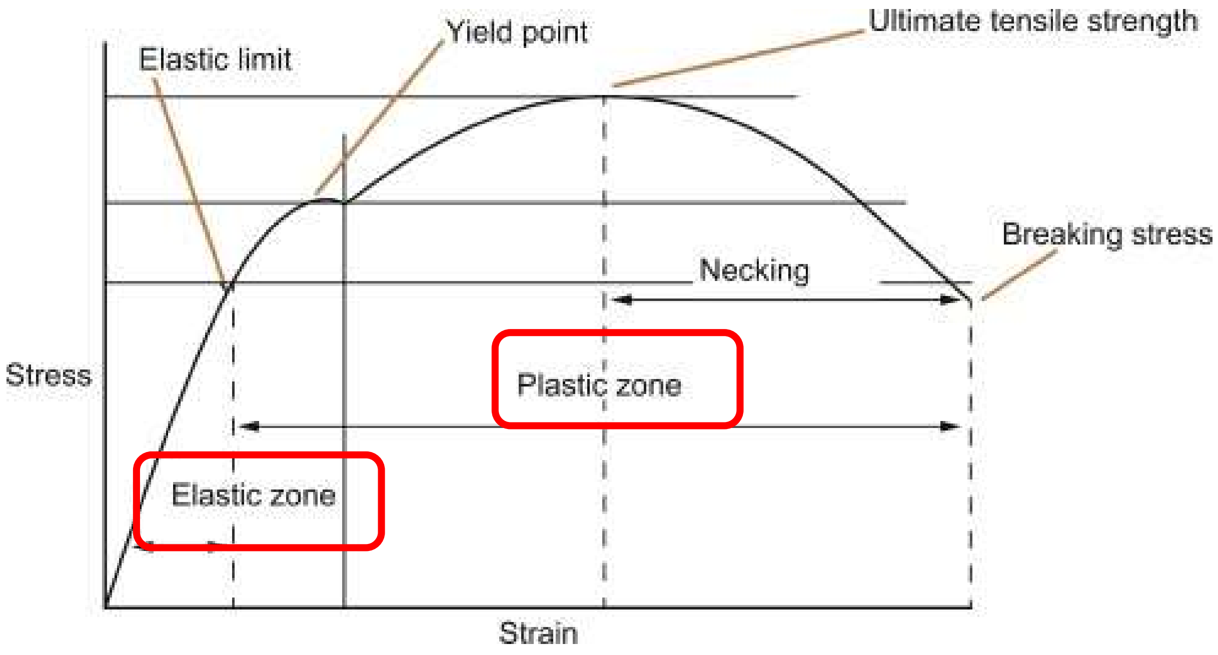
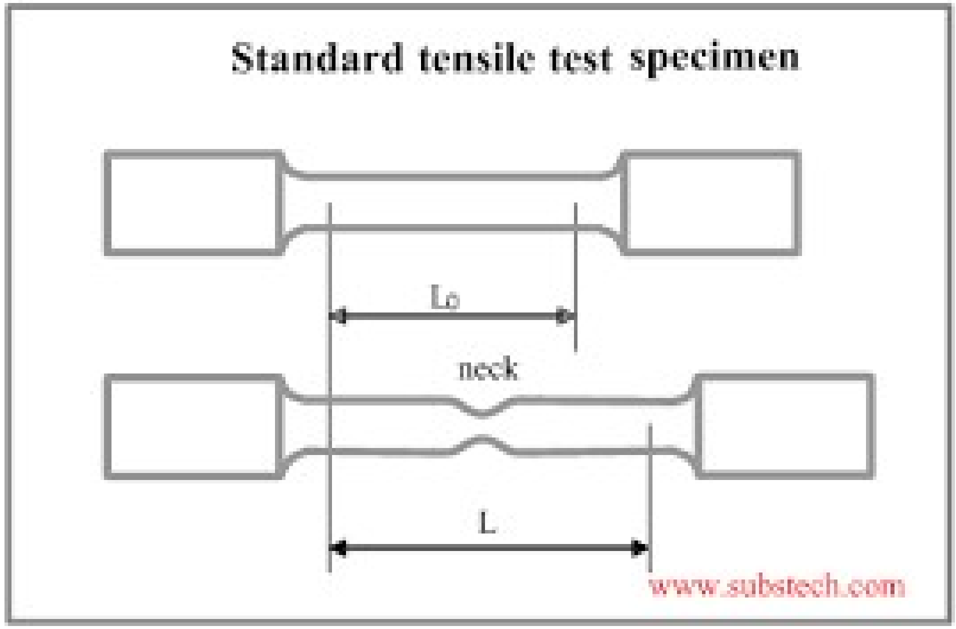
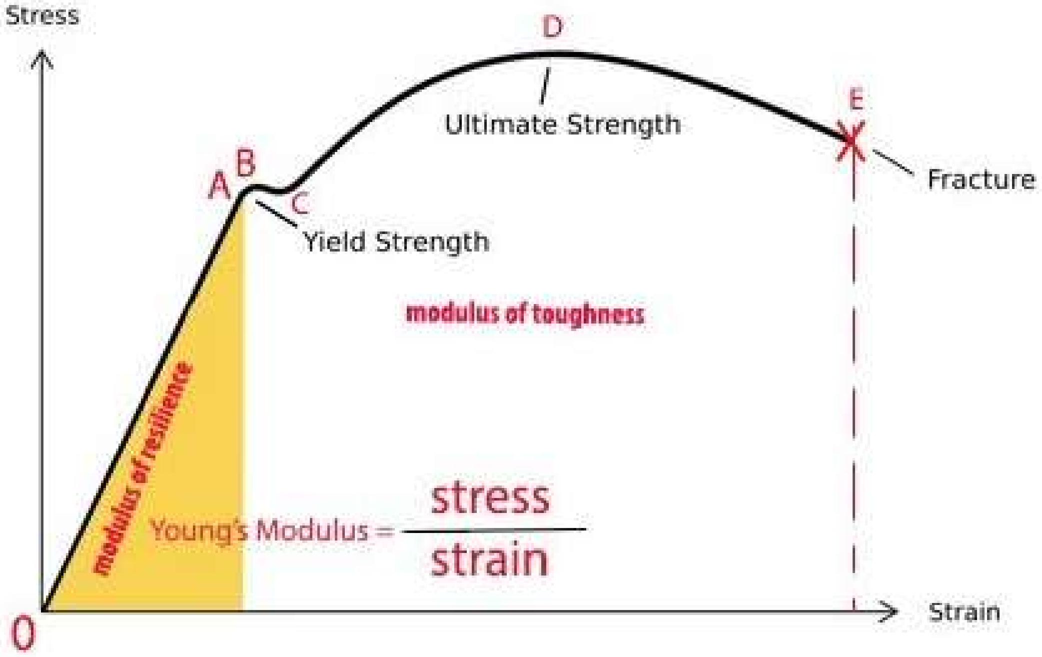




Standard tensile test specimen
L_0
neck
L
www.substech.com

آزمون کشش در دمای محیط



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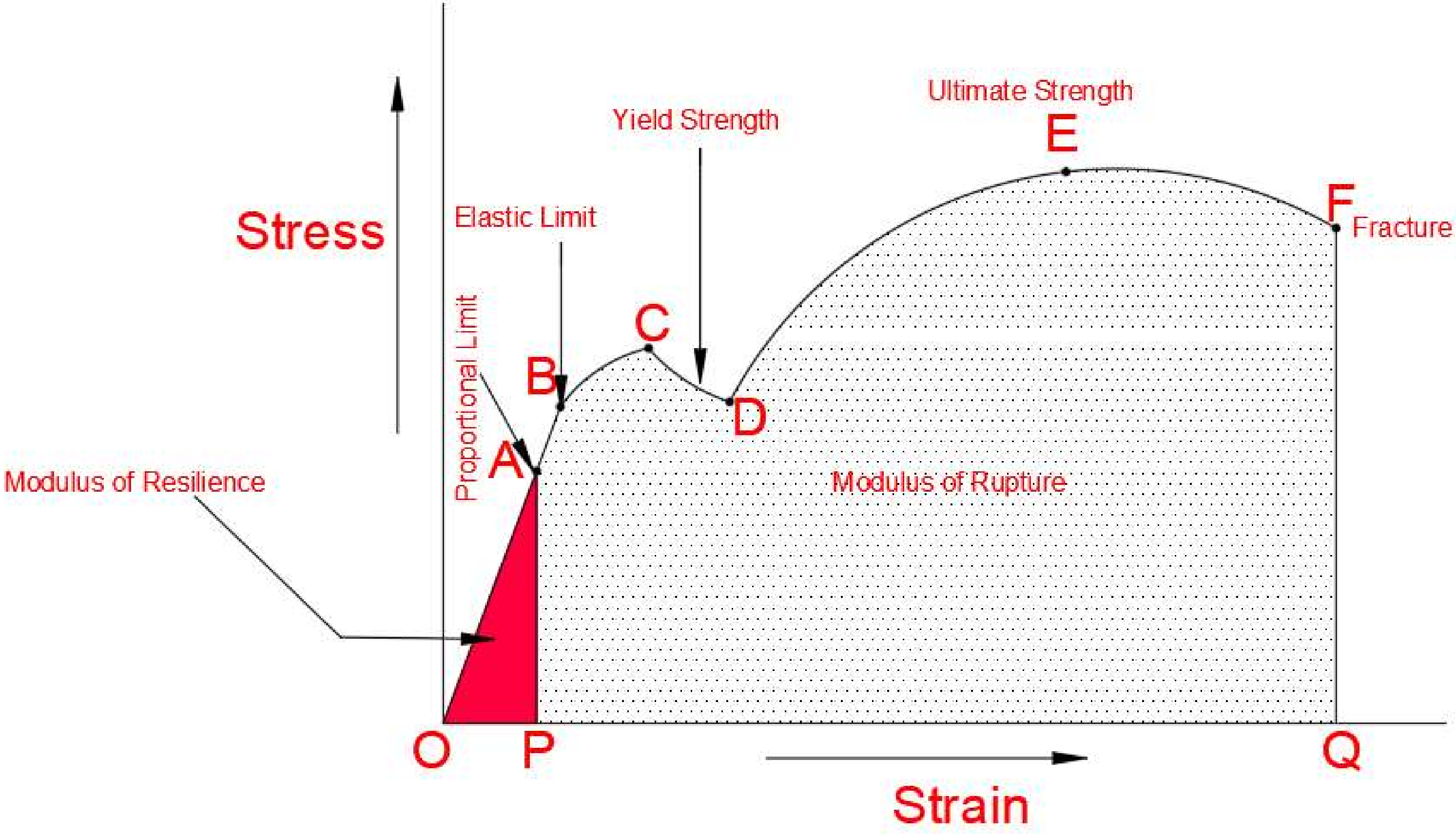
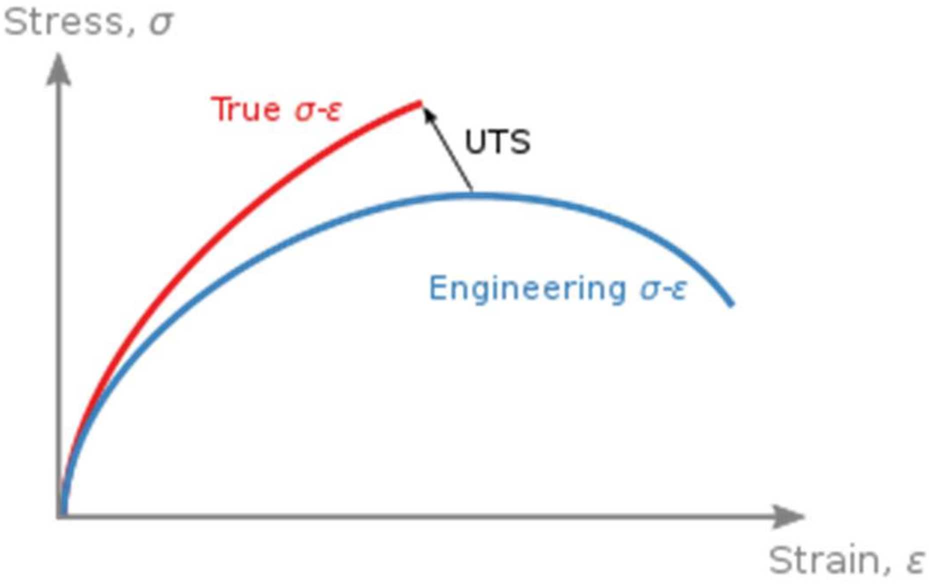


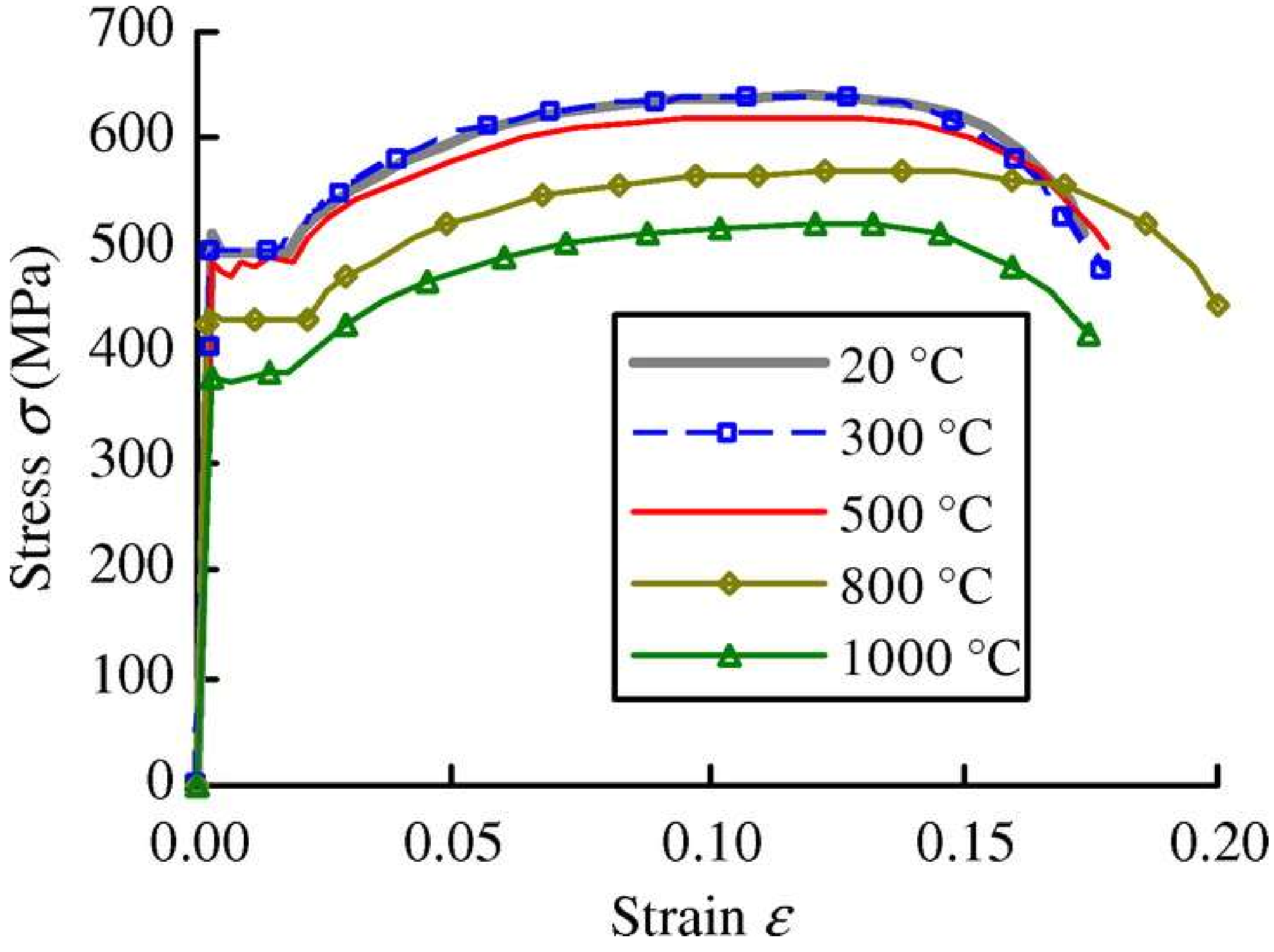
نمودار تنش-کرنش مهندسی
و تنش-کرنش واقعی



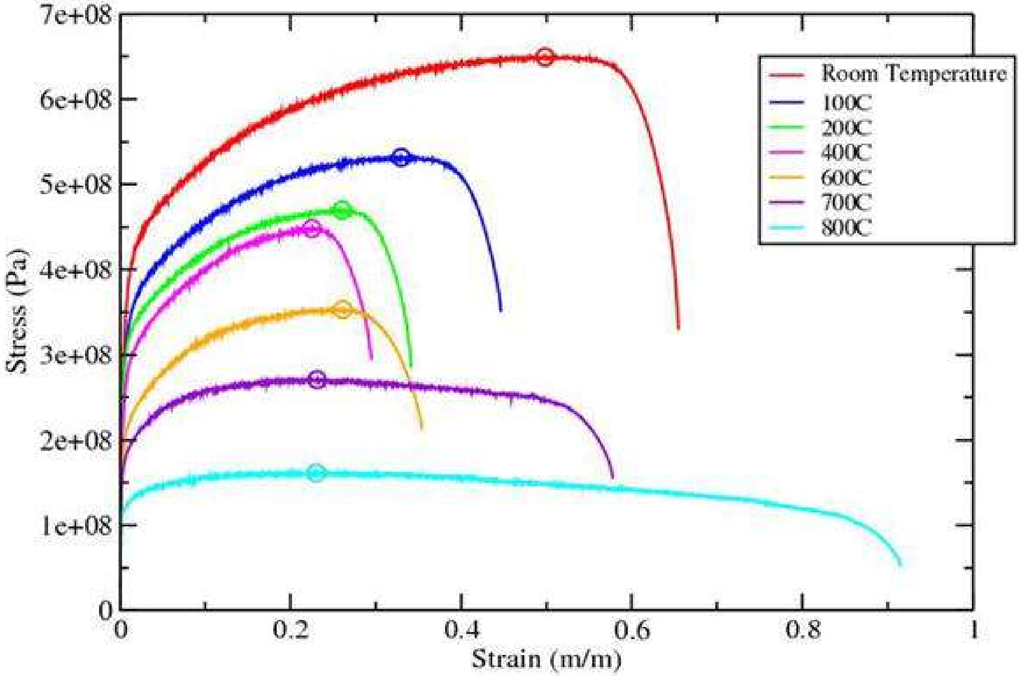
$\sigma=S(1+e)$

$\epsilon=\ln(1+e)$

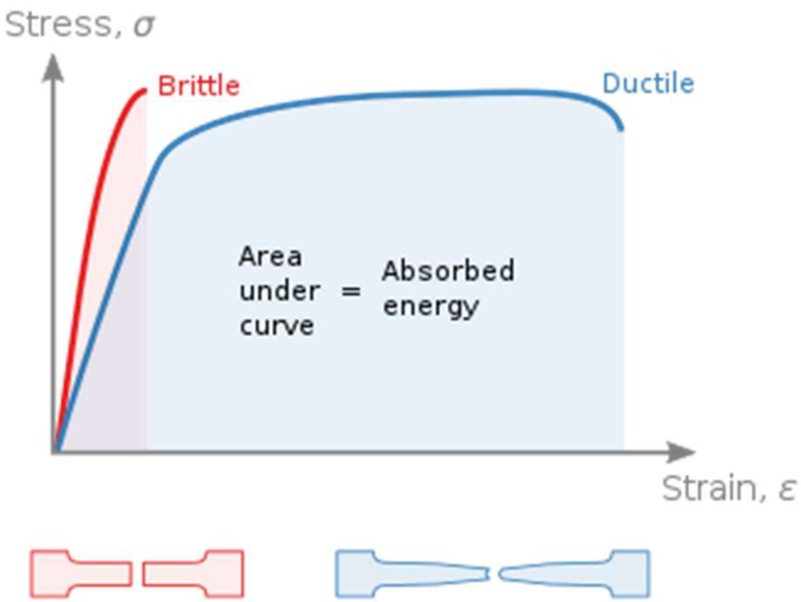
تاثیر دما بر رفتار ماده درآزمون کشش



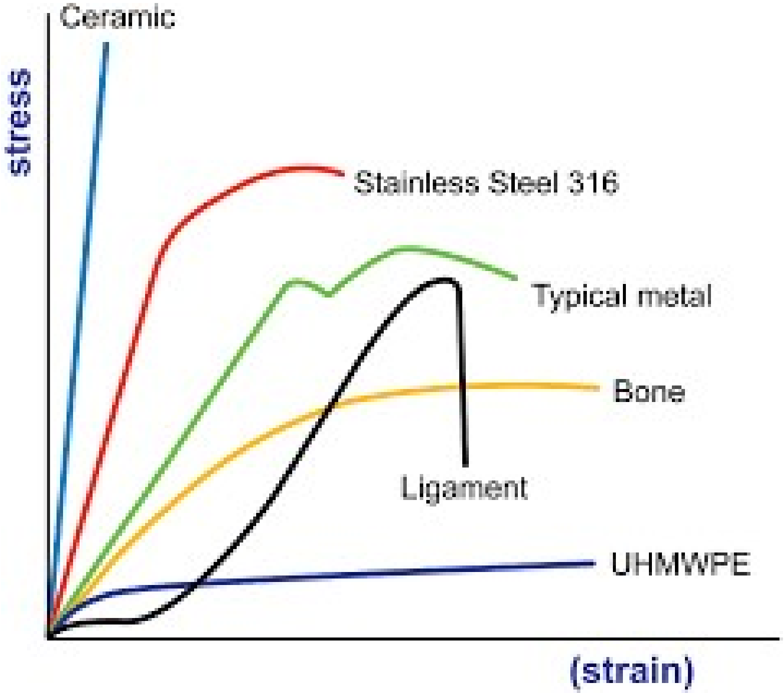
تاثیر دما بر رفتار ماده درآزمون کشش



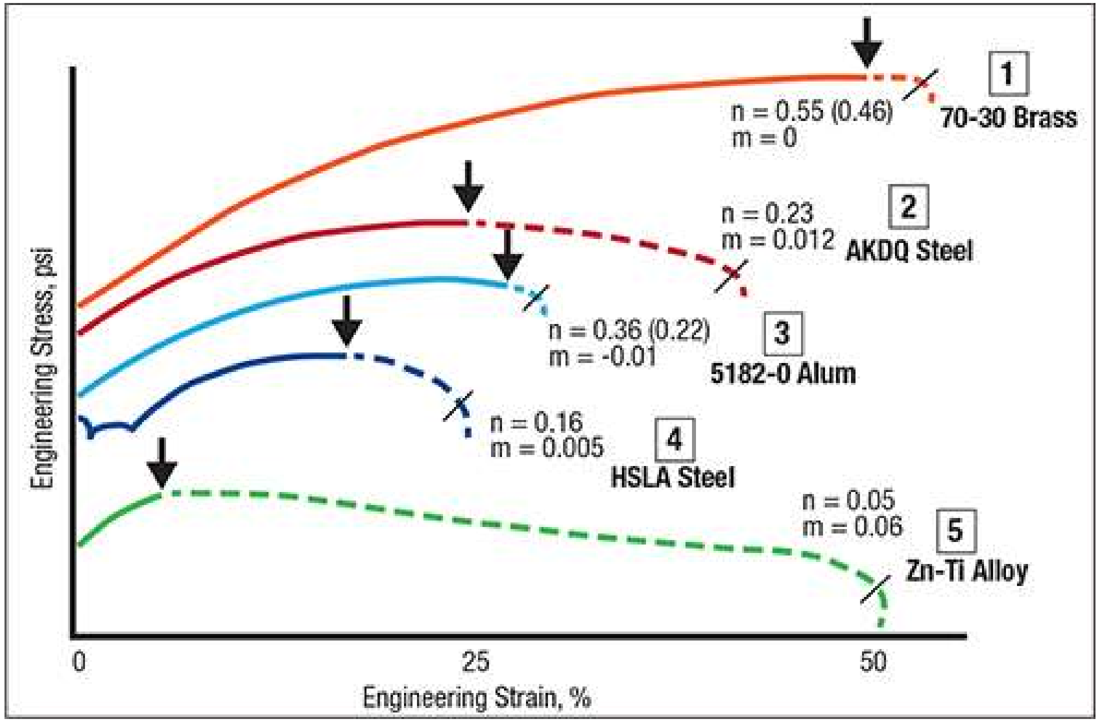
رفتار متفاوت مواد در برابر یک نیروی کششی



رفتار متفاوت مواد در برابر یک نیروی کششی



رفتار متفاوت مواد در برابر یک نیروی کششی



تغییر شکل در مواد

۱- تغییر شکل مستقل از زمان

-تغییر شکل دائم (Plastic)

-تغییرشکل موقت (Elastic)

۲- تغییرشکل وابسته به زمان

- -تغییر شکل دائم (Creep)

-تغییرشکل موقت (Inelastic)

Creep

- Materials in service are often exposed to elevated temperatures or static loads for long duration of time.
- Deformation under such circumstances may be termed as creep.
- **Time-dependent deformation** of a material while under an applied load that is below its **yield strength.**
- Mostly occurs at elevated temperature though some materials creep at room temperature.
- Creep is a deformation mechanism that may or may not constitute a failure mode.

Creep

- Creep is a time-dependent process where a material under an applied stress exhibits a dimensional change at high temprature.
- High temperature progressive deformation of a material at constant stress is called creep.
- The process is also temperature-dependent
- Creep always increases with temperature.

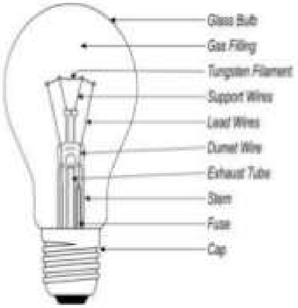
کاربرد خزش

High Temperature Applications

Oil Refinery

Steam turbine used in power plant

Components exposed to high temperature.



Sagging of the filament coil increases with time due to creep deformation caused by the weight of the filament. Too much deformation--the adjacent turns of the coil touch one another--causing an electrical short and local overheating, which quickly leads to failure of the filament

Chapter 1

Introduction

High temperature affects these parameters:

- Oxidation: environment + metal
- Slip system
- Phase transformation
- Vibration of atoms (bond energy and elastic modulus
- Climb of dislocation
- Diffusion (Xv)
- Grain growth
- Over aging
- Shear of precipitated particles
- Solving the precipitated particles in the matrix
- Thermal expansion

All resulted in decreased in strength

DESCRIPTION OF CREEP

Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly 0.5 Tm, where Tm is the absolute melting temperature.

Introduction to Creep Behavior

Definition of creep in materials science
Creep is the slow, time-dependent deformation of materials under constant stress, particularly at elevated temperatures. It is a critical concern in materials science due to its impact on the strength and lifespan of materials.

Importance of understanding creep behavior in engineering applications
Creep behavior is essential for predicting material performance over time, ensuring safety and reliability in engineering applications such as power generation, aerospace, and automotive industries.

At what temperature the material will creep?

- Different metals have different melting temperatures. e.g. Pb 327°C, W 3407°C.
- Material will creep when the temperature will be **> 0.5Tm (Tm = absolute melting temperature).**

Metal	**Melting temp.**		**0.5xMelting Temp**	
Lead	327^{o}C	600^{o}K	327^{o}K	27^{o}C
W	3407	3680	1840	1567

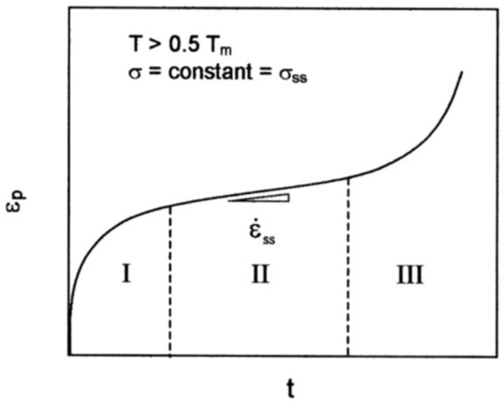
Ideal creep curve

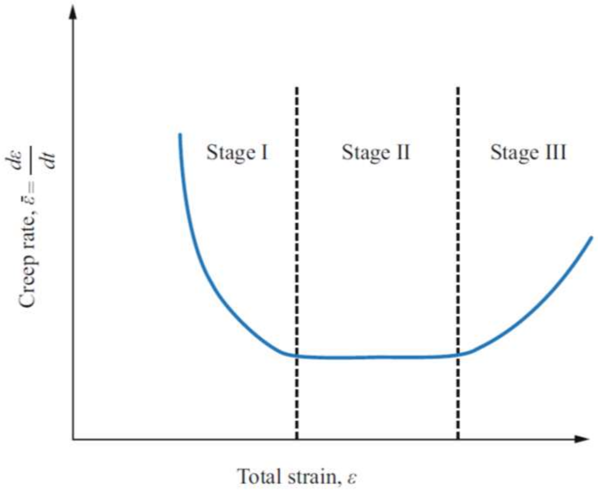
Three regions are delineated:

1- Stage I, or primary creep,
which denotes that portion where the creep-rate (plastic strain-rate), $d\epsilon/dt$ is changing with increasing plastic strain or time.

2- Constant strain-rate conditions (Stage II, secondary, or steady-state creep), $d\epsilon/dt$ is constant with increasing plastic strain or time hardens.

3- Cavitation and/or cracking increase the apparent strain-rate or decrease the flow stress. This regime is termed Stage III, or tertiary creep, and leads to fracture.





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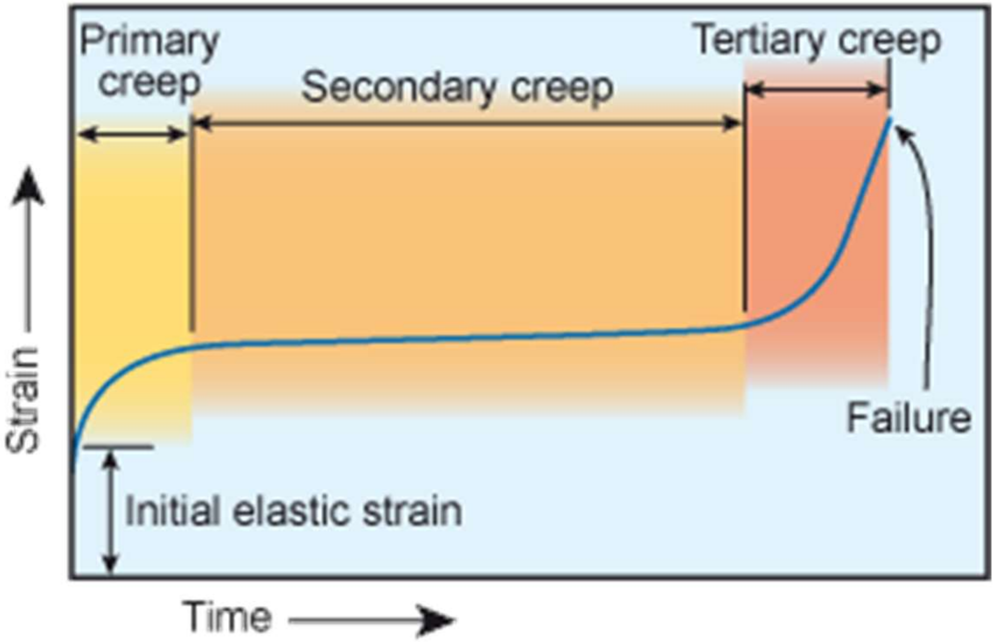
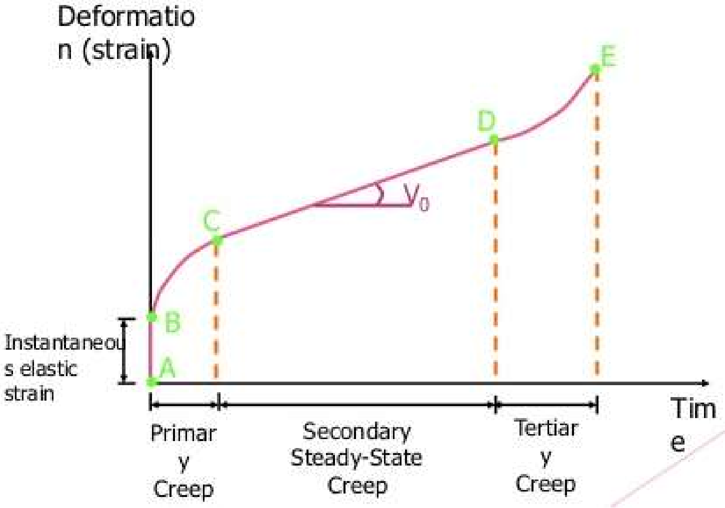
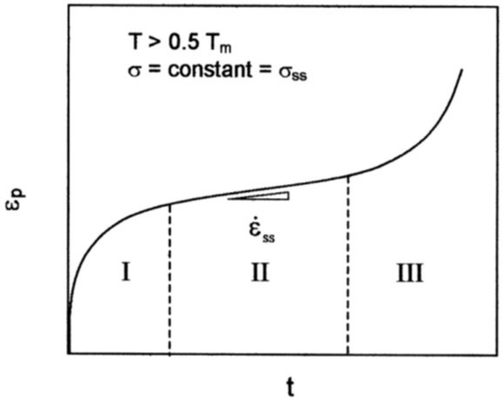
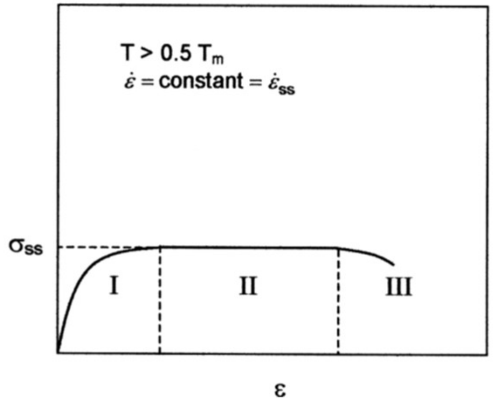
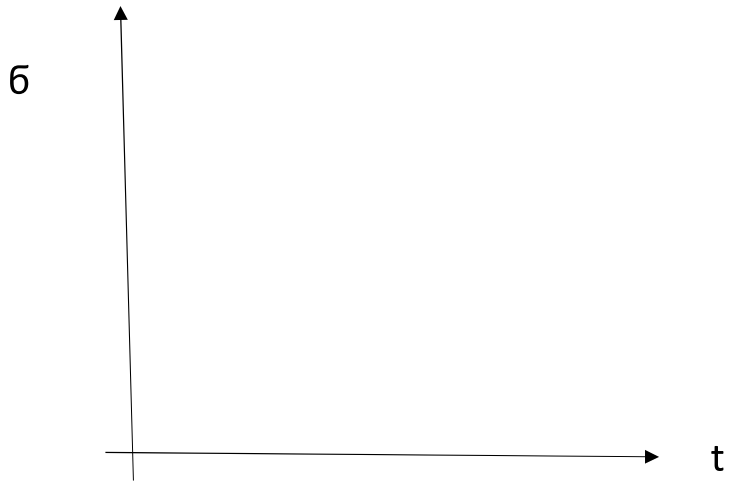

Primary creep
Secondary creep
Tertiary creep
Strain
Initial elastic strain
Failure
Time


Deformation (strain)
E
D
C
B
A
V_0
Instantaneous elastic strain
Time
Primary Creep
Secondary Steady-State Creep
Tertiary Creep


T > 0.5 T$_m$
σ = constant = σ$_{ss}$
ε$_p$
$\dot{\varepsilon}_{ss}$
I
II
III
t


T > 0.5 T$_m$
$\dot{\varepsilon}$ = constant = $\dot{\varepsilon}_{ss}$
σ$_{ss}$
I
II
III
ε


б
t

Stress rate-strain rate effect

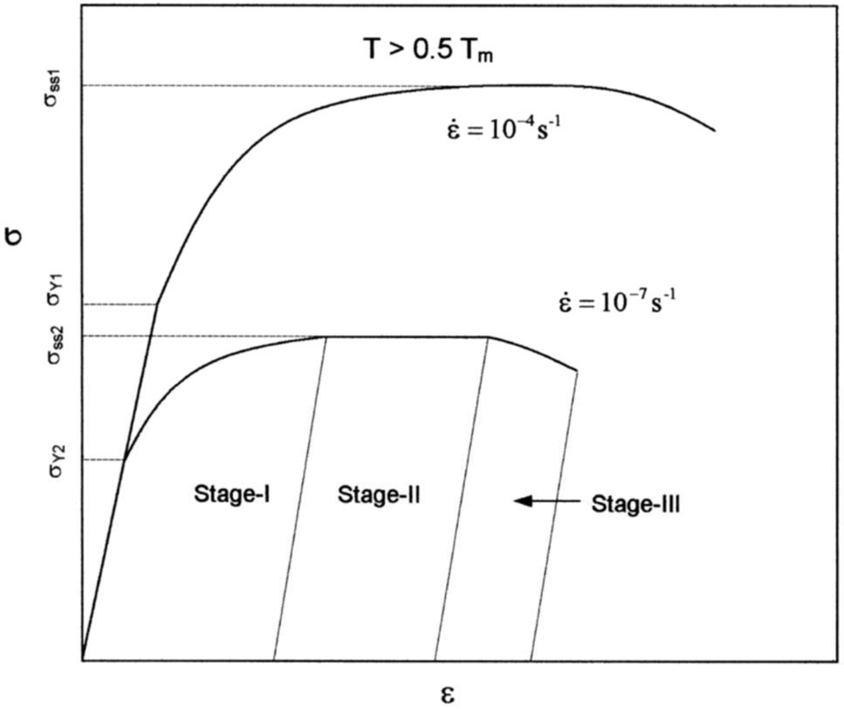


Figure 2. Creep behavior at two different constant strain-rates.

Temperature effect

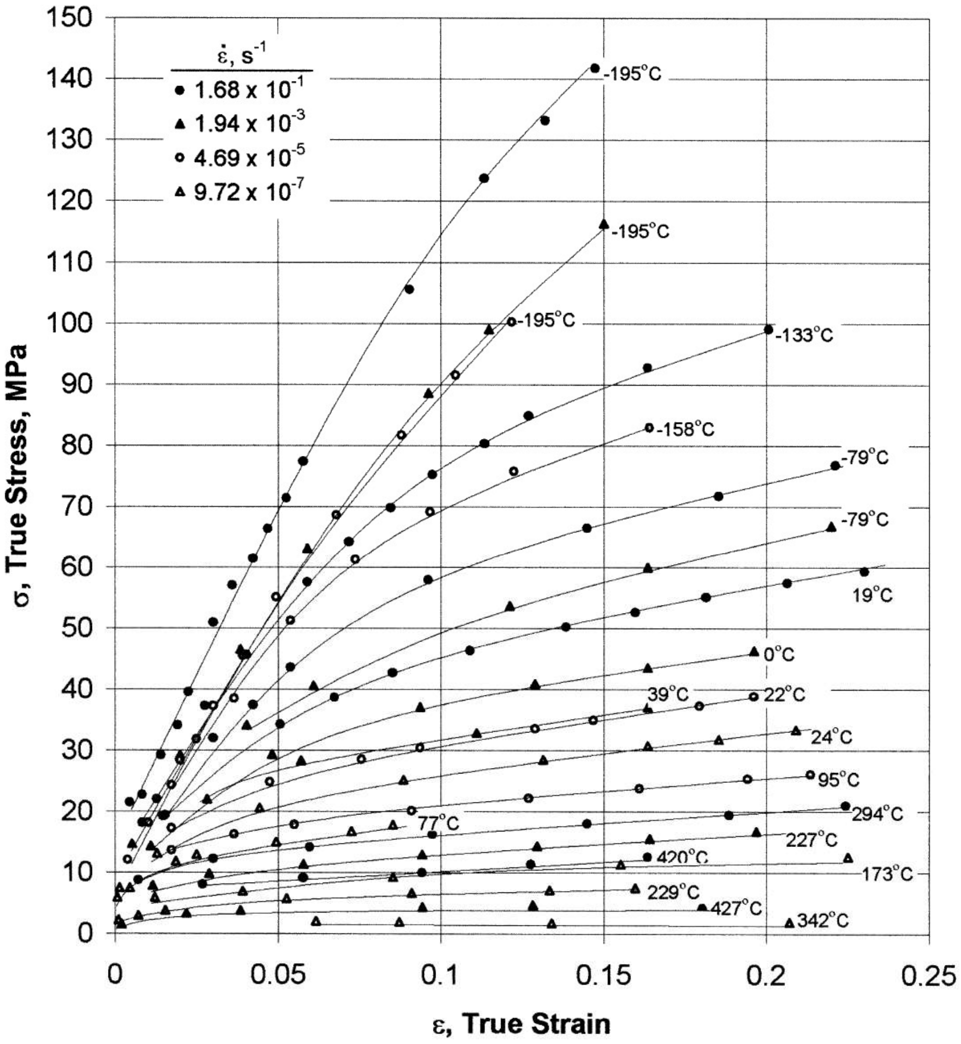
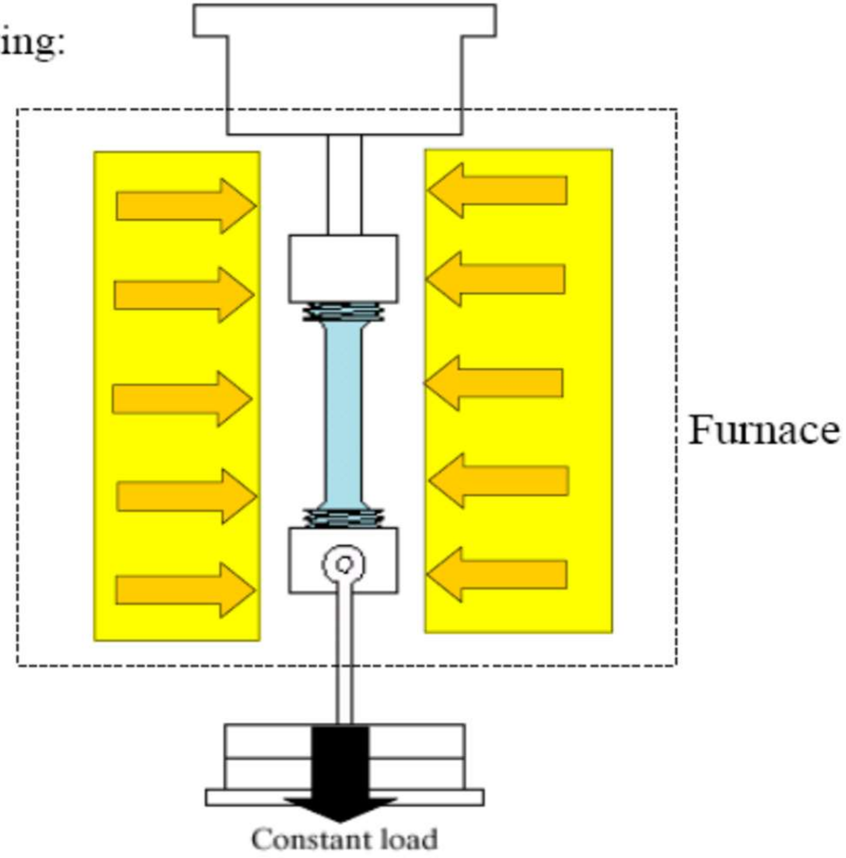


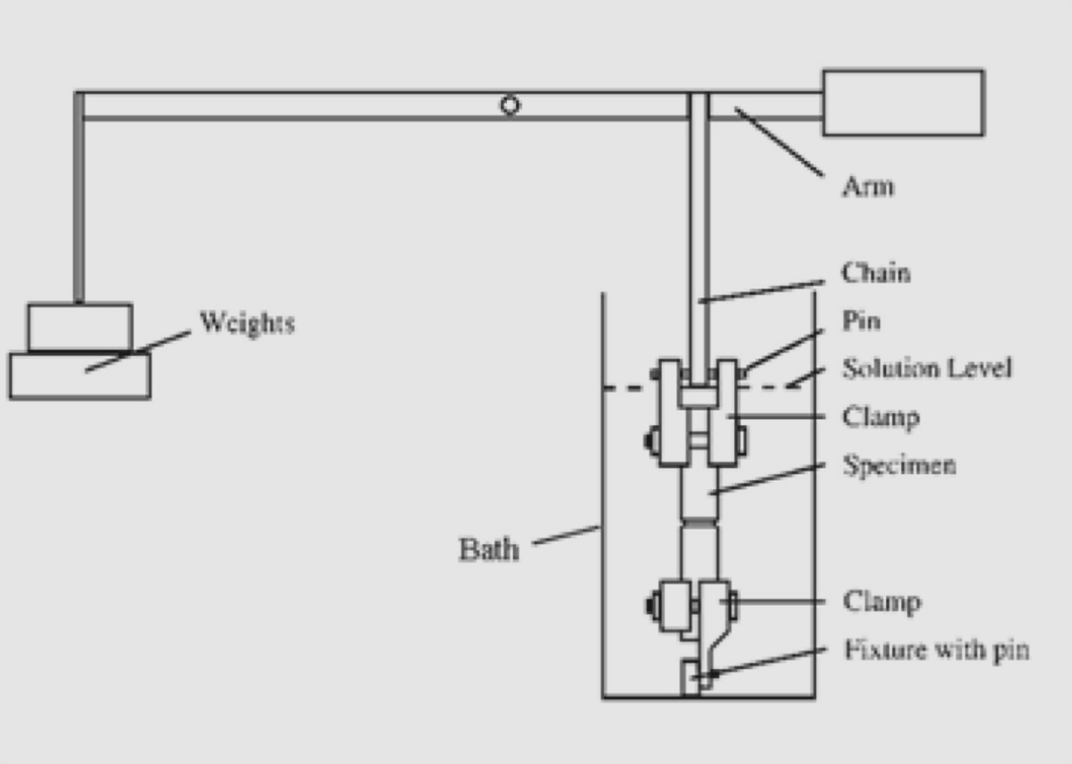
Figure 5. The stress versus strain behavior of high-purity aluminum. Data from Ref. [15].

Creep

Creep is a **time-dependent and permanent** deformation of materials when subjected to a constant load at a **high temperature** (> 0.4 T_m). Examples: turbine blades, steam generators.

Creep testing:




Arm
Chain
Weights
Pin
Solution Level
Clamp
Specimen
Bath
Clamp
Fixture with pin

Creep Design

In high-temperature design it is important to make sure:

(a) that the creep strain ε^{cr} during the design life is acceptable;
(b) that the creep ductility ε_f^{cr} (strain to failure) is adequate to cope with the acceptable creep strain;
(c) that the time-to-failure, $\boldsymbol{t_f}$, at the design loads and temperatures is longer (by a suitable safety factor) than the design life.

Factors Influencing Creep Behavior

Photo by Kelly Sikkema on Unsplash

The impact of temperature on creep rates

Typically, as temperature rises, the creep rate increases exponentially as thermal activation enhances atomic mobility, leading to greater deformation over time.

Effect of stress levels and material properties

Higher applied stresses magnify creep rates in materials. Additionally, material properties such as strength, ductility, and microstructure play vital roles in determining overall creep resistance.

Influence of time and environmental conditions on creep

Long exposure times and varying environmental conditions (e.g., corrosive environments) can significantly alter creep behavior, leading to unexpected failures if not accounted for.

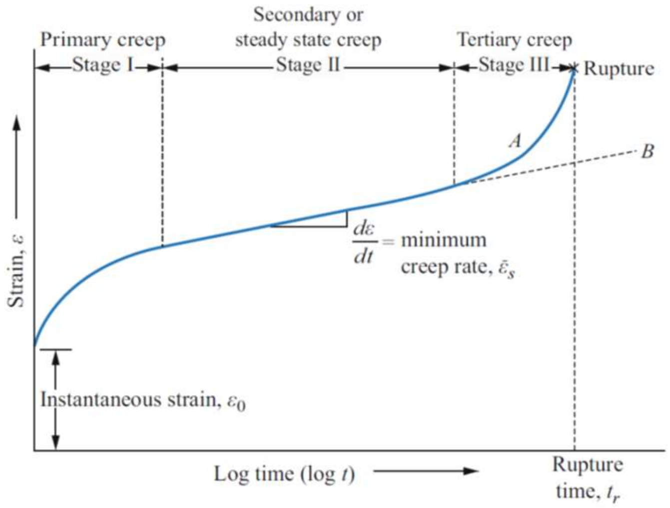


Fig. 7.2 Constant-temperature typical creep curve showing the three distinct stages of creep. Curve '*A*' for constant-load test and curve '*B*' for constant-stress test

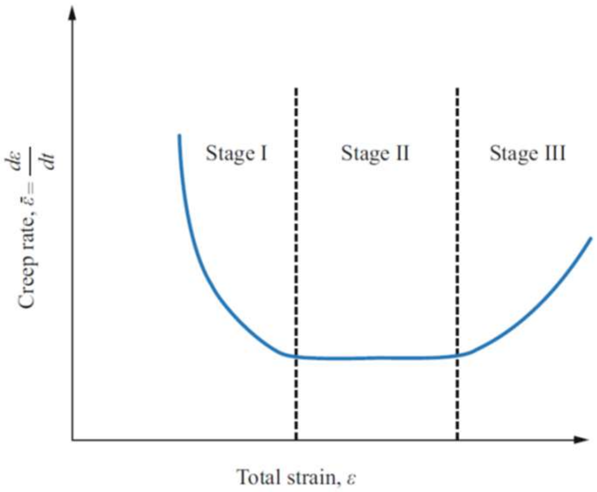
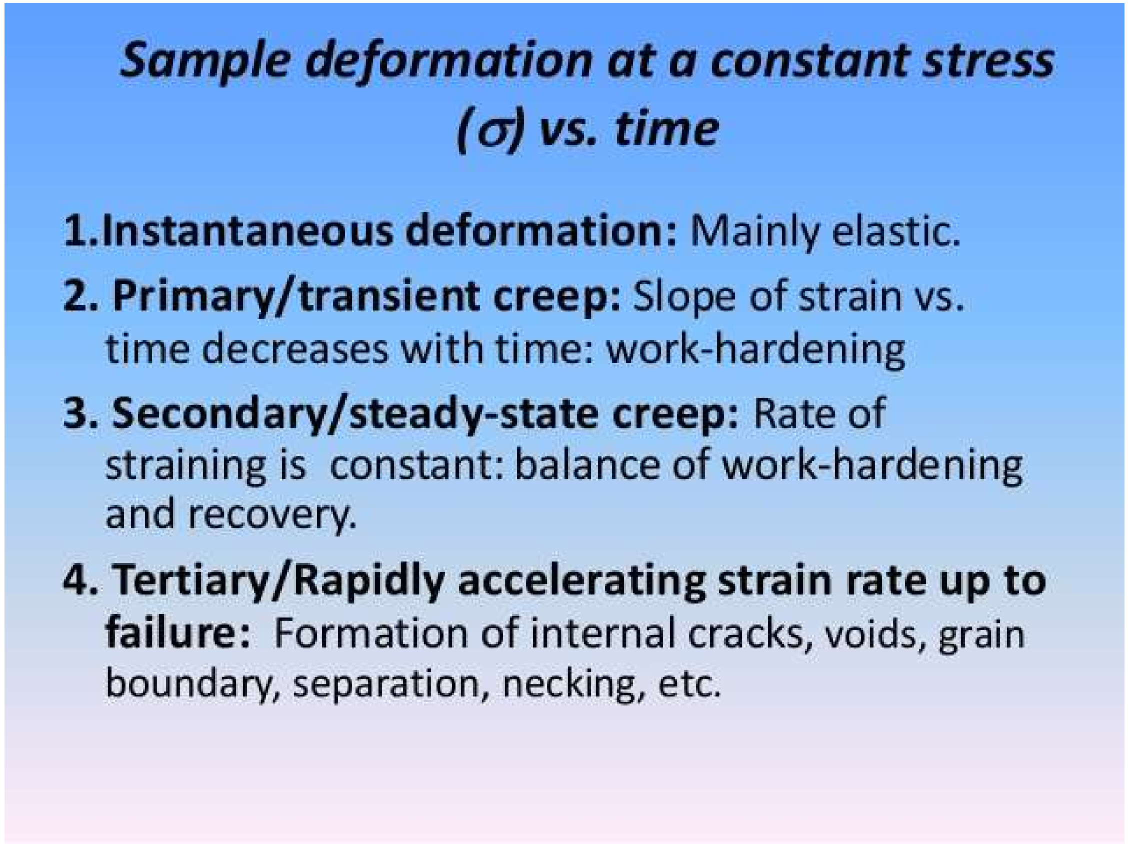


Fig. 7.3 Creep rate as a function of total strain

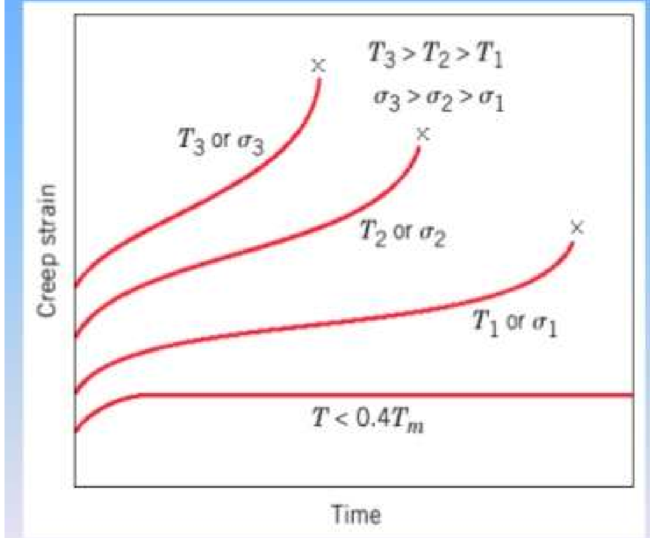
€=f (T, SIGMA, t)



Sample deformation at a constant stress (σ) vs. time

1. **Instantaneous deformation:** Mainly elastic.
2. **Primary/transient creep:** Slope of strain vs. time decreases with time: work-hardening
3. **Secondary/steady-state creep:** Rate of straining is constant: balance of work-hardening and recovery.
4. **Tertiary/Rapidly accelerating strain rate up to failure:** Formation of internal cracks, voids, grain boundary, separation, necking, etc.

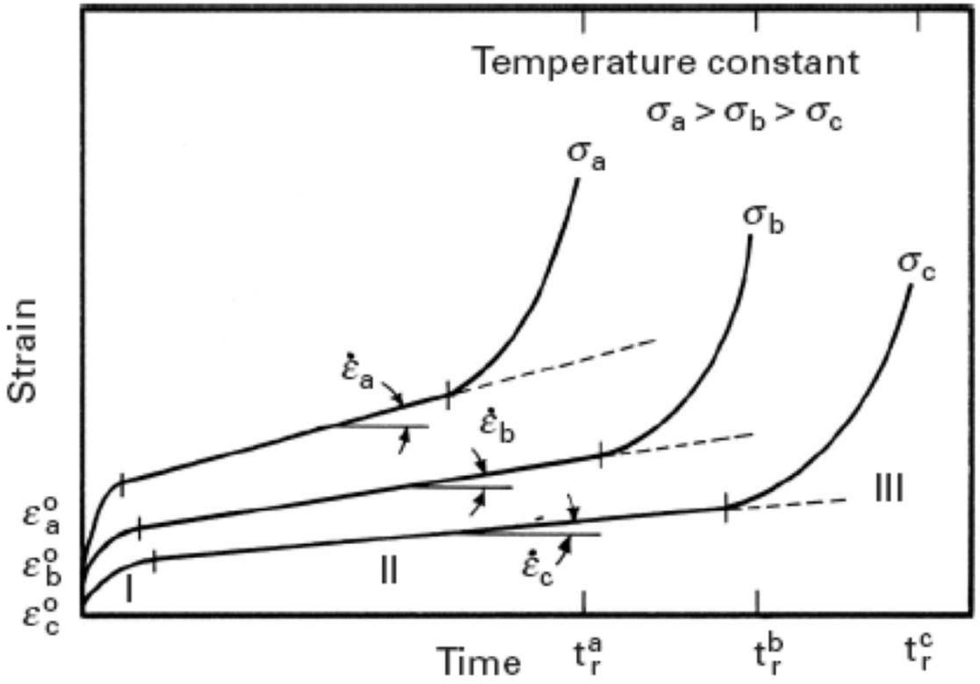
Creep: stress and temperature effects



With Increasing stress or temperature:

- The instantaneous strain increases
- The steady-state creep rate increases
- The time to rupture decreases

Effects of Temperature on Creep



- ➢The instantaneous strain increases
- ➢The steady-state creep rate increases
- ➢The time to rupture decreases

Basic Mechanisms of Creep

Explanation of key creep mechanisms: dislocation movement, diffusion, and grain boundary sliding

Creep occurs through several key mechanisms: dislocation movement (where lattice defects move), diffusion (atomic movement that allows material rearrangement), and grain boundary sliding (where grains slide past each other).

Mechanisms of Creep

- Different mechanisms are responsible for creep in different materials and under different loading and temperature conditions. The mechanisms include

- Stress-assisted vacancy diffusion
- Grain boundary diffusion (diffusion creep)
- Grain boundary sliding
- Dislocation Glide
- Dislocation creep

Homologous temp = $\frac{\text{Testing temperature}}{\text{Melting temperature}}$

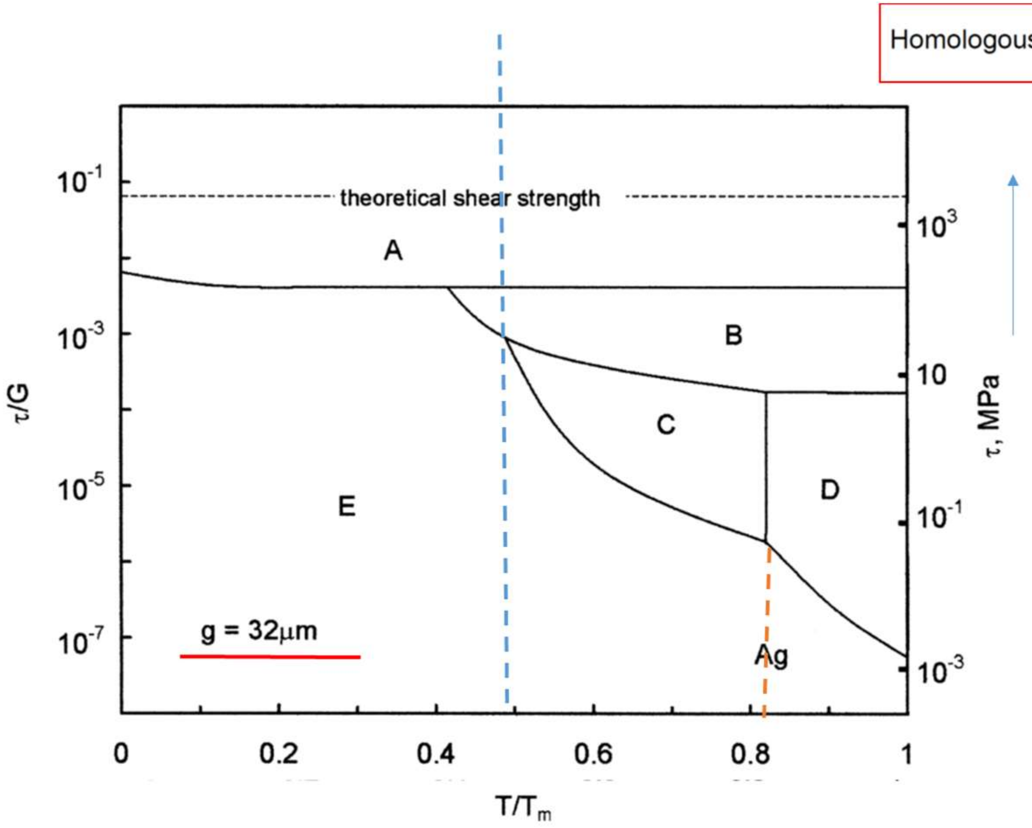


Figure 6. Ashby deformation map of silver from [33]. grain sizes 32 and 100 μm, $\dot{\varepsilon} = 10^{-8}\,s^{-1}$, A – dislocation glide, B – Five-Power-Law Creep, C – Coble creep, D – Nabarro-Herring creep, E – elastic deformation.

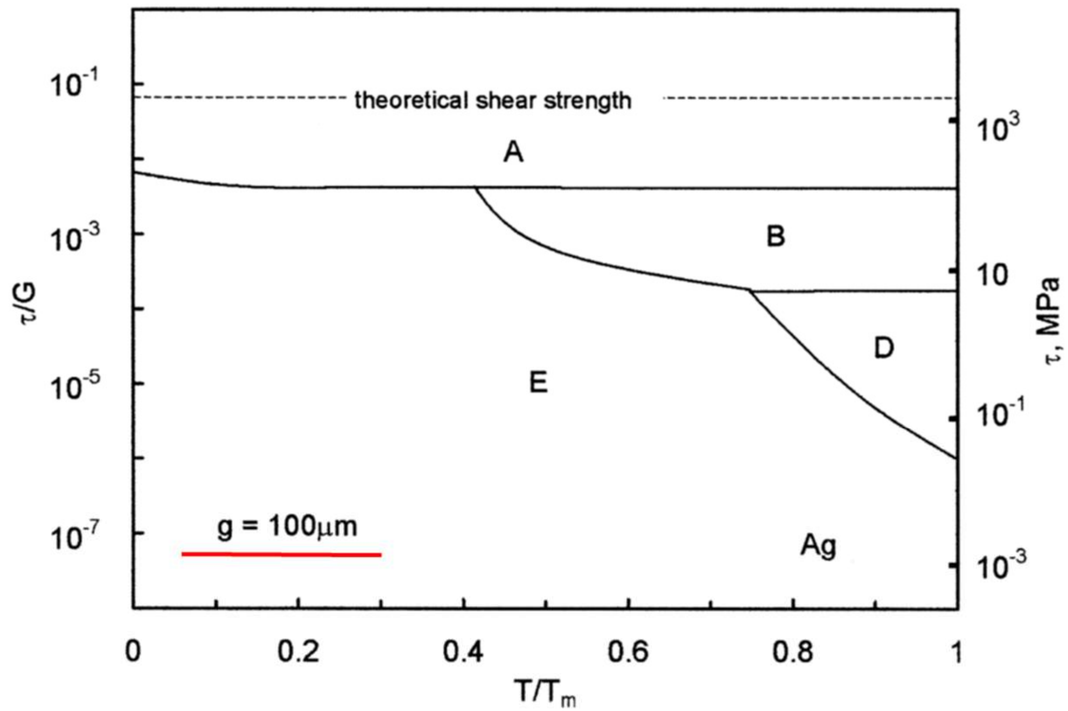
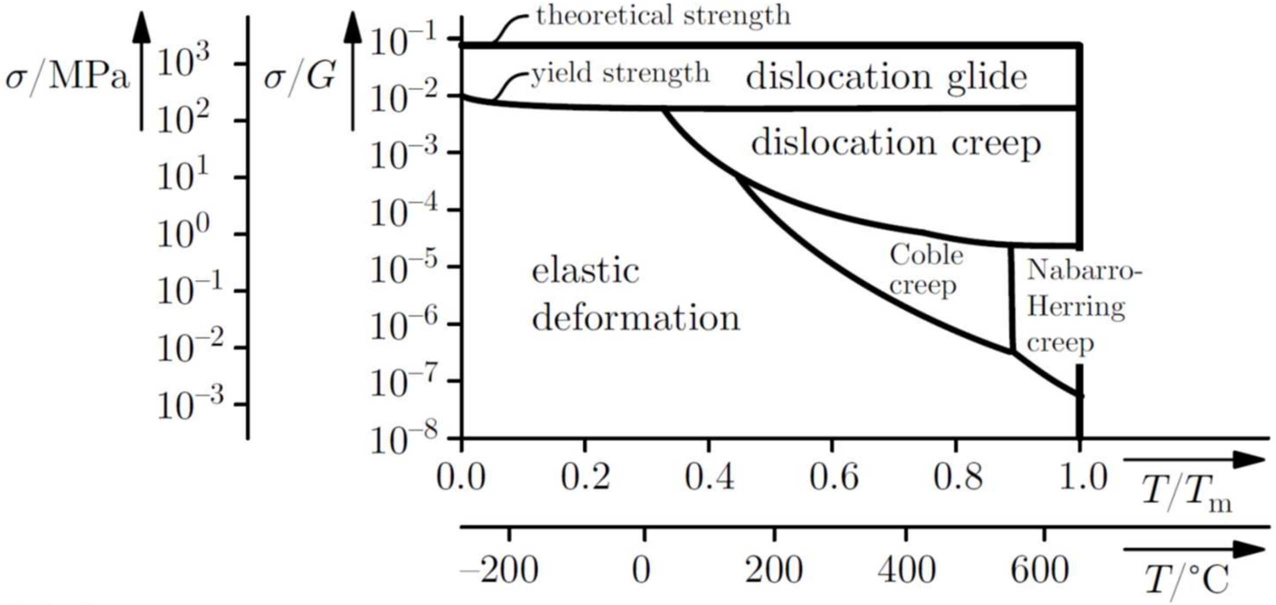
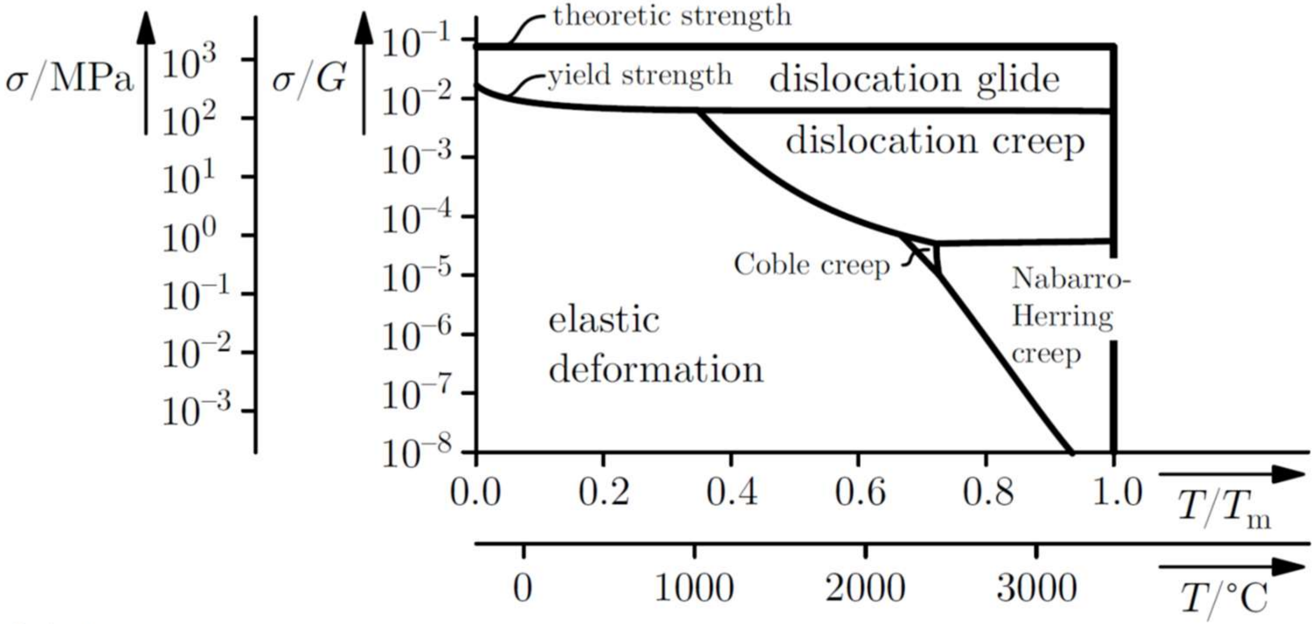


Figure 6. Ashby deformation map of silver from [33]. grain sizes 32 and 100 μm, $\dot{\varepsilon} = 10^{-8}\,s^{-1}$, A – dislocation glide, B – Five-Power-Law Creep, C – Coble creep, D – Nabarro-Herring creep, E – elastic deformation.



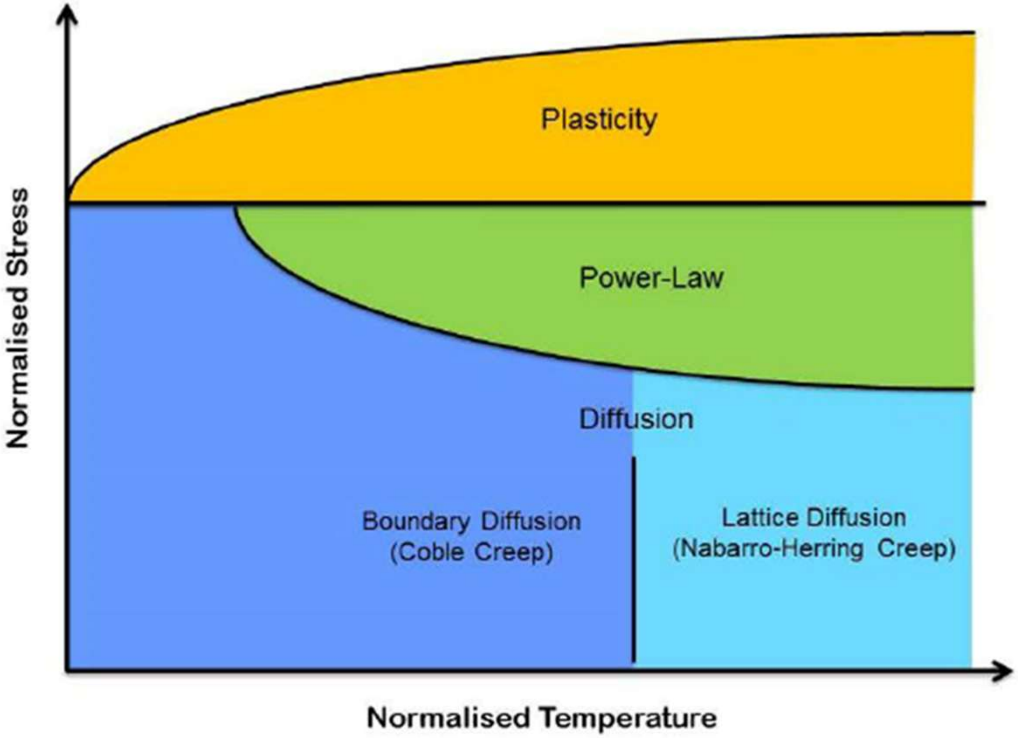
(a) Aluminium

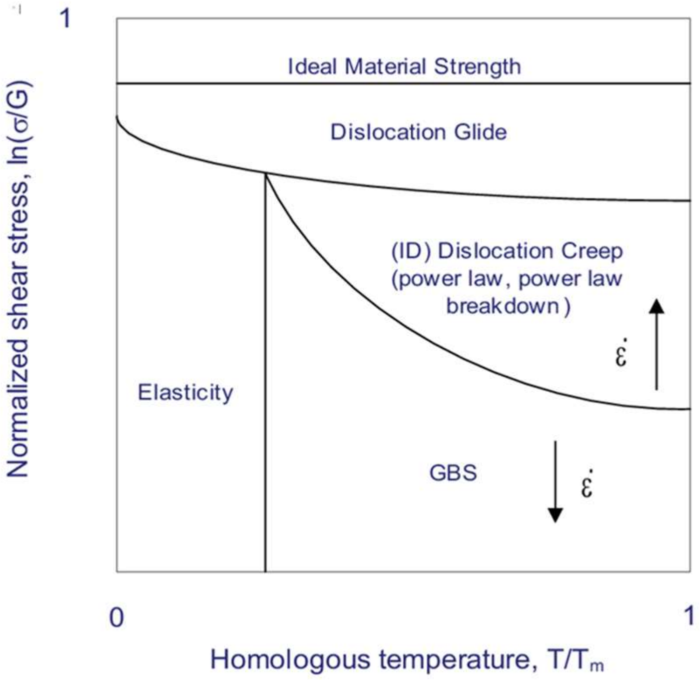
grain size is 32 µm

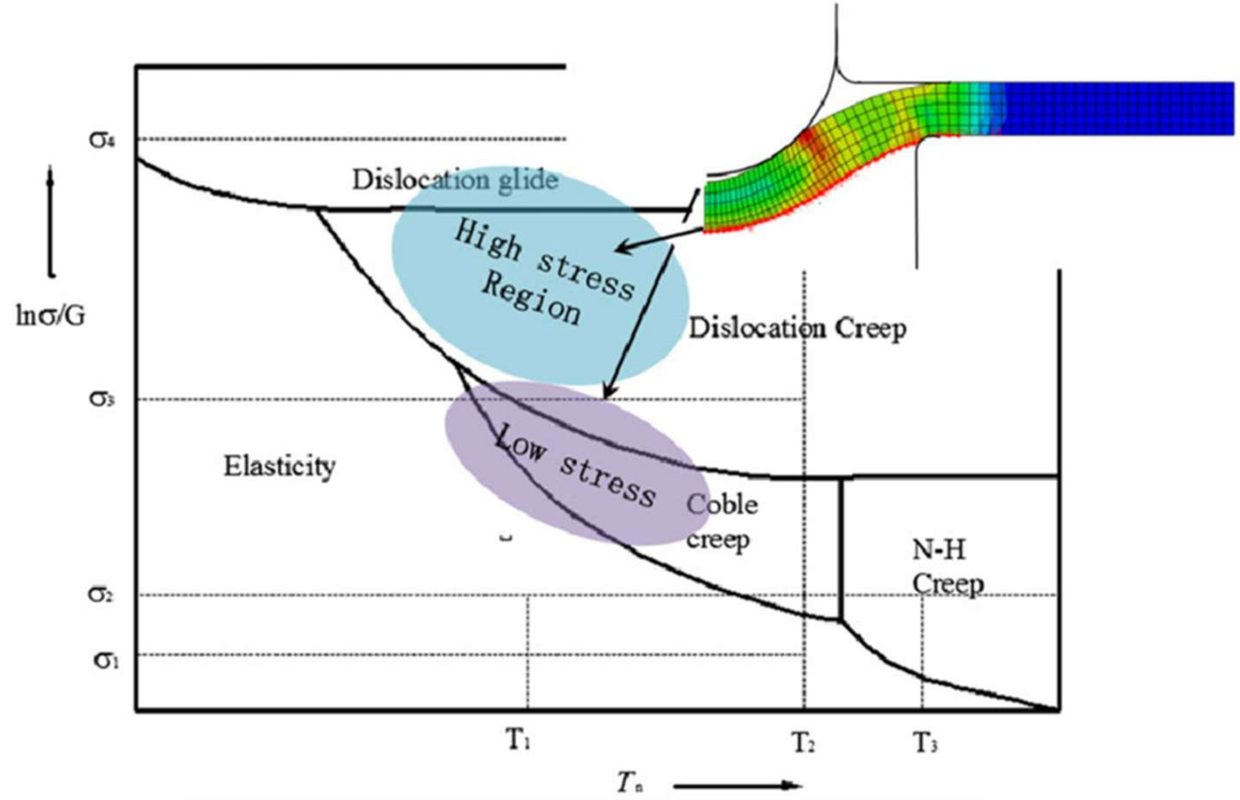


(b) Tungsten

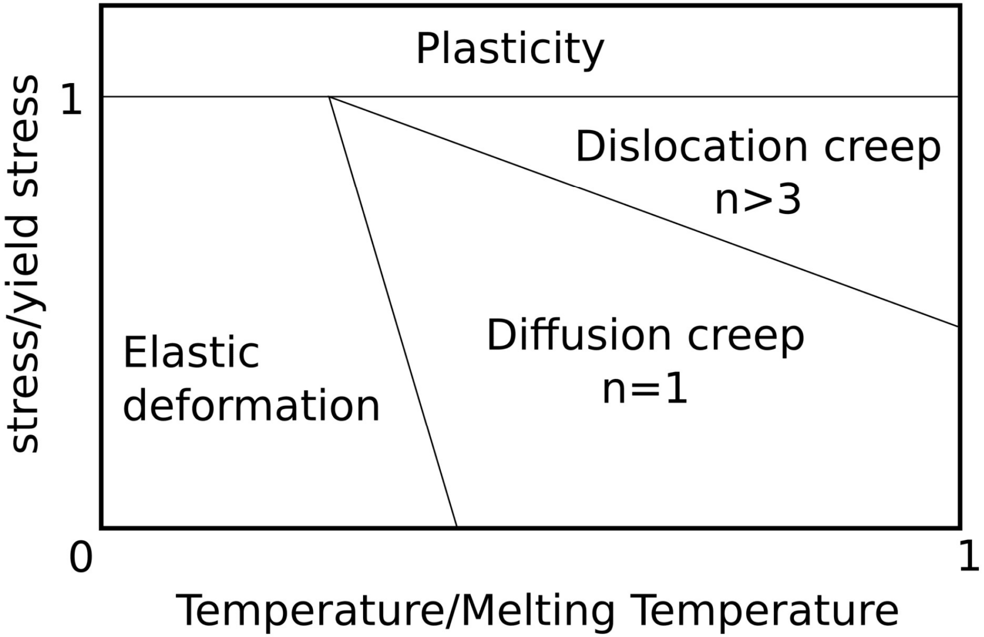
grain size is 32 µm


Plasticity
Power-Law
Diffusion
Boundary Diffusion (Coble Creep)
Lattice Diffusion (Nabarro-Herring Creep)
Normalised Stress
Normalised Temperature


1
Ideal Material Strength
Dislocation Glide
(ID) Dislocation Creep (power law, power law breakdown)
$\dot{\varepsilon}$
Elasticity
GBS
$\dot{\varepsilon}$
0
1
Normalized shear stress, ln(σ/G)
Homologous temperature, T/T_m

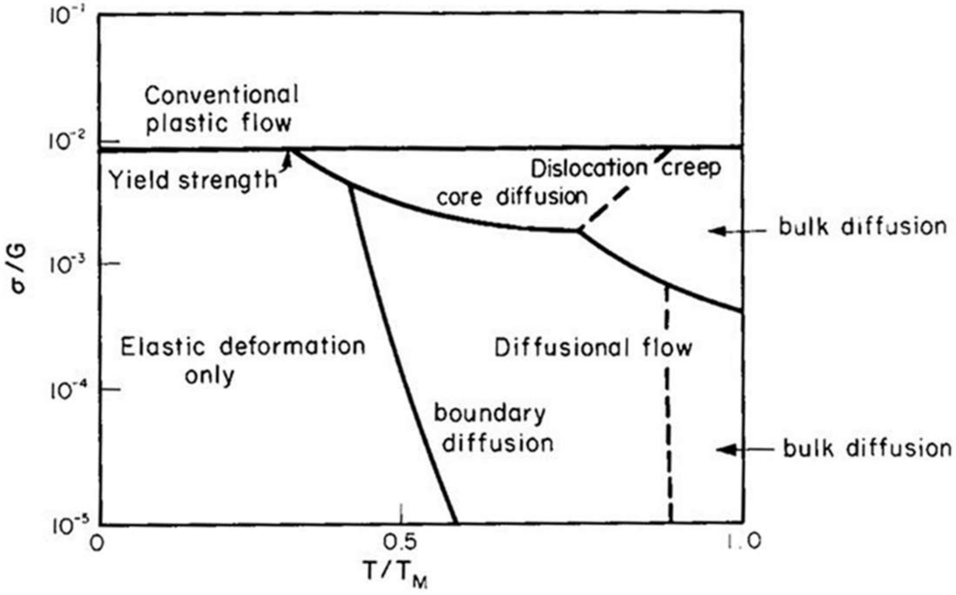


Schematic illustration of deformation mechanism map



Example of an Ashby deformation mechanism map

Deformation Maps



From: Ashby & Jones

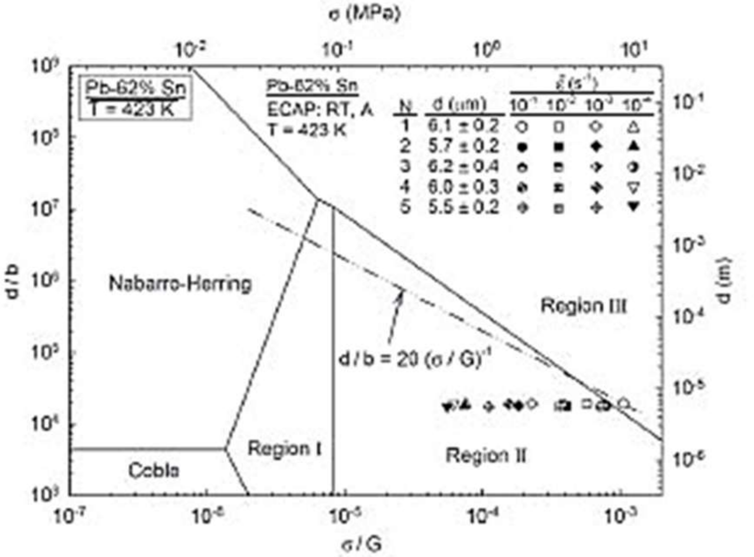
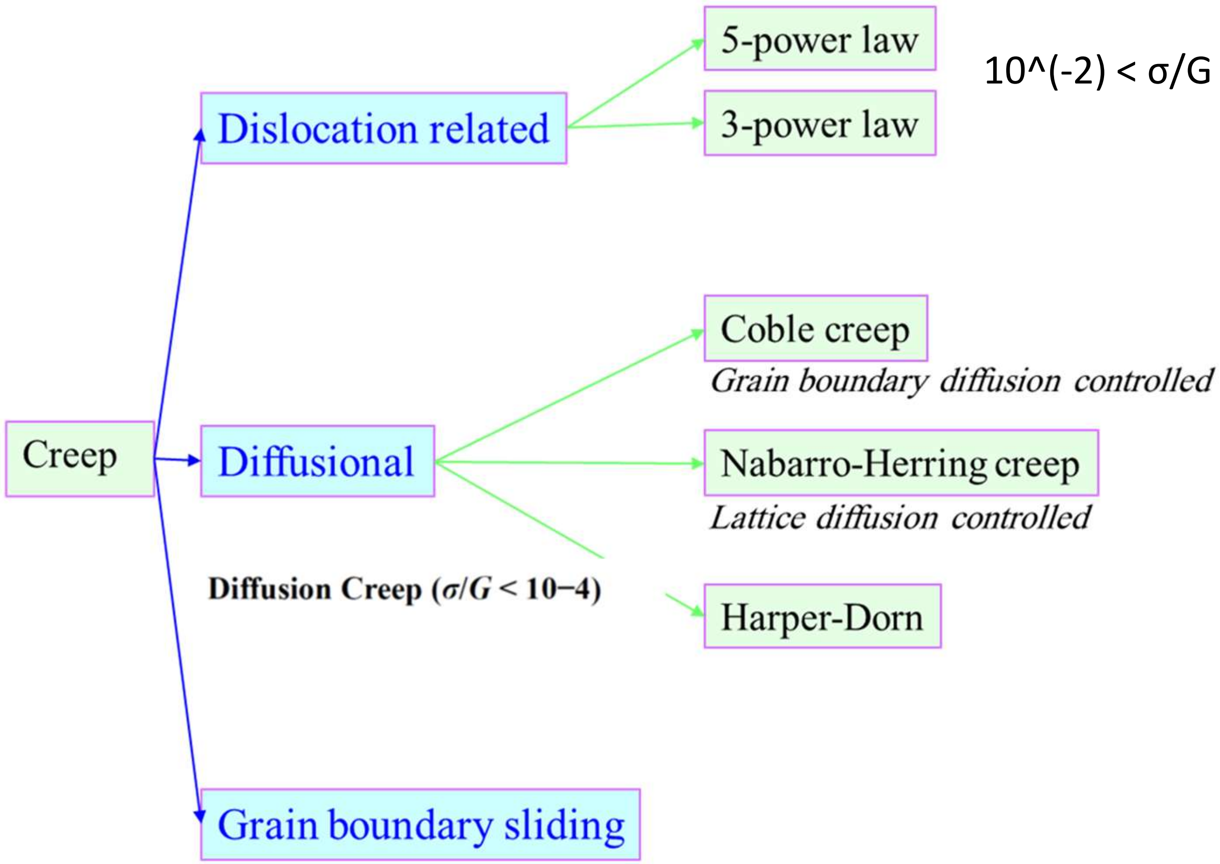


Figure 6. A deformation mechanism map of normalized grain size versus normalized stress for a Pb-62% Sn alloy tested at 423 K[37].

Creep Mechanisms *of crystalline materials*



Creep

- Dislocation related
  - 5-power law
  - 3-power law
- Diffusional
  - Coble creep
    Grain boundary diffusion controlled
  - Nabarro-Herring creep
    Lattice diffusion controlled
  - Harper-Dorn
- Grain boundary sliding

10^(-2) < σ/G < 10^(-4)

Diffusion Creep ($\sigma/G < 10{-}4$)

Chapter 3

Diffusional-Creep

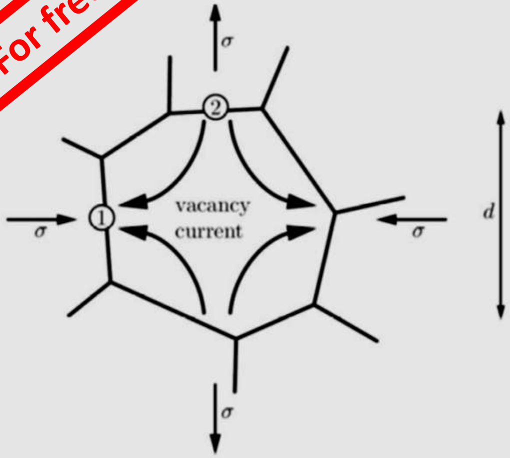
Creep at high temperatures ($T \approx T_{\mathrm{m}}$) and very low stresses in fine-grained materials was attributed 50 years ago by Nabarro [237] and Herring [51] to the mass transport of vacancies through the grains from one grain boundary to another. Excess vacancies are created at grain boundaries perpendicular to the tensile axis with a uniaxial tensile stress. The concentration may be calculated using [23]

$$n_v = n \exp\left(\frac{Q_v}{RT}\right)$$

$$c = c_v\left[\exp\left(\frac{\sigma b^3}{\mathrm{k}T}\right) - 1\right] \tag{76}$$

where c_v is the equilibrium concentration of vacancies. Usually $(\sigma b^3/\mathrm{k}T) \propto 1$, and therefore equation (76) can be approximated by

$$c = \left[c_v\left(\frac{\sigma b^3}{\mathrm{k}T}\right)\right] \tag{77}$$



$$C_V^+ = C_0 \exp -\left(\frac{H_V - \sigma\Omega}{kT}\right) = C_V \cdot \exp\left(\frac{\sigma\Omega}{kT}\right)$$

$$C_V^- = C_0 \exp -\left(\frac{H_V + \sigma\Omega}{kT}\right) = C_V \cdot \exp\left(\frac{-\sigma\Omega}{kT}\right)$$

$$J_V = -D_V \nabla C_V = D_V \frac{\Delta C_V}{\Delta x} = D_V \frac{\Delta C_V}{d}$$

$$\Delta C_V = C^+ - C^- = C_V \left(e^{\frac{\sigma\Omega}{kT}} - e^{\frac{-\sigma\Omega}{kT}} \right) \approx C_V \cdot \frac{2\sigma\Omega}{kT}$$

$$J_V = \frac{D_V}{d} \cdot C_V \cdot \frac{2\sigma\Omega}{kT}$$

Coble creep mechanism

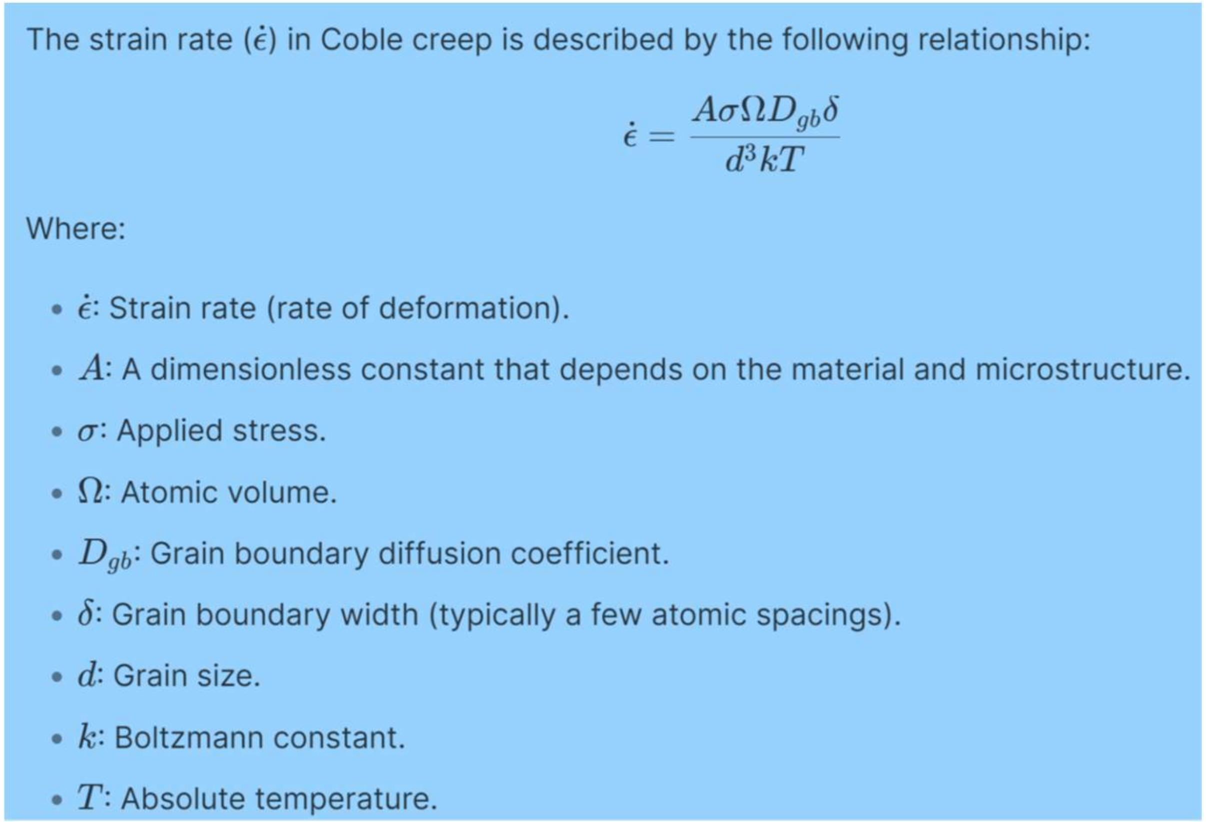
a form of diffusion creep, is a mechanism for deformation of crystalline solids. Coble creep occurs through the diffusion of atoms in a material along the grain boundaries, which produces a net flow of material and a sliding of the grain boundaries.

Coble creep is named after Robert L. Coble, who first reported his theory of how materials creep over time in 1962 in the Journal of Applied Physics.

This mechanism is particularly significant in fine-grained materials and at intermediate to high temperatures

$0.5\ T_m < T < 0.8\ T_m$

Coble creep mechanism



The strain rate ($\dot{\epsilon}$) in Coble creep is described by the following relationship:

$$\dot{\epsilon} = \frac{A\sigma\Omega D_{gb}\delta}{d^3 kT}$$

Where:

- $\dot{\epsilon}$: Strain rate (rate of deformation).
- A: A dimensionless constant that depends on the material and microstructure.
- σ: Applied stress.
- Ω: Atomic volume.
- D_{gb}: Grain boundary diffusion coefficient.
- δ: Grain boundary width (typically a few atomic spacings).
- d: Grain size.
- k: Boltzmann constant.
- T: Absolute temperature.

Coble mechanism

The strain-rate suggested by Coble is

$$\dot{\varepsilon}_{ss} = \frac{\alpha_3 D_{gb} \sigma b^4}{kTg^3}$$

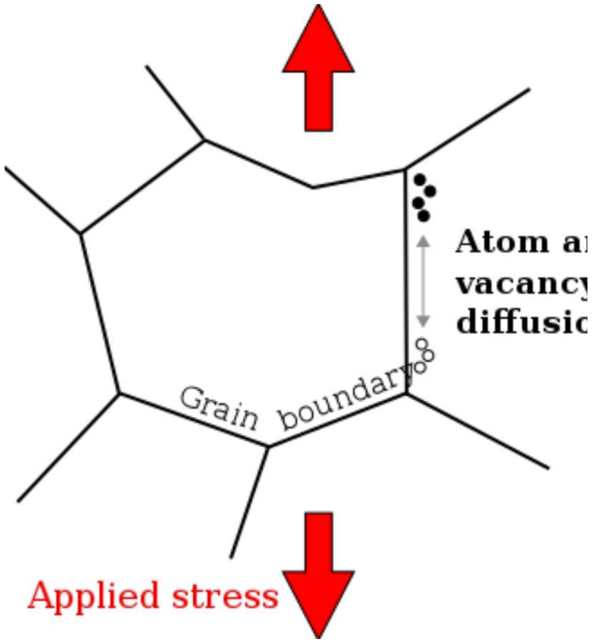
$$D_\nu = D_{0\nu} \exp\left(\frac{-Q_m}{kT}\right)$$

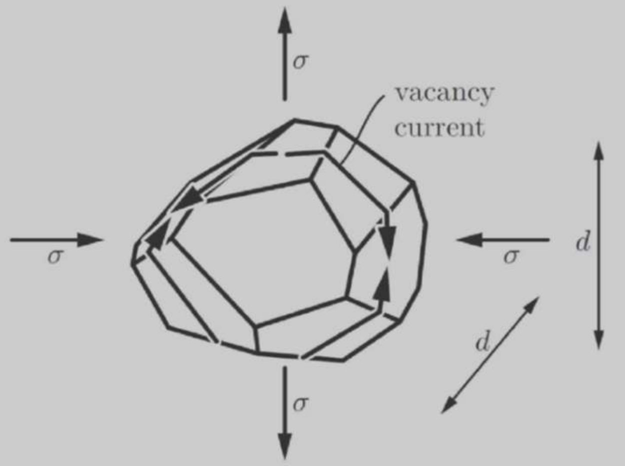
D , σ, T ↑ $\dot{\epsilon}$ ↑

g ↓ $\dot{\epsilon}$ ↑

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

The **Boltzmann constant**	
$1.380\,649 \times 10^{-23}$[2]	$J{\cdot}K^{-1}$





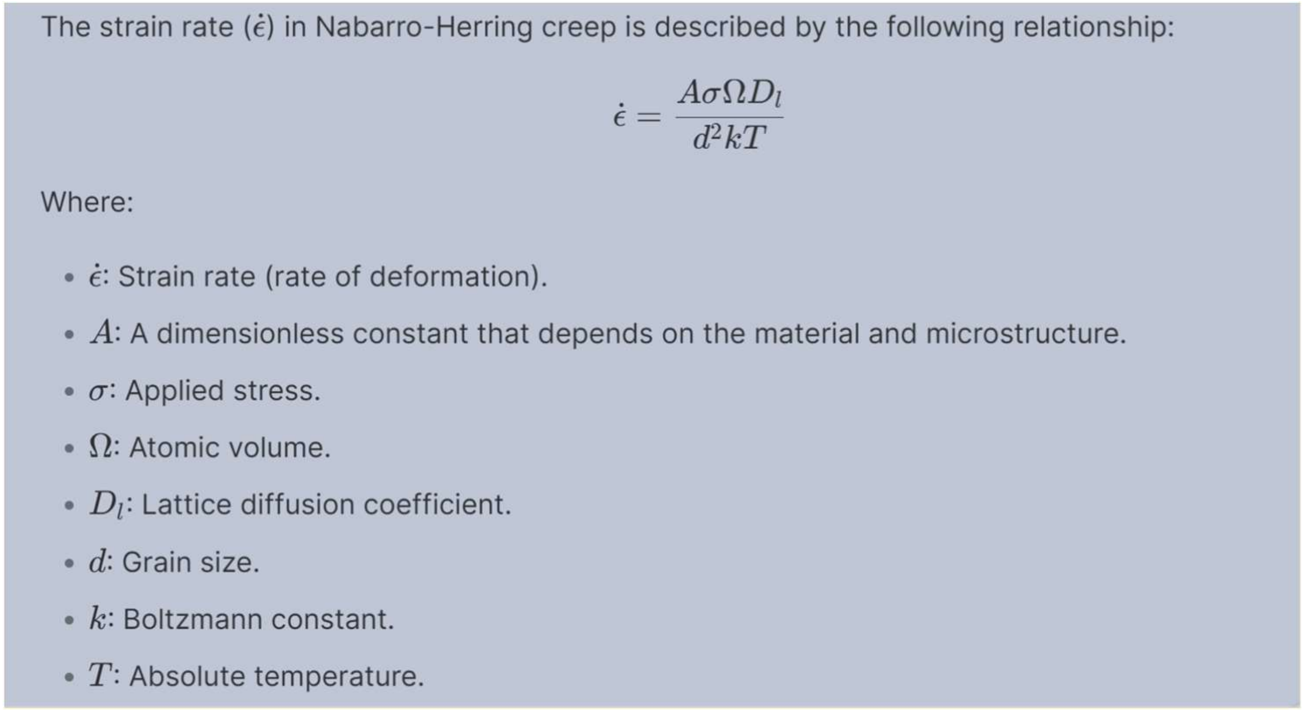
Movement of vacancies along grain boundaries in diffusion creep

- Under an applied stress, atoms migrate from grain boundaries experiencing compressive stress to those experiencing tensile stress.
- Grain boundaries have a more disordered atomic structure compared to the crystalline lattice, making them high-diffusivity pathways.

Nabarro-Herring Creep Mechanism

Nabarro-Herring creep is a **diffusion-controlled creep mechanism** that occurs in crystalline materials at very high temperatures. It is characterized by the diffusion of atoms through the **crystal lattice** (bulk diffusion) under an applied stress. This mechanism is particularly significant in coarse-grained materials and at temperatures close to the melting point.

Nabarro and Herring mechanism



The strain rate ($\dot{\epsilon}$) in Nabarro-Herring creep is described by the following relationship:

$$\dot{\epsilon} = \frac{A\sigma\Omega D_l}{d^2kT}$$

Where:

- $\dot{\epsilon}$: Strain rate (rate of deformation).
- A: A dimensionless constant that depends on the material and microstructure.
- σ: Applied stress.
- Ω: Atomic volume.
- D_l: Lattice diffusion coefficient.
- d: Grain size.
- k: Boltzmann constant.
- T: Absolute temperature.

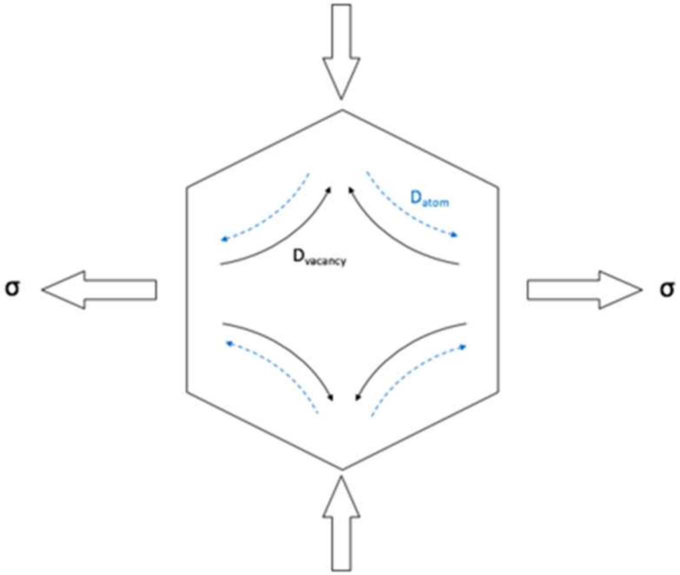
Nabarro and Herring mechanism

The resulting strain-rate is given by,

$$\dot{\varepsilon}_{\mathrm{ss}} = \frac{D_{\mathrm{sd}}\sigma b^3}{\mathrm{k}Tg^2}$$

$$\dot{\epsilon}_{NH} = A_{NH}\left(\frac{D_L}{d^2}\right)\left(\frac{\sigma\Omega}{kT}\right)$$

where A_{NH} is a constant that absorbs the approximations in the derivation.

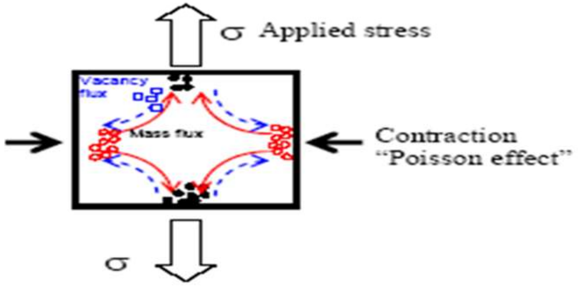


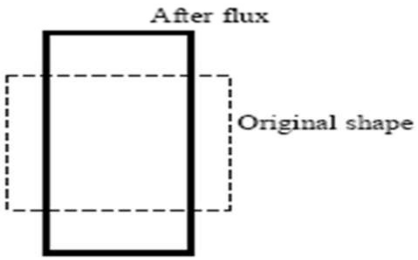
Nabarro-Herring Creep

- Occurs solely by diffusional mass transport.
- Is important for much higher T's and lower σ's than was the case for dislocation glide creep.
- Can occur in crystalline and amorphous materials.

★ Applied stress creates tensile and compressive regions.

  - Concentration of vacancies in tensile region > compressive
  - Vacancy concentration gradient → diffusion
  - Diffusion leads to shape change



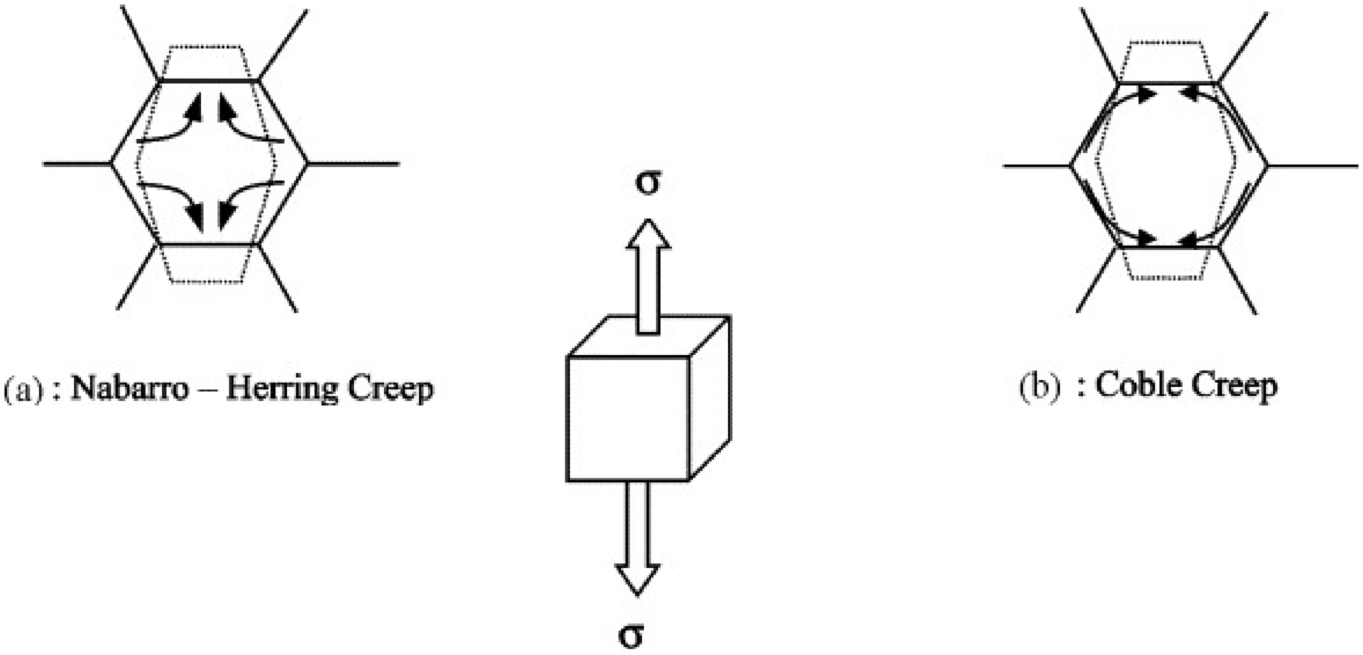


$$\boxed{\dot{\varepsilon}_{NH} \approx \frac{A_{NH} D_L G b}{kT}\left(\frac{b}{d}\right)^2\left(\frac{\sigma}{G}\right)}$$

$A_{NH} \cong 10\text{-}15$

D_L = lattice diffusion coefficient

$$\begin{aligned}\dot{\varepsilon} &= A_{\mathrm{NH}}\frac{\sigma\Omega}{kT}\frac{D_0}{d^2}\exp\left(-\frac{Q_{\mathrm{V}}+Q_{\mathrm{ex}}}{kT}\right)\\ &= A_{\mathrm{NH}}\frac{\sigma\Omega}{kT}\frac{D_{\mathrm{V}}}{d^2}\,.\end{aligned}$$



(a) : Nabarro – Herring Creep

(b) : Coble Creep

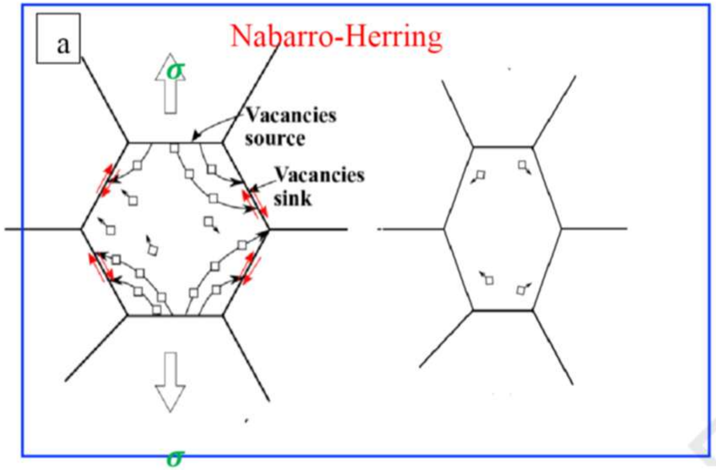
Mechanism	favorable conditions	Description	A	n	p
Nabarro–Herring creep	High temperature, low stress and small grain size	Vacancy diffusion through the crystal lattice	10–15	1	2
Coble creep	Low stress, fine grain sizes and temperature less than those for which NH creep dominates	Vacancy diffusion along grain boundaries	30–50	1	3

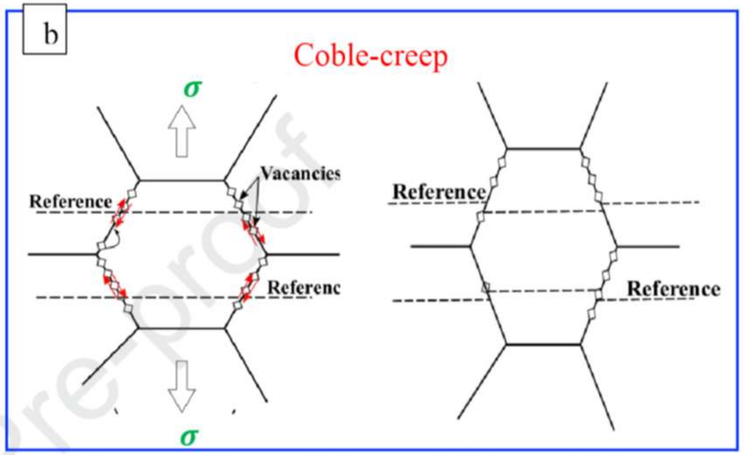
Key Differences Summary

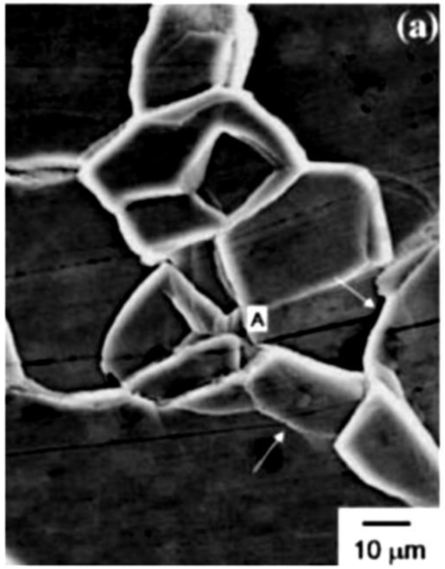
Feature	Coble Creep	Nabarro-Herring Creep
Diffusion Pathway	Grain boundary diffusion	Lattice (bulk) diffusion
Grain Size Dependence	$\propto \frac{1}{d^3}$	$\propto \frac{1}{d^2}$
Temperature Range	Intermediate to high temperatures	Very high temperatures
Activation Energy	Lower (grain boundary diffusion)	Higher (lattice diffusion)
Microstructural Role	Grain boundaries are critical	Bulk lattice is critical

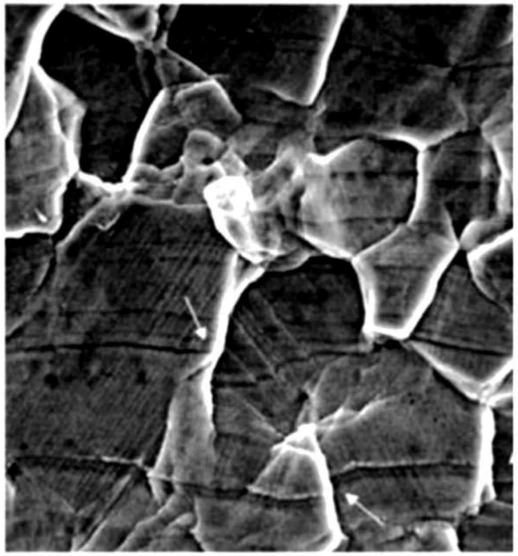
- Coble creep is important in materials used at high temperatures, such as turbine blades, nuclear reactors, and aerospace components.

Nabarro-Herring Creep vs. Coble Creep









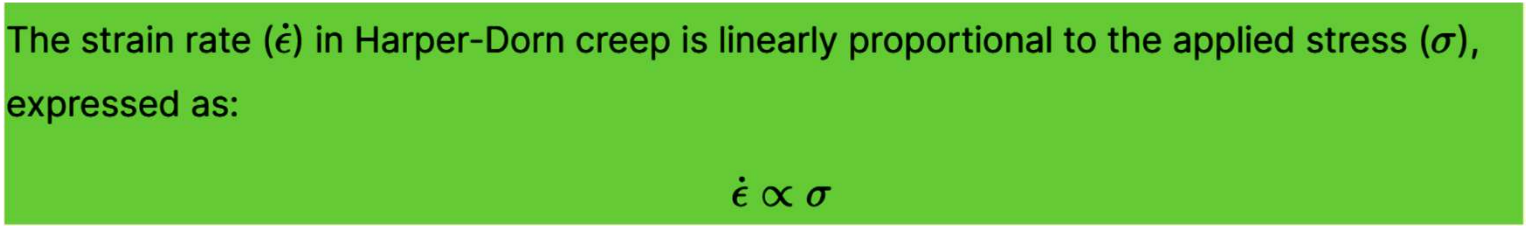
Chapter 4

Harper–Dorn Creep

is a low-stress, high-temperature creep mechanism observed in certain crystalline materials, particularly in high-purity metals like aluminum.

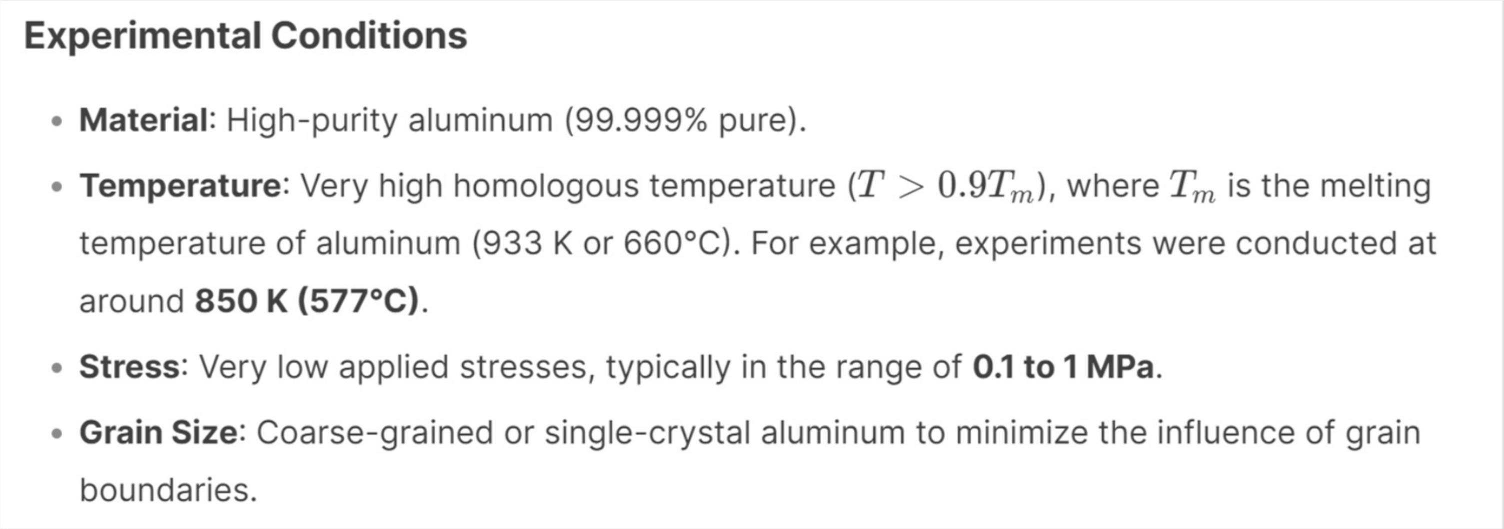
It was first identified by Harper and Dorn in 1957 during experiments on pure aluminum at temperatures close to its melting point and under very low stresses.

This mechanism is characterized by a stress exponent of approximately 1, indicating a linear relationship between the applied stress and the strain rate, which distinguishes it from other creep mechanisms like power-law creep.



The strain rate ($\dot{\epsilon}$) in Harper-Dorn creep is linearly proportional to the applied stress (σ), expressed as:

$$\dot{\epsilon} \propto \sigma$$



Experimental Conditions

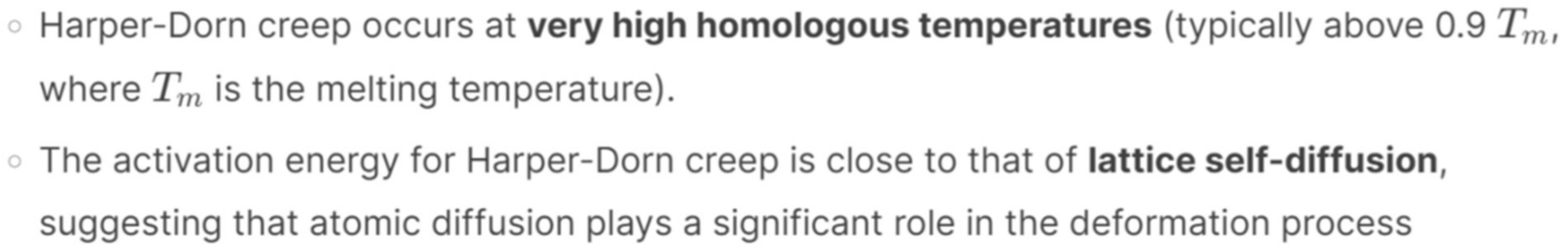
- **Material**: High-purity aluminum (99.999% pure).
- **Temperature**: Very high homologous temperature ($T > 0.9T_m$), where T_m is the melting temperature of aluminum (933 K or 660°C). For example, experiments were conducted at around **850 K (577°C)**.
- **Stress**: Very low applied stresses, typically in the range of **0.1 to 1 MPa**.
- **Grain Size**: Coarse-grained or single-crystal aluminum to minimize the influence of grain boundaries.

3.3 mm grain size

$$\dot{\varepsilon}_{\mathrm{ss}} = \mathrm{A}_{\mathrm{HD}}\left(\frac{D_{\mathrm{sd}}Gb}{\mathrm{k}T}\right)\left(\frac{\sigma}{G}\right)^{1}$$

where A_{HD} is a constant.

Harper-Dorn creep



- Harper-Dorn creep occurs at **very high homologous temperatures** (typically above 0.9 T_m, where T_m is the melting temperature).
- The activation energy for Harper-Dorn creep is close to that of **lattice self-diffusion**, suggesting that atomic diffusion plays a significant role in the deformation process

Harper-Dorn creep often exhibits a primary creep stage, where the strain rate decreases over time before reaching a steady state. This is attributed to the gradual stabilization of the dislocation network.

$$\dot{\varepsilon}_{\mathrm{ss}} = \mathrm{A}_{\mathrm{HD}}\left(\frac{D_{\mathrm{sd}}Gb}{\mathrm{k}T}\right)\left(\frac{\sigma}{G}\right)^{1}$$

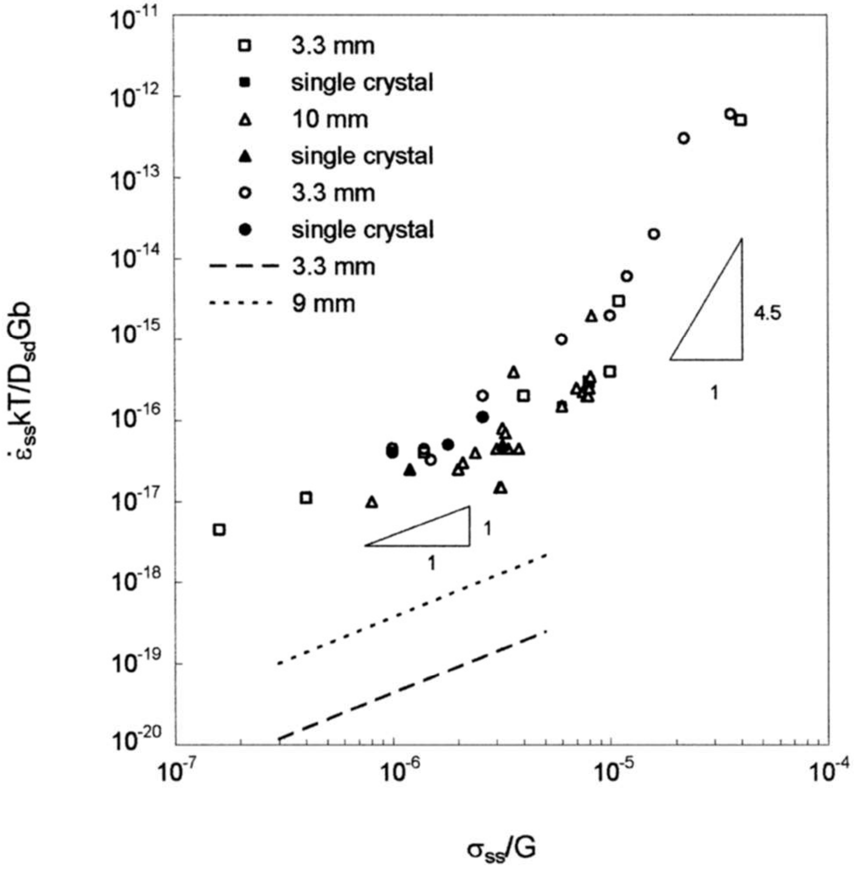
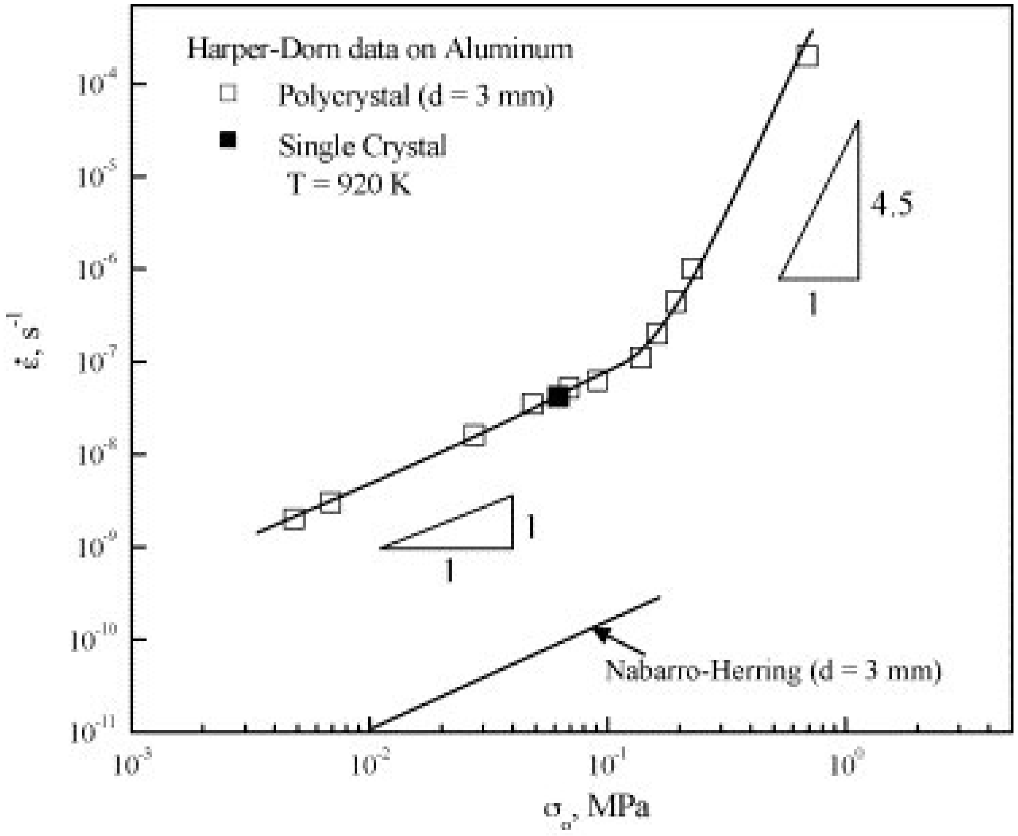


Figure 50. Comparison between the diffusion-coefficient compensated strain-rate versus modulus-compensated stress for pure aluminum based on [50,269,294], with theoretical predictions for Nabarro–Herring creep [295].



The dislocation density in Harper-Dorn creep remains constant and independent of the applied stress. This is a unique feature that differentiates it from other creep mechanisms, where dislocation density typically increases with stress.

$$\dot{\varepsilon}_{\mathrm{ss}} = \mathrm{A}_{10}\frac{D_{\mathrm{eff}}}{b^2}\left(\frac{\sigma}{E}\right)^n$$

Comparison with Other Creep Mechanisms

Feature	Harper-Dorn Creep	Nabarro-Herring Creep	Coble Creep	Power-Law Creep
Stress Exponent (n)	1	1	1	3–5
Temperature Range	Very high ($> 0.9T_m$)	High ($> 0.6T_m$)	Intermediate to high	High ($> 0.6T_m$)
Grain Size Dependence	Independent	d^{-2}	d^{-3}	Weak dependence
Dislocation Density	Constant	Not applicable	Not applicable	Increases with stress

Chapter 6

Superplasticity

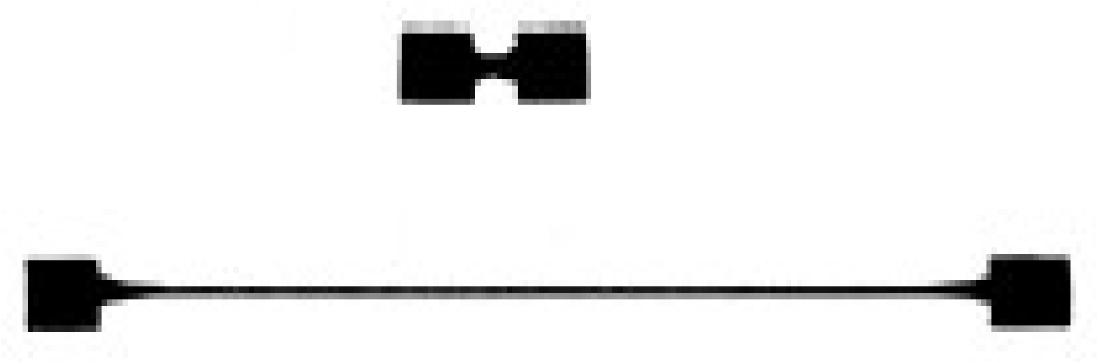
Superplasticity

- ***Superplasticity*** is the ability to withstand very large deformation in tension without necking.
- Give elongation > 1000%.
- Materials with high ***strain rate sensitivity*** (***m***) at high temperature ($T > 0.5T_m$) → ***superplasticity***
- Materials characteristics: ***fine grain size*** (<10 μm) with the presence of ***second phase of similar strength to the matrix*** to inhibit grain growth and to avoid extensive internal cavity formation.
- Grain boundary should be ***high angle*** and ***mobile*** to promote grain boundary sliding and to avoid the formation of local stress concentration respectively.

- Superplastic deformation can be utilized to help shape complex geometry at high temperatures

Superplasticity

strain rate of 10−3 -10−5 s−1



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.)

Grain-boundary sliding. It is a shear process occurring in the direction of grain boundary, causing the movement of grains relative to each other in polycrystals. Grain boundaries lying at about 45° to the applied tensile stress will experience the maximum shear stress and slide the most. It is encouraged by decreasing the strain rate and/or increasing the temperature.

$$\sigma \geq 10^{-2}G.$$

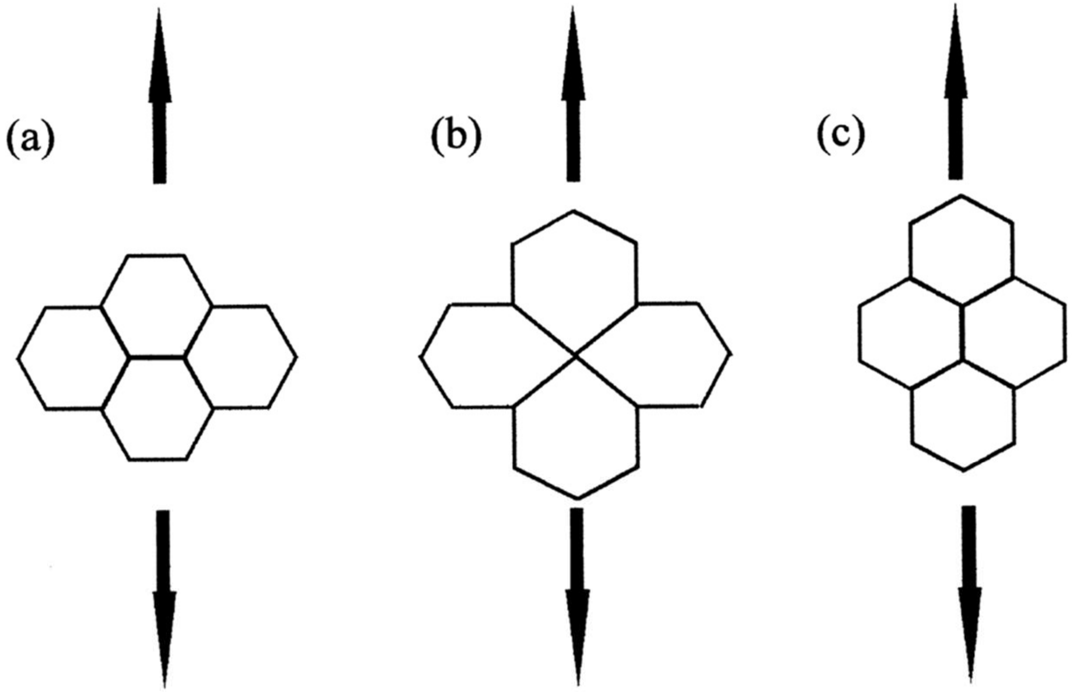
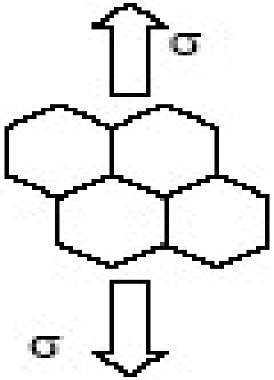


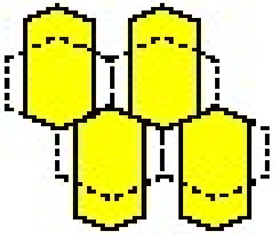
Figure 58. Ashby–Verral model of GBS accommodated by diffusional flow [436].

دانه ها نباید کروی باشند و حتما باید گوشه ای باشند

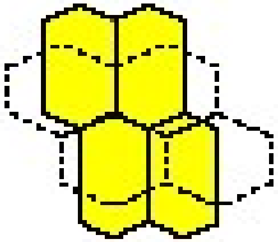
Grain Boundary Sliding

One of the processes to accommodate grain-boundary strain at elevated temperature is grain-boundary migration.





Voids are created during diffusion-assisted flow.



Grain boundary sliding occurs to keep material from falling apart

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

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

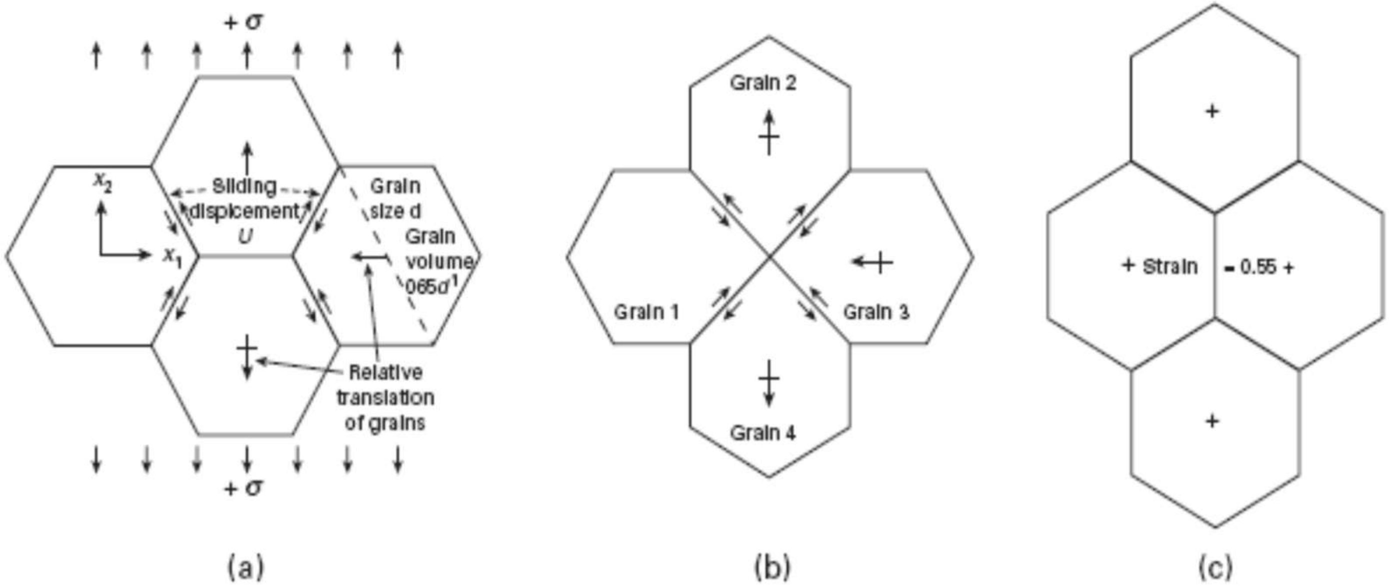
لغزش مرزدانه‌ای یکی از مکانیزم‌های تغییرشکل مواد در اثر حرکت دانه‌ها نسبت به یکدیگر در دمای همولوگ بالا و سرعت کرنش پایین است. این مکانیزم نقش عمده‌ای در خزش و سوپرپلاستیسیتهٔ ریز–ساختار دارد.

شبکهٔ مرزدانه‌ای در فرآیندهایی از قبیل مهاجرت مرزدانه، مهاجرت فصل مشترک سه‌تایی، چرخش دانه‌ها و فعالیت نابجایی در خود مرزدانه یا به کمک نابجایی‌های شبکه به لغزش مرزدانه نیاز دارد. مکانیزم اصلی لغزش مرزدانه‌ای حرکت نابجایی‌ها در اثر لغزش و صعود آنها در اطراف مرزدانه هاست.

میزان لغزش مرزدانه ای وابسته به تنش و نوع ماده موجب ایجاد کرنش صفر تا ۵۰ درصد می شود.

با ایجاد رسوب و فاز های سخت مثل انواع کاربیدها در مرز سه دانه و موجی کردن مرزدانه می توان جلوی این مکانیزم را گرفت.

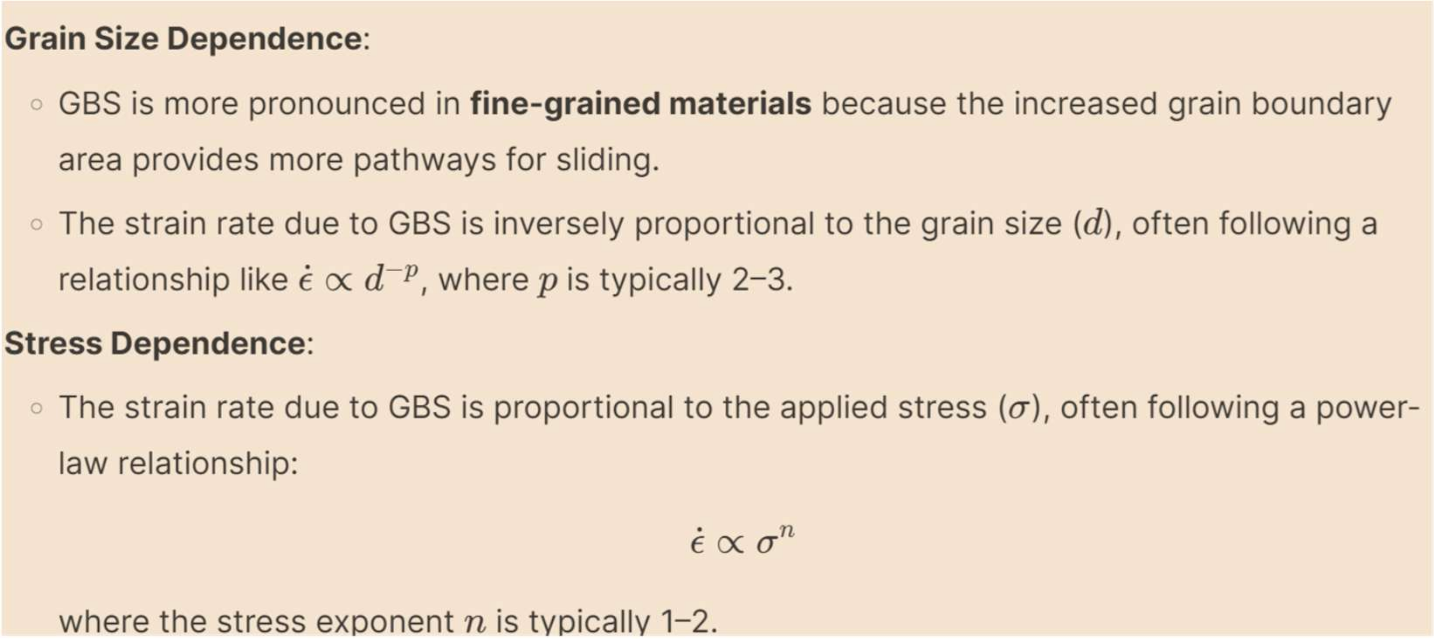
Ashby-Verrall's Model



Grain-boundary sliding assisted by diffusion in Ashby–Verrall's model.

(Reprinted with permission from M. F. Ashby and R. A. Verrall, *Acta Met.*, 21 (1973) 149.)

Grain-boundary sliding



Grain Size Dependence:

- GBS is more pronounced in **fine-grained materials** because the increased grain boundary area provides more pathways for sliding.
- The strain rate due to GBS is inversely proportional to the grain size (d), often following a relationship like $\dot{\epsilon} \propto d^{-p}$, where p is typically 2–3.

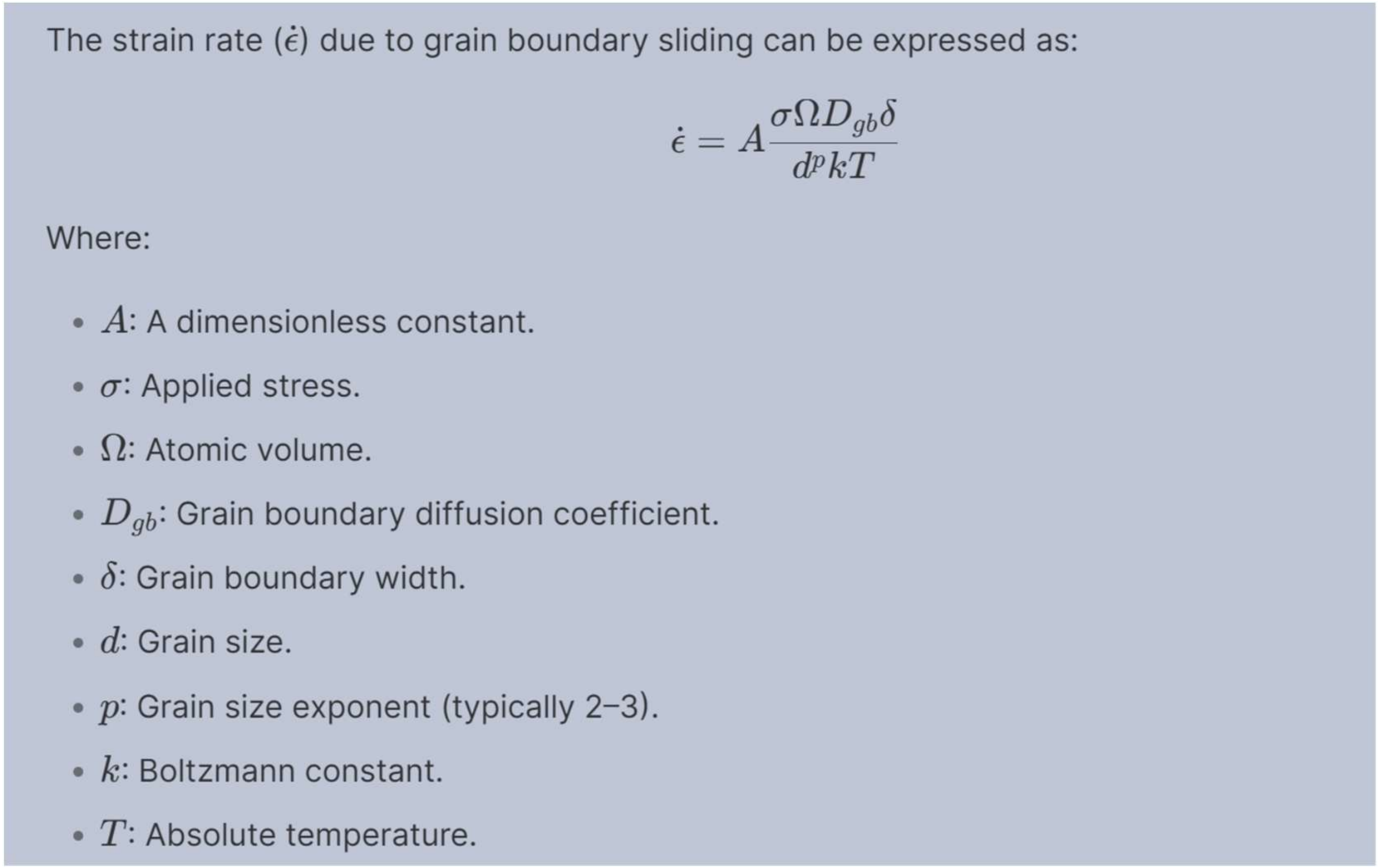
Stress Dependence:

- The strain rate due to GBS is proportional to the applied stress (σ), often following a power-law relationship:

  $$\dot{\epsilon} \propto \sigma^n$$

  where the stress exponent n is typically 1–2.

Grain-boundary sliding



The strain rate ($\dot{\epsilon}$) due to grain boundary sliding can be expressed as:

$$\dot{\epsilon} = A\frac{\sigma\Omega D_{gb}\delta}{d^p kT}$$

Where:

- A: A dimensionless constant.
- σ: Applied stress.
- Ω: Atomic volume.
- D_{gb}: Grain boundary diffusion coefficient.
- δ: Grain boundary width.
- d: Grain size.
- p: Grain size exponent (typically 2–3).
- k: Boltzmann constant.
- T: Absolute temperature.

$$\dot{\varepsilon}_{ss} = K_2(b/g)^{p'} D(\sigma/E)^2$$

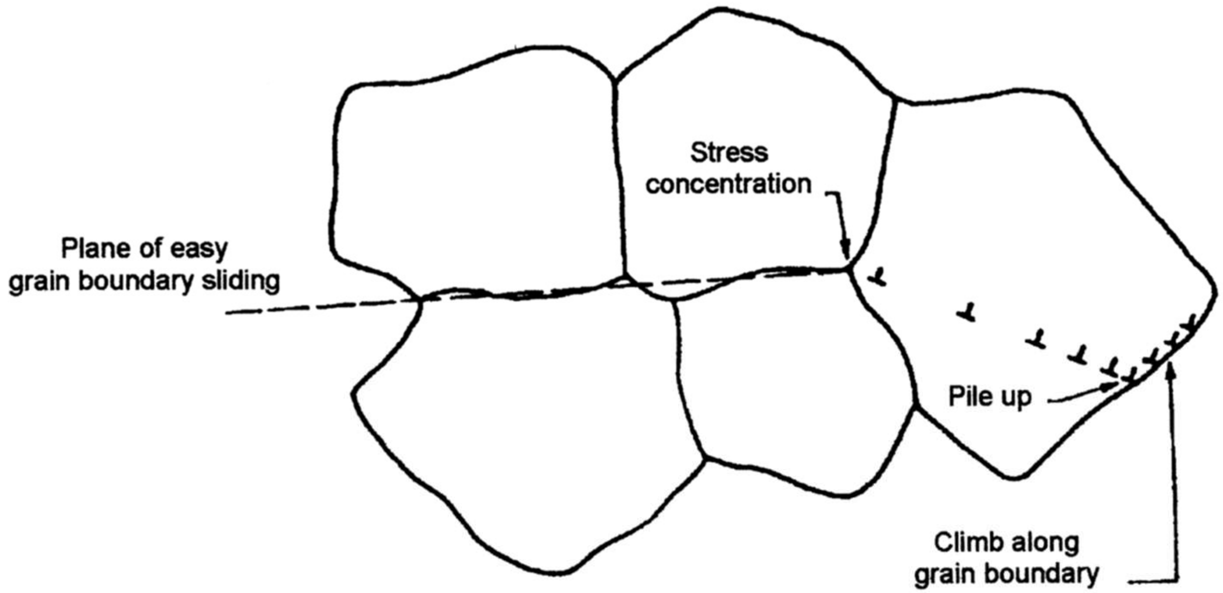


Figure 59. Ball–Hutchinson model of GBS accommodated by dislocation movement [443].

$$\dot{\varepsilon}_{ss} = K_3(b/g)^2 D_{sd}(\sigma/E)^2$$

$$\dot{\varepsilon}_{ss} = K_4(b/g)^3 D_{gb}(\sigma/E)^2$$

Superplastic flow

The ***superplastic flow*** is given by

$$\dot{\varepsilon} = 10^{8}\left(\frac{\sigma}{E}\right)^{2}\frac{bD_{gb}}{\overline{L}^{3}}$$ *Eq.3* For grain boundary diffusion

$$\dot{\varepsilon} = 2\times10^{9}\left(\frac{\sigma}{E}\right)^{2}\frac{D_{o}}{\overline{L}^{2}}$$ *Eq.3* For lattice self-diffusion

Where $\overline{L}$ is the mean linear intercept measure of grain size.
in this case ***n*** = 2, → ***m*** = 0.5

The predominant mechanism for superplasticity deformation is ***grain-boundary sliding*** accommodated by slip.

Comparison with Other Creep Mechanisms

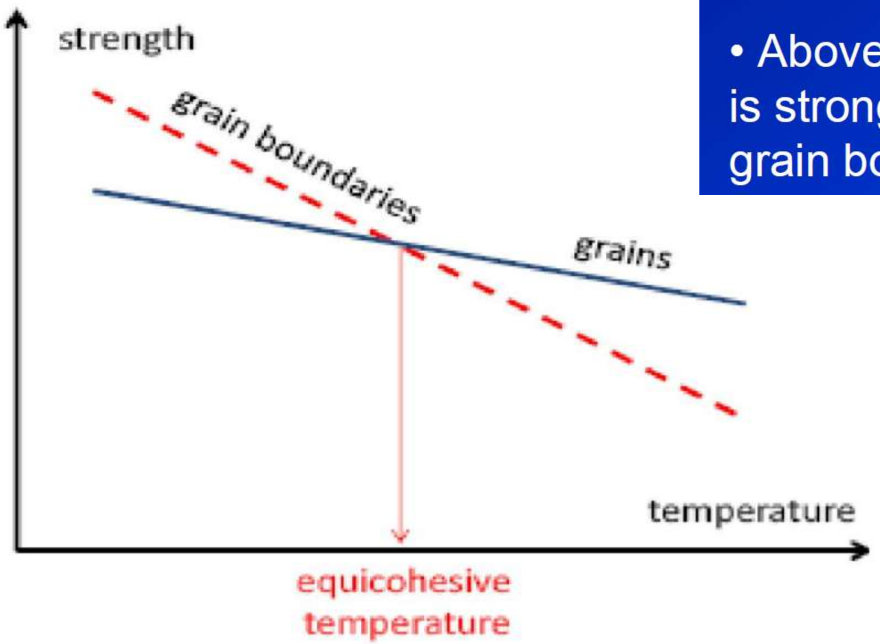
Feature	Grain Boundary Sliding (GBS)	Nabarro-Herring Creep	Coble Creep	Dislocation Creep
Dominant Mechanism	Sliding along grain boundaries	Lattice diffusion	Grain boundary diffusion	Dislocation motion
Grain Size Dependence	d^{-2} to d^{-3}	d^{-2}	d^{-3}	Weak dependence
Temperature Range	Intermediate to high	High	Intermediate to high	High
Stress Exponent (n)	1–2	1	1	3–5

در دماهای پایین مرزهای دانه مستحکم اند . با افزایش دما ، مرز های دانه شروع به ذوب شدن کرده و حالت نرم پیدا می کنند . به دلیل وجود تنش برشی اعمالی بر روی جسم و نرم شدن مرز های دانه ، مرز های دانه در کنار هم می لغزند و موجب تغییر شکل در ساختار کریستالی ماده می گردند.

Equicohesive temperature

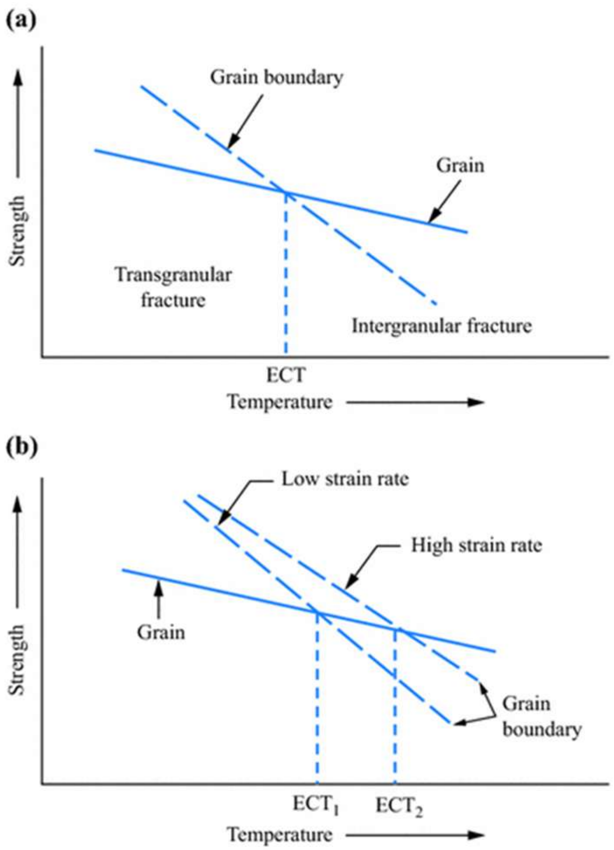
- *Strength of GB = grain at the equicohesive temperature (ECT).*

- Below ***ECT*** small grain sized material is stronger due to high density of grain boundaries to improve strength.
- Above ***ECT*** large grain sized material is stronger due to less tendency for grain boundary sliding.

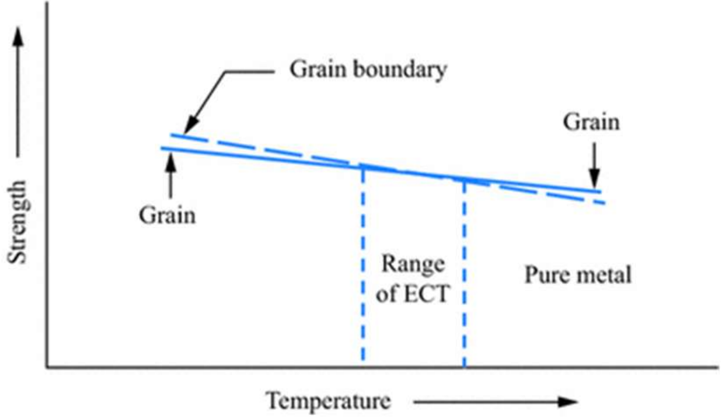


ECT ***Temp***

Transgranular fracture ←→ ***Intergranular fracture***



تاثیر درجه خلوص



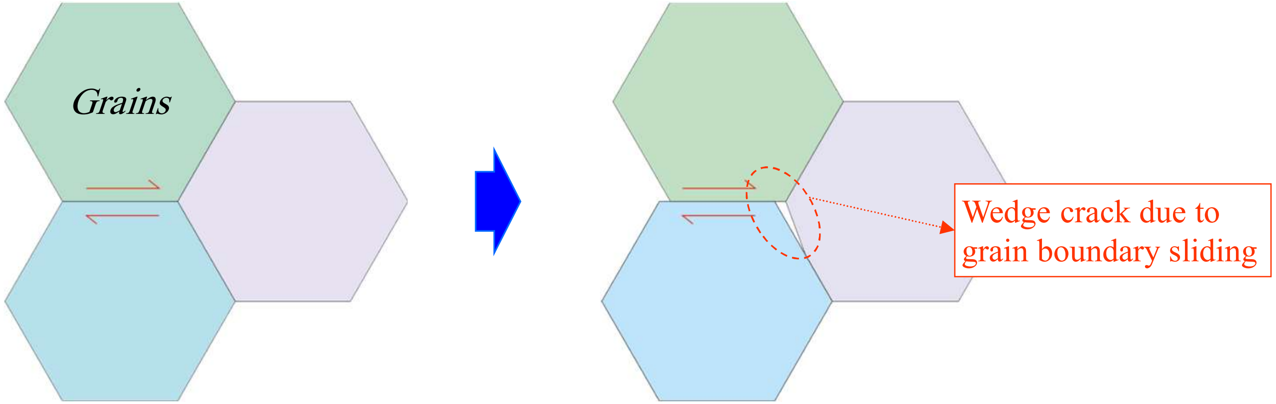
Strain rate ↓ **ECT** ↓

Increasing the tendency for intergranular failure

تاثیر سرعت کرنش

Grain boundary sliding

- ❑ At low temperatures, the grain boundaries are '*stronger*' than the crystal interior and impede the motion of dislocations.
- ❑ Being a higher energy region, the grain boundaries *pre-melt* before the crystal interior.
- ❑ Above the *equicohesive* temperature, due to shear stress at the 'local scale', grain boundaries slide past one another to cause plastic deformation.
- ❑ The relative motion of grain boundaries can lead to wedge cracks at triple lines (junction of three grains). If these wedge cracks are not healed by diffusion (or slip), microstructural damage will accumulate ,leading to specimen failure.



Chapter 2

Five-Power-Law Creep

$0.5–0.6\ T_{\mathrm{m}}$,

2.1.1 *Activation Energy and Stress Exponents*

In pure metals and Class M alloys (similar creep behavior similar to pure metals), there is an established, largely phenomenological, relationship between the steady-state strain-rate, $\dot{\varepsilon}_{ss}$, (or creep rate) and stress, σ_{ss}, for steady-state 5-power-law (PL) creep:

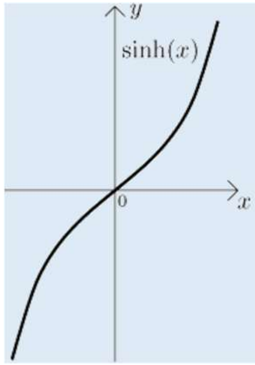
$$\dot{\varepsilon}_{ss} = A_0 \exp[-Q_c/kT](\sigma_{ss}/E)^n \tag{3}$$

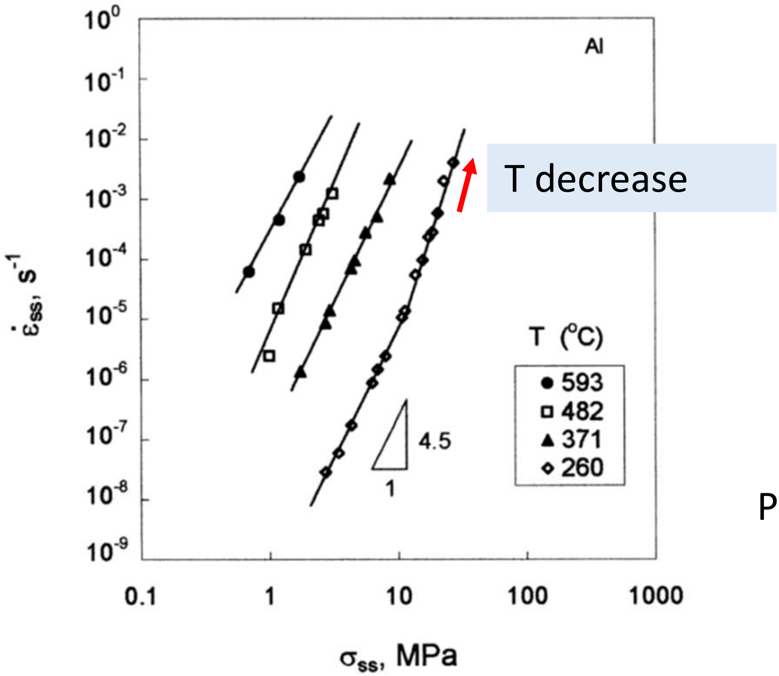
where A_0 is a constant, k is Boltzmann's constant, and E is Young's modulus (although, as will be discussed subsequently, the shear modulus, G, can also be used). This is consistent with Norton's Law [34]. The activation energy for creep, Q_c, has been found to often be about that of lattice self-diffusion, Q_{sd}. The exponent n is constant and is about 5 over a relatively wide range of temperatures and strain-rates (hence "five-power-law" behavior) power-law-breakdown (PLB) occurs, and n increases

the temperature decreases below roughly 0.5–0.6 Tm

Between this two laws:

$$\dot{\varepsilon}_{ss} = A_1 \exp[-Q_c/kT][\sinh \alpha_1(\sigma_{ss}/E)]^5$$





T decrease

Figure 7. The steady-state stress versus strain-rate for high-purity aluminum at four temperatures, from Ref. [136].

Polycrystal Single crystal

$$\sigma_{ss}/E \text{ or } \sigma_{ss}/G.$$

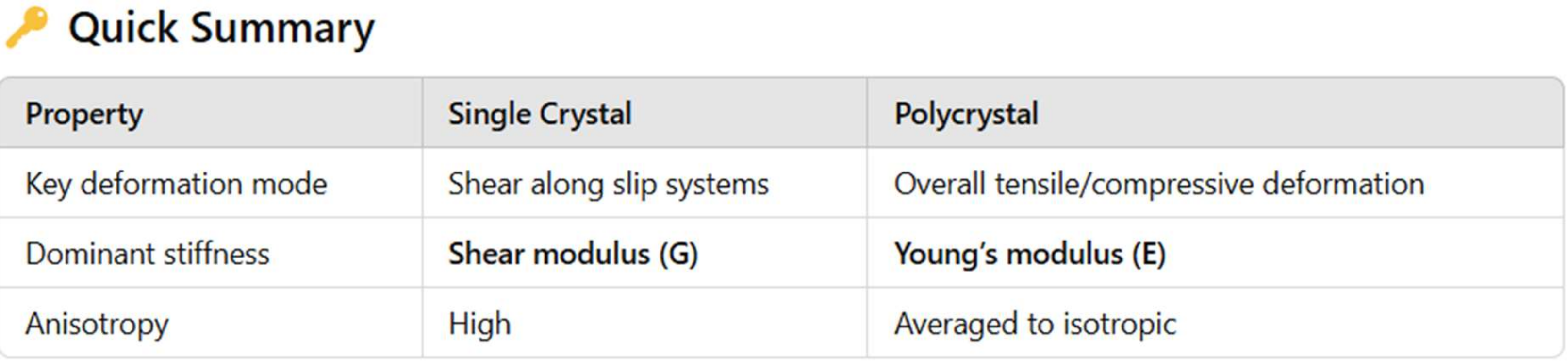
The stress exponent is about 4.5 for aluminum. Although this is not precisely five, it is constant over a range of temperature, stress, and strain-rate, and falls within the range of 4–7 observed in pure metals and class M alloys

Modulus of rigidity or shear modulus

Modulus of elasticity or Young’s modulus

$$G = \frac{E}{2\,(1 + v)}$$

$\frac{\tau}{G}$	$\frac{\sigma}{G}$	تنش مربوط به به حرکت نابه جایی با مدول برشی متناسب است بیشتر برای مواد تک بلور
	$\frac{\sigma}{E}$	تنش مربوط به به حرکت نابه جایی با مدول برشی متناسب است بیشتر برای مواد پر بلور



Quick Summary

Property	Single Crystal	Polycrystal
Key deformation mode	Shear along slip systems	Overall tensile/compressive deformation
Dominant stiffness	**Shear modulus (G)**	**Young’s modulus (E)**
Anisotropy	High	Averaged to isotropic

$$\dot{\varepsilon}_{ss} = A_2 \exp[-Q_{sd}/kT](\sigma_{ss})^{n(\cong 5)}$$

$$Q_c = -k\left[\delta(\ln\dot{\varepsilon}_{ss})/\delta(1/T)\right]_{\sigma_{ss}/E,s}$$

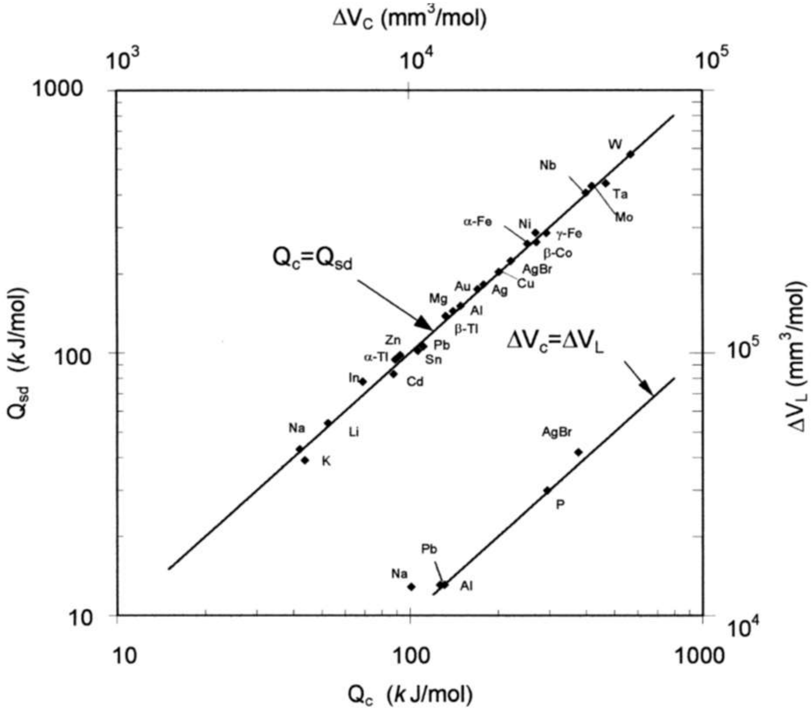
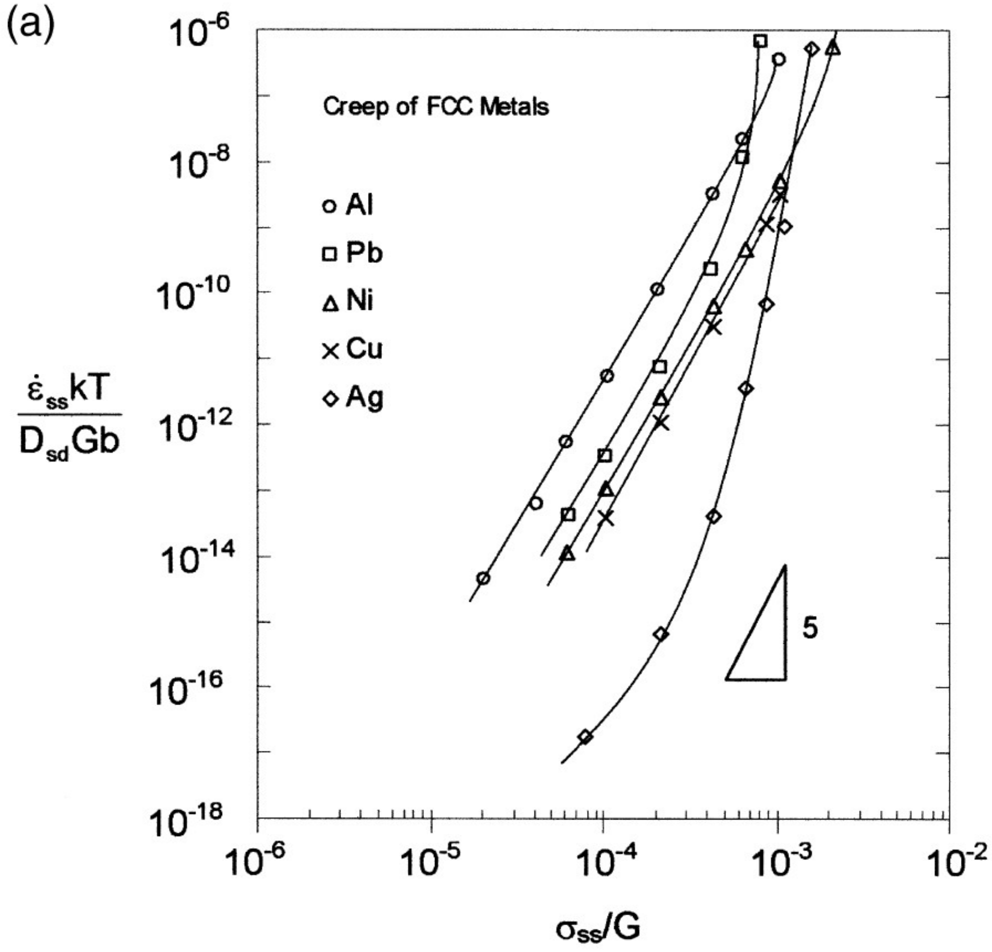


Figure 8. The activation energy and volume for lattice self-diffusion versus the activation energy and volume for creep. Data from Ref. [26].


(a)
Creep of FCC Metals
○ Al
□ Pb
△ Ni
× Cu
◇ Ag
5
$\frac{\dot{\varepsilon}_{ss}kT}{D_{sd}Gb}$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
σ_{ss}/G

Stacking Fault Energy

$$\dot{\varepsilon}_{ss} = A_6(\chi/Gb)^3(D_{sd}Gb/kT)(\sigma_{ss}/G)^5$$

where χ is the stacking fault energy.

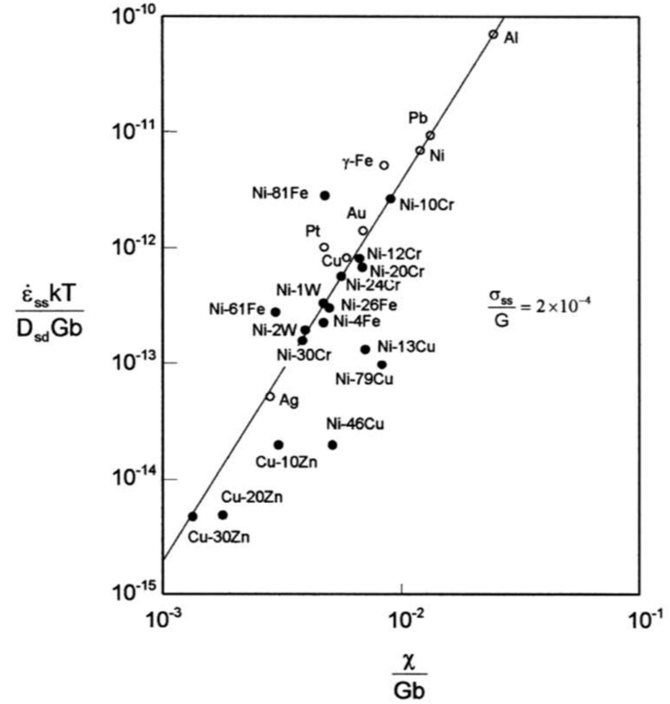


Figure 14. The effect of stacking fault energy on the (compensated) steady-state strain-rate for a variety of metals and Class M alloys based on Ref. [73].

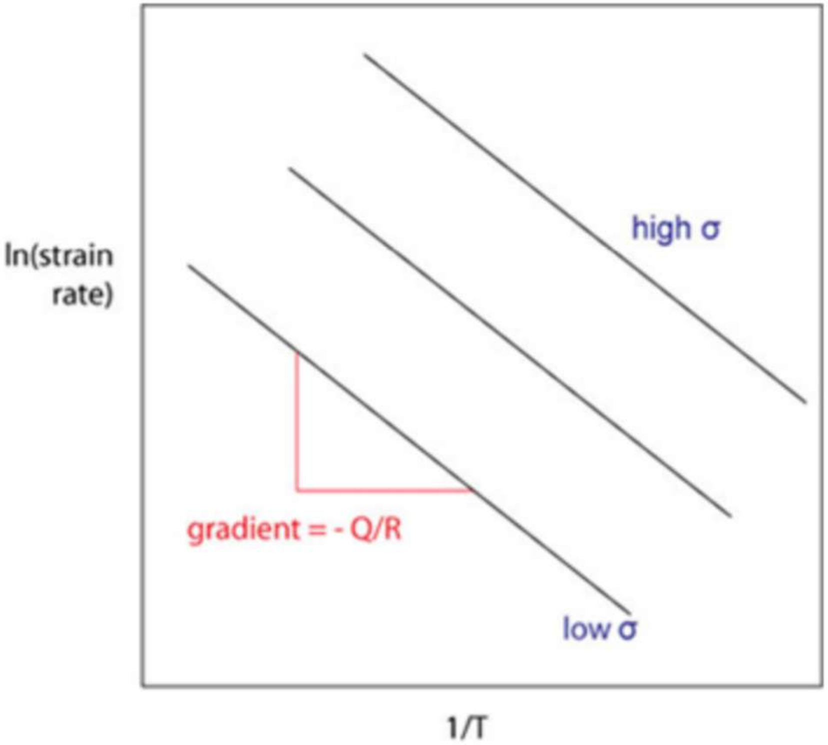
Lower SFE materials display wider stacking faults and have more difficulties for cross-slip.

The width of stacking fault is a consequence of the balance between the repulsive force between two partial dislocations

A stacking fault is created by the dissociation of a perfect dislocation into two partial dislocations.

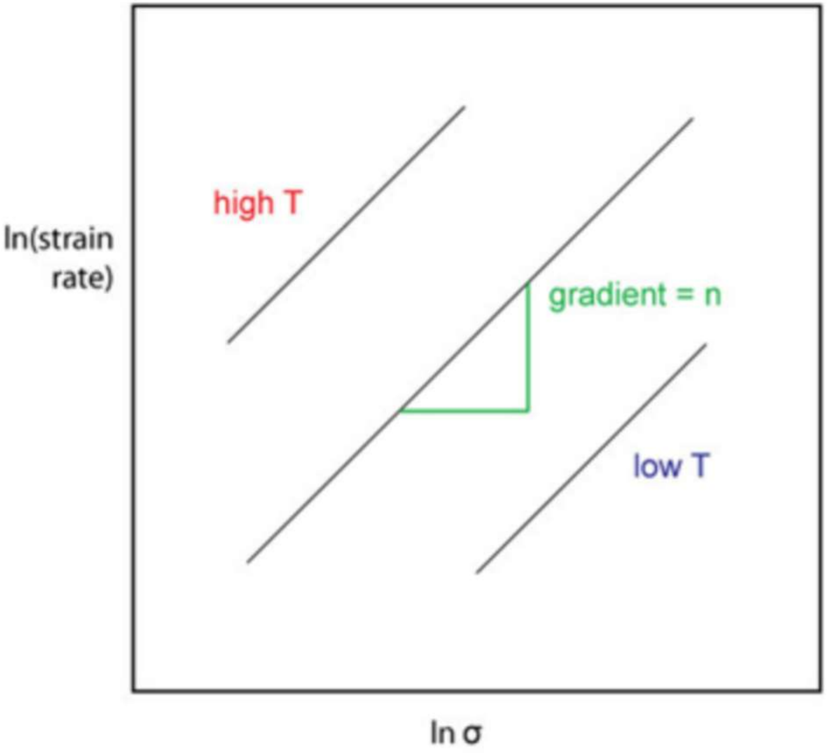
درصورتی که میزان انرژی نقض انباشتگی برای دو آلیاژ A و B به ترتیب ۱۰۰ و ۲۰۰ ارگ (erg) بر سانتی متر مربع باشد. کدامیک از آلیاژهای ذیل را در شرایط خزشی انتخاب می کنید؟ قانون خزشی برای این آلیاژها از کدام قانون پیروی می کند؟

$$\dot{\varepsilon}_{ss} = A_2 \exp[-Q_{sd}/kT](\sigma_{ss})^{n(\cong 5)}$$



The stress exponent *n* can be determined by plotting the strain rate as a function of stress.

$$\dot{\varepsilon}_{ss} = A_2 \exp[-Q_{sd}/kT](\sigma_{ss})^{n(\cong 5)}$$



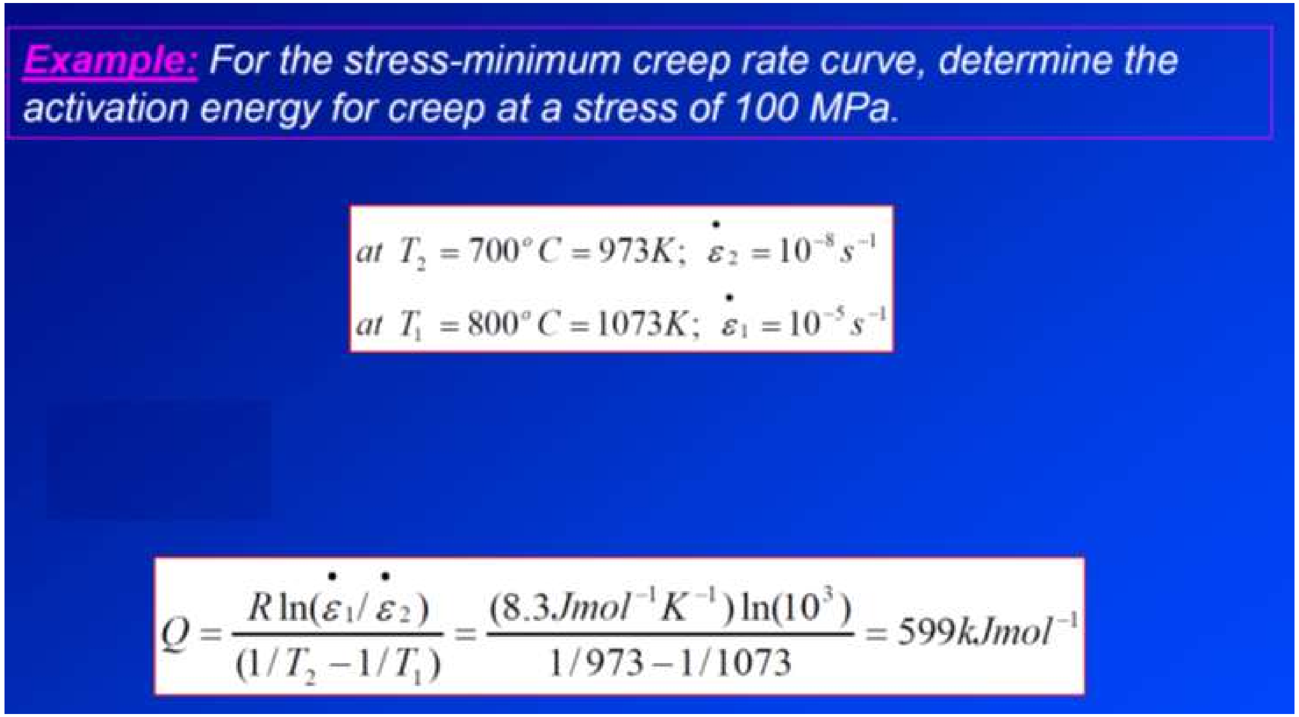
The creeping coil experiment - variable stresses in a single specimen

$$\dot{\varepsilon}_{ss} = A_2 \exp[-Q_{sd}/kT](\sigma_{ss})^{n(\cong 5)}$$

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

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

$$Q = R\left(\ln\frac{t_2}{t_1}\right)\left(\frac{T_1 \cdot T_2}{T_1 - T_2}\right)$$



Example: For the stress-minimum creep rate curve, determine the activation energy for creep at a stress of 100 MPa.

$$at\ T_2 = 700^\circ C = 973K;\ \dot{\varepsilon}_2 = 10^{-8}\,s^{-1}$$

$$at\ T_1 = 800^\circ C = 1073K;\ \dot{\varepsilon}_1 = 10^{-5}\,s^{-1}$$

$$Q = \frac{R\ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)}{(1/T_2 - 1/T_1)} = \frac{(8.3Jmol^{-1}K^{-1})\ln(10^3)}{1/973 - 1/1073} = 599kJmol^{-1}$$

Chapter 5

Three-Power-Law Viscous Glide Creep

Creep of solid solution alloys (designated Class I [16] or class A alloys [338]) at intermediate stresses and under certain combinations of materials parameters, which will be discussed later, can often be described by three regions [36,339,340]. This is illustrated in Figure 52. With increasing stress, the stress exponent, *n*, changes in value from 5 to 3 and again to 5 in regions I, II, and III, respectively. This section will focus on region II, the so-called Three-Power-Law regime.

The mechanism of deformation in region II is viscous glide of dislocations [36]. This is due to the fact that the dislocations interact in several possible ways with the solute atoms, and their movement is impeded [343]. There are two competing mechanisms over this stress range, dislocation climb and glide, and glide is slower and thus rate controlling.

The **3-power law viscous glide creep** describes a creep mechanism where **dislocations move under the influence of an external stress but are hindered by a viscous drag force**.

Nickel-based superalloys are widely used in turbine blades for **jet engines and power plants** due to their high-temperature strength and creep resistance.
At **moderate stress and high temperatures (600–900°C)**, **3-power law viscous glide creep** is often observed before power-law creep (dislocation climb) dominates at even higher stresses.

Temperature: 0.4−0.6 Tm

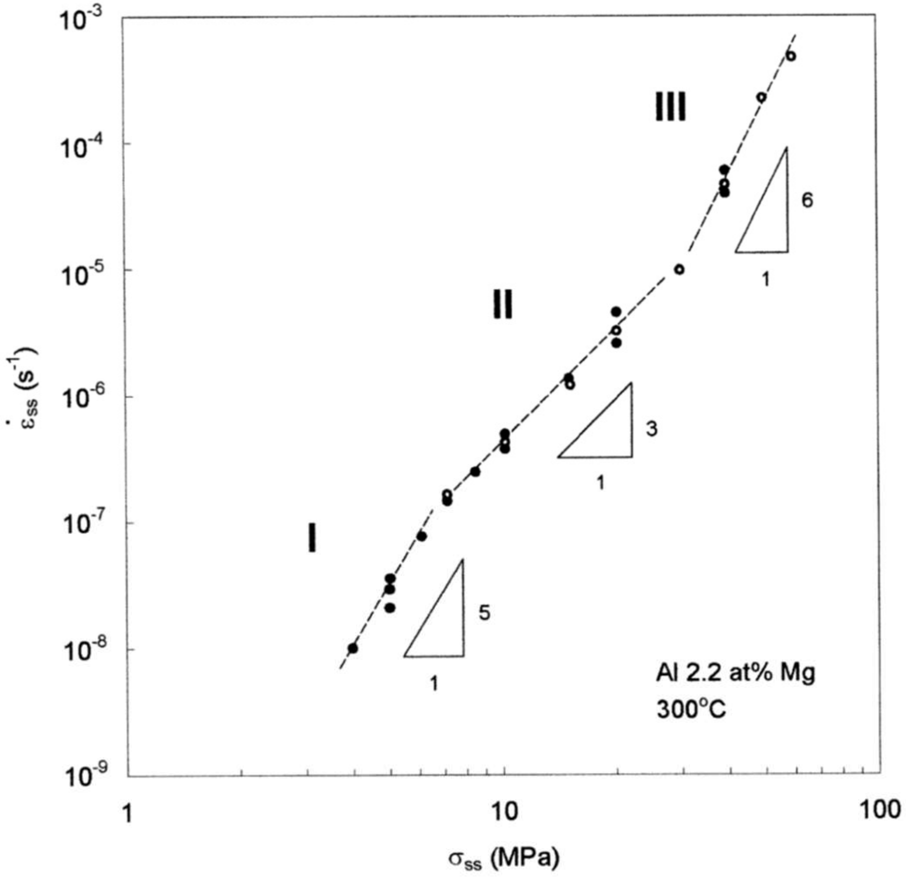


Figure 52. steady-state creep rate vs. applied stress for an Al-2.2 at%Mg alloy at 300°C. Three different creep regimes, I, II, and III, are evident. Based on Refs. [341,342].

Three-Power-Law mechanism

$\dot{\varepsilon} = 1/2\,\bar{v}\,b\,\rho_m$

$\bar{v}$ is proportional to σ

ρ_m is proportional to σ^2

$$\dot{\varepsilon}_{ss} \cong \frac{0.35}{A} G \left(\frac{\sigma}{G}\right)^3$$

Cottrell–Jaswon eq.

$$\boxed{\dot{\varepsilon}_{ss} \cong \frac{\pi(1-\nu)kT\tilde{D}}{6e^2 C b^5 G}\left(\frac{\sigma}{G}\right)^3}$$

where e is the solute–solvent size difference, C is the concentration of solute atoms and $\tilde{D}$ is the diffusion coefficient for the solute atoms, calculated using Darken's analysis.

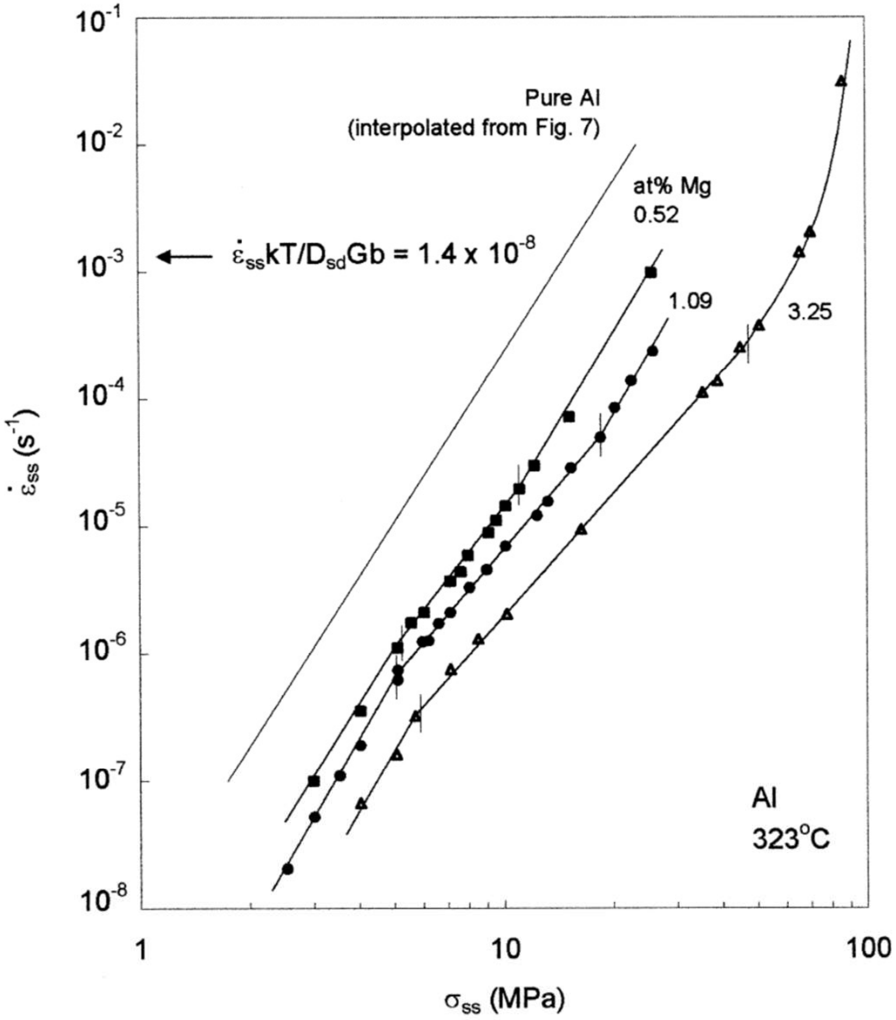


Figure 53. steady-state creep-rate vs. applied stress for three Al–Mg alloys (Al-0.52 at.%Mg, ν; Al-1.09 at.%Mg, λAl-3.25 at.%Mg, σ) at 323°C [356].

Solute drag creep

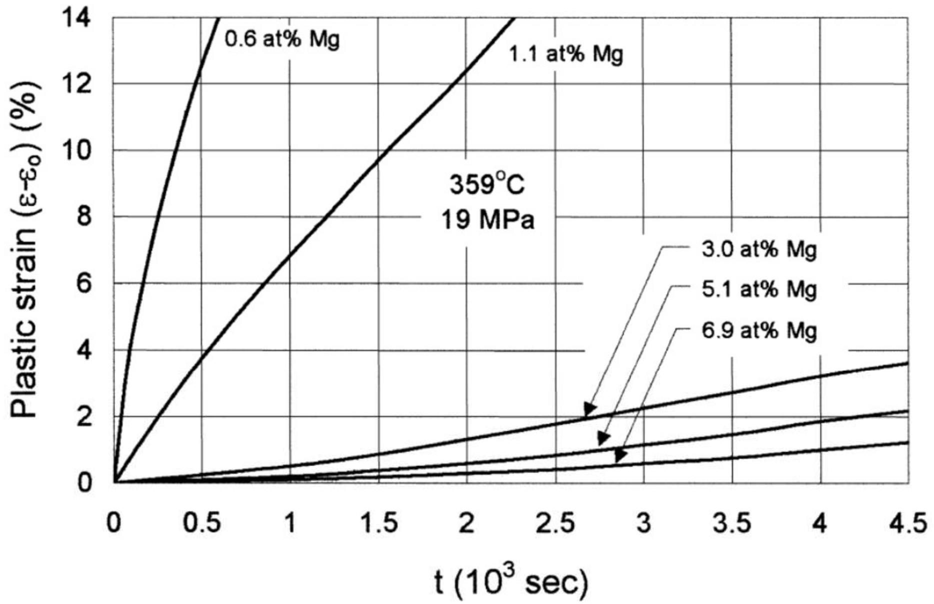
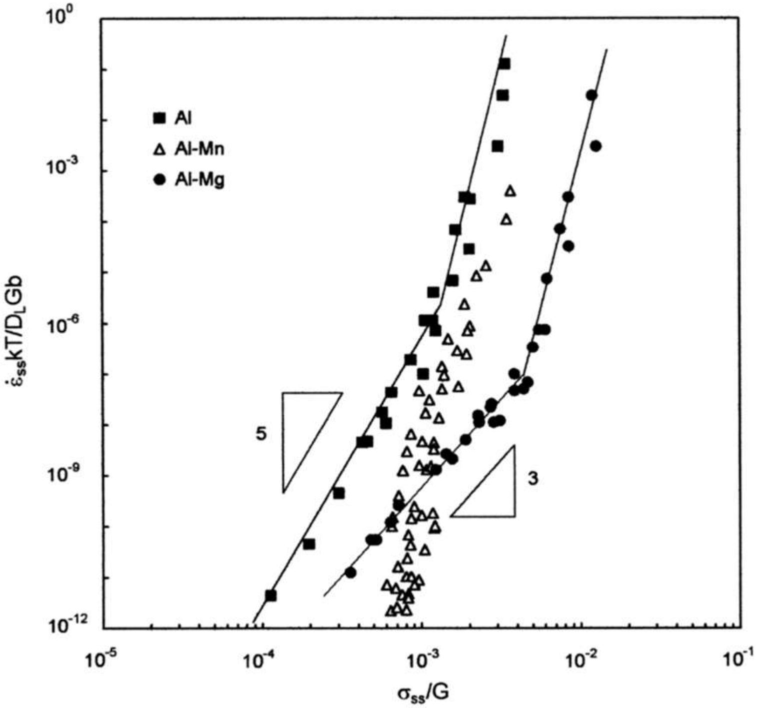


Figure 54. Creep behavior of several aluminum alloys with different magnesium concentrations: 0.6 at.% and 1.1 at.% (class II (M)) and 3.0 at.%, 5.1 at.%, and 6.9 at.% (class I (A)). The tests were performed at 359°C and at a constant stress of 19 MPa [349].

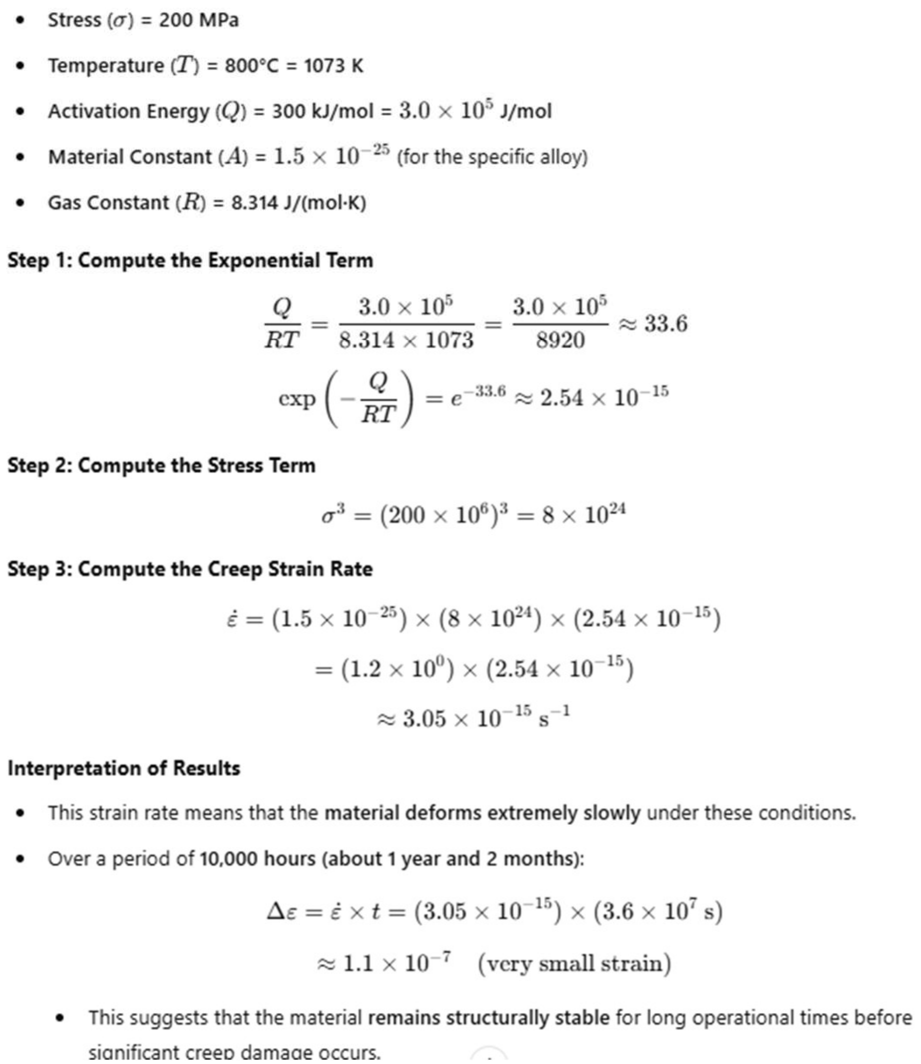


). Steady-state relation between strain-rate $\dot{\varepsilon}$ and flow stress for the alloys of this work compared to literature data from slow tests (Al, Al–Mg, Al–Mn). Adapted from Ref. [556].

Example Scenario

Consider a **nickel-based superalloy** turbine blade operating at **800°C** under a stress of **200 MPa**. We want to estimate the **creep strain rate** ($\dot{\varepsilon}$) using the 3-power law viscous glide creep equation:

$$\dot{\varepsilon} = A\sigma^3 \exp\left(\frac{-Q}{RT}\right)$$



- Stress (σ) = 200 MPa
- Temperature (T) = 800°C = 1073 K
- Activation Energy (Q) = 300 kJ/mol = 3.0×10^5 J/mol
- Material Constant (A) = 1.5×10^{-25} (for the specific alloy)
- Gas Constant (R) = 8.314 J/(mol·K)

Step 1: Compute the Exponential Term

$$\frac{Q}{RT} = \frac{3.0 \times 10^5}{8.314 \times 1073} = \frac{3.0 \times 10^5}{8920} \approx 33.6$$

$$\exp\left(-\frac{Q}{RT}\right) = e^{-33.6} \approx 2.54 \times 10^{-15}$$

Step 2: Compute the Stress Term

$$\sigma^3 = (200 \times 10^6)^3 = 8 \times 10^{24}$$

Step 3: Compute the Creep Strain Rate

$$\dot{\varepsilon} = (1.5 \times 10^{-25}) \times (8 \times 10^{24}) \times (2.54 \times 10^{-15})$$

$$= (1.2 \times 10^{0}) \times (2.54 \times 10^{-15})$$

$$\approx 3.05 \times 10^{-15} \text{ s}^{-1}$$

Interpretation of Results

- This strain rate means that the **material deforms extremely slowly** under these conditions.
- Over a period of **10,000 hours (about 1 year and 2 months)**:

$$\Delta\varepsilon = \dot{\varepsilon} \times t = (3.05 \times 10^{-15}) \times (3.6 \times 10^7 \text{ s})$$

$$\approx 1.1 \times 10^{-7} \quad \text{(very small strain)}$$

  - This suggests that the material **remains structurally stable** for long operational times before significant creep damage occurs.

Chapter 8

Creep Behavior of Particle-Strengthened Alloys

The creep behavior of second phase in the matrix:

1- Shape of precipitates

2- The coherency

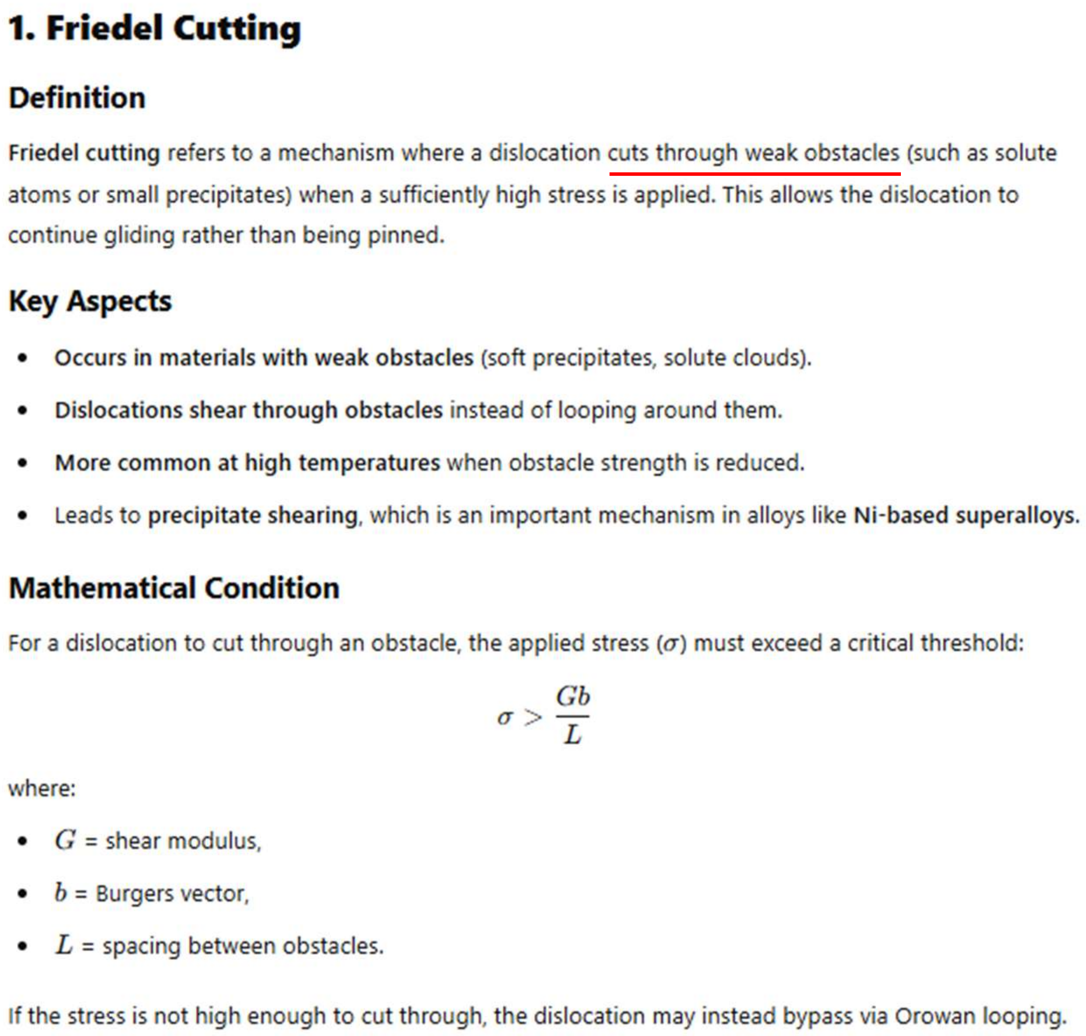
3- Volume content

4- Particle size
5- Distribution of particles

It is well known that second-phase particles provide enhanced strength at lower temperatures

Friedel cutting or Orowan by passing

Both Friedel cutting and Orowan bypassing describe how dislocations overcome obstacles in a material, playing a crucial role in dislocation motion, strengthening mechanisms, and creep behavior.



1. Friedel Cutting

Definition

Friedel cutting refers to a mechanism where a dislocation cuts through weak obstacles (such as solute atoms or small precipitates) when a sufficiently high stress is applied. This allows the dislocation to continue gliding rather than being pinned.

Key Aspects

- **Occurs in materials with weak obstacles** (soft precipitates, solute clouds).
- **Dislocations shear through obstacles** instead of looping around them.
- **More common at high temperatures** when obstacle strength is reduced.
- Leads to **precipitate shearing**, which is an important mechanism in alloys like **Ni-based superalloys.**

Mathematical Condition

For a dislocation to cut through an obstacle, the applied stress (σ) must exceed a critical threshold:

$$\sigma > \frac{Gb}{L}$$

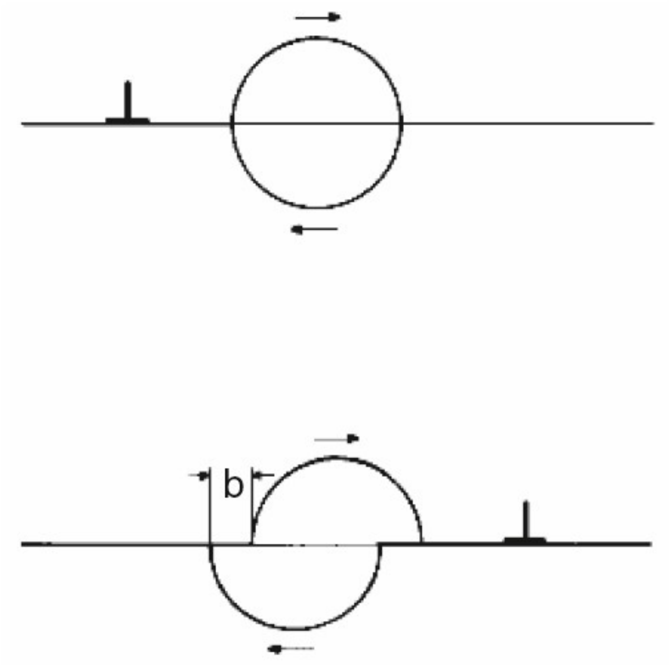
where:

- G = shear modulus,
- b = Burgers vector,
- L = spacing between obstacles.

If the stress is not high enough to cut through, the dislocation may instead bypass via Orowan looping.

Friedel cutting: Dislocation is passing through particle and shifts its upper part with respect to the lower part. Extra surface energy has to be generated which limits this process to small particles.

Friedel cutting is possible for small and coherent particles only due to the extra surface energy which has to be raised when cutting the particle.



2. Orowan Bypassing

Definition

Orowan bypassing (or the **Orowan mechanism**) describes how a dislocation bypasses strong obstacles (such as hard precipitates) by looping around them, leaving behind **dislocation loops**.

Key Aspects

- **Occurs in materials with strong obstacles** (e.g., hard precipitates in aluminum or nickel alloys).
- **Dislocations bow around the obstacle** due to applied stress.
- Forms a **dislocation loop** around the precipitate, increasing material strength.

Mathematical Condition

For a dislocation to bypass an obstacle, the applied stress (σ) must be high enough to bend the dislocation into a loop:

$$\sigma > \frac{Gb}{r}$$

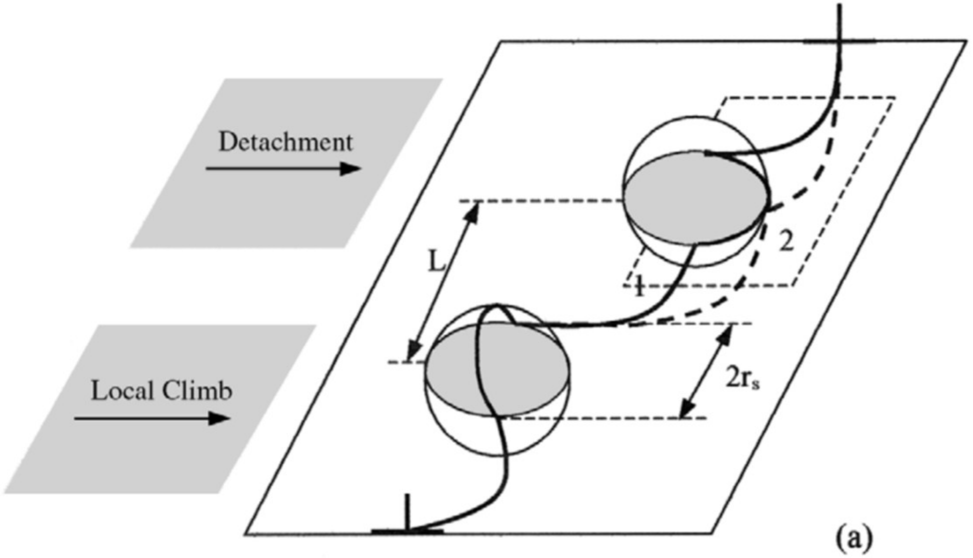
where:

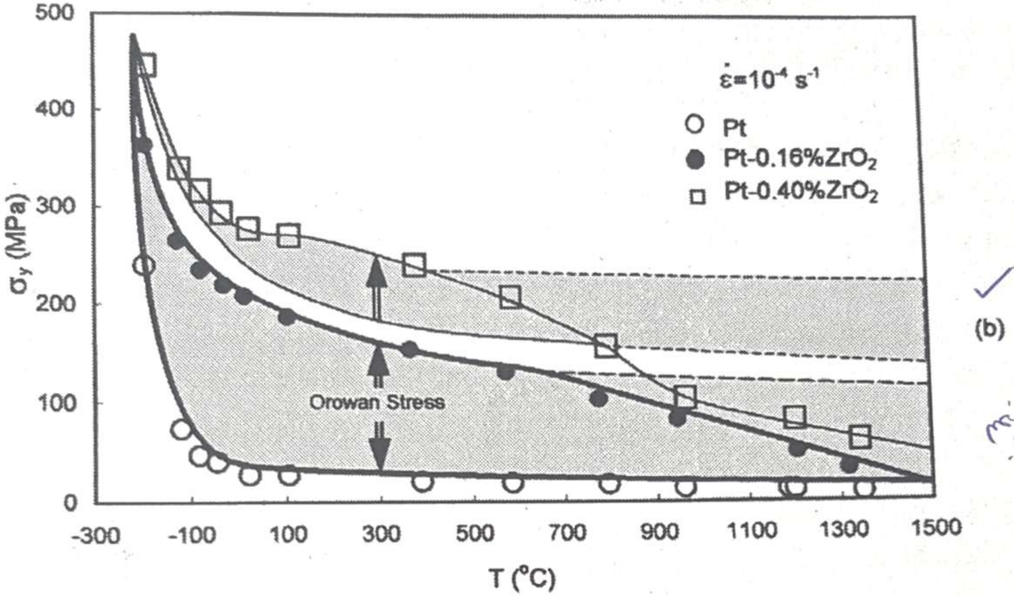
- r = obstacle radius (smaller obstacles require higher stress).

Since the bypassed obstacle remains intact, the **Orowan mechanism leads to precipitation strengthening** and is key in high-strength materials.

Orowan by passing

The Orowan stress is determined by the bypass stress based on an Orowan loop mechanism
Strengthening from coherent particles can occur in a variety of ways that usually involve particle cutting.





کاهش استحکام با تأخیر
صورت می‌گیرد به دلیل سخت شدن
حرکت نابجایی ها ✓
و حضور رسوبات باعث تغییر
مکانیزم خزش مانند قانون توان پنجم
را لغو می‌کند.

Figure 68. Compressive 0.2% yield stress versus temperature. Shaded: Orowan stress given as low-temperature yield-stress increment due to oxide dispersoids. (a) ODS Superalloy MA 754, (b) Pt-based ODS alloys. From Ref. [544].

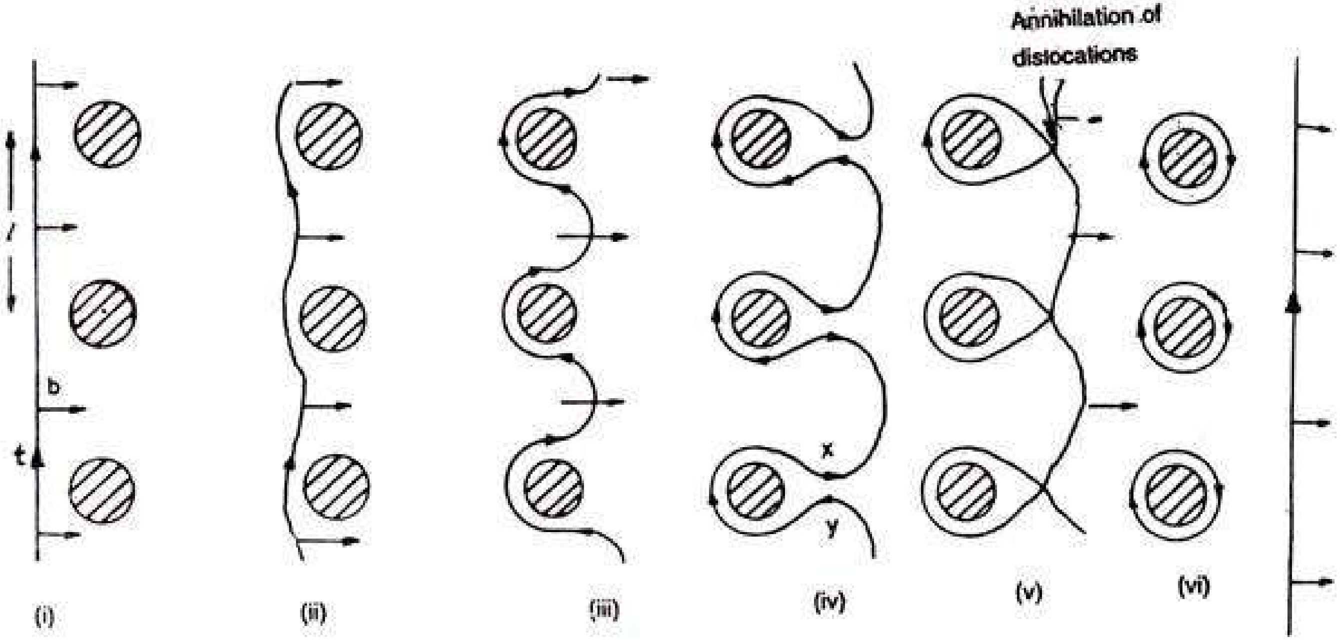


Fig. 13.10. Interaction of a dislocation with a row of widely spaced precipitates to bypass them

وقتی که ذرات رسوبی و زمینه دارای شبکه کریستالی مشابه باشد - بهطور مثال دارای اختلاف پارامتر شبکه در حدود ۰/۲ درصد- در این حالت رسوب با زمینه هم سیما بوده و نابجاییها میتوانند از روی سطح رسوب عبور کنند.

اما اگر رسوب با زمینه هم سیما نباشد در این صورت رفتار نابجایی با رسوب دو حالت دارد. اگر اندازه ذرات کوچک باشد نابجایی به صورت برش و اگر بزرگ باشد نابجایی رسوب را دور میزند.

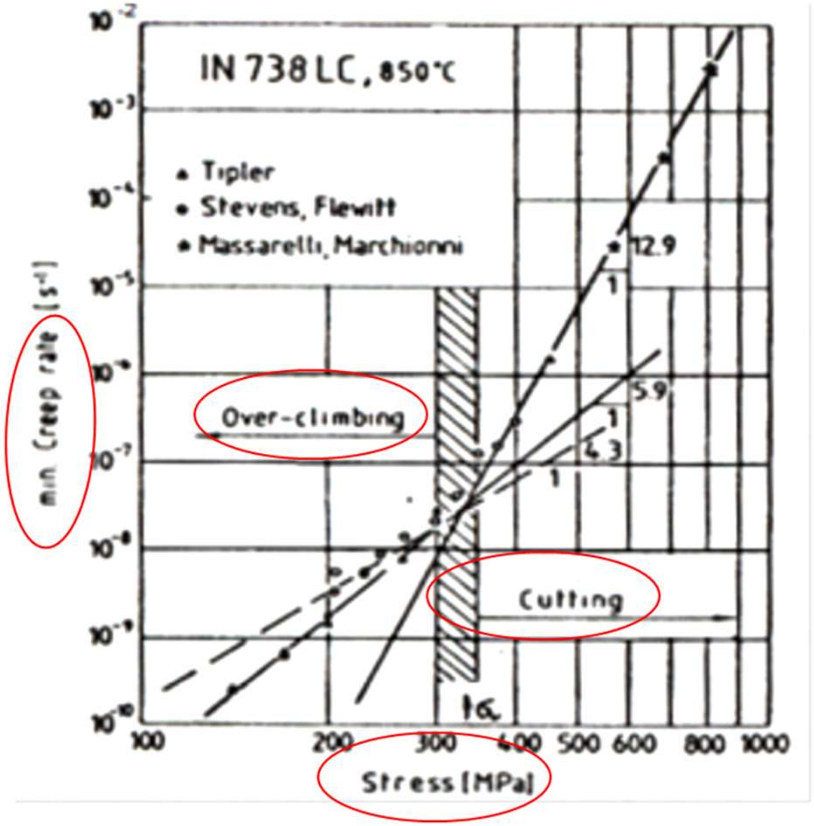
زمانی‌که رسوب درشت باشد امکان برش آنها با انرژی بیشتری رخ میدهد که کمتر اتفاق میافتد و نابجایی سعی می‌کند با دور زدن و تشکیل حلقههای اروان از ذره عبور کند.

Friedel Cutting vs. Orowan Bypassing

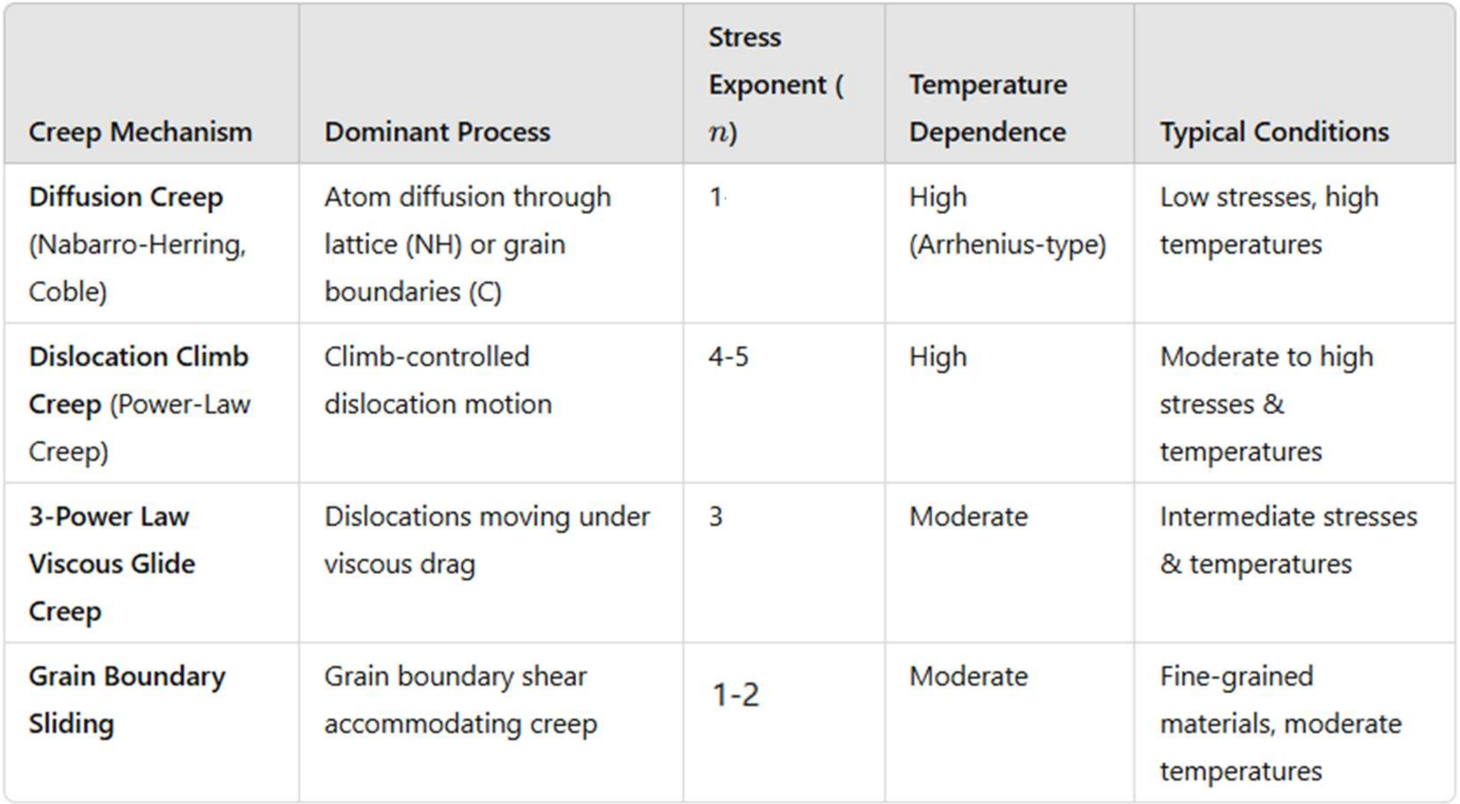
Mechanism	Obstacle Strength	Outcome
Friedel Cutting	Weak obstacles (shearable)	Dislocation cuts through, no loops
Orowan Bypassing	Strong obstacles (non-shearable)	Dislocation loops around

Real-World Examples

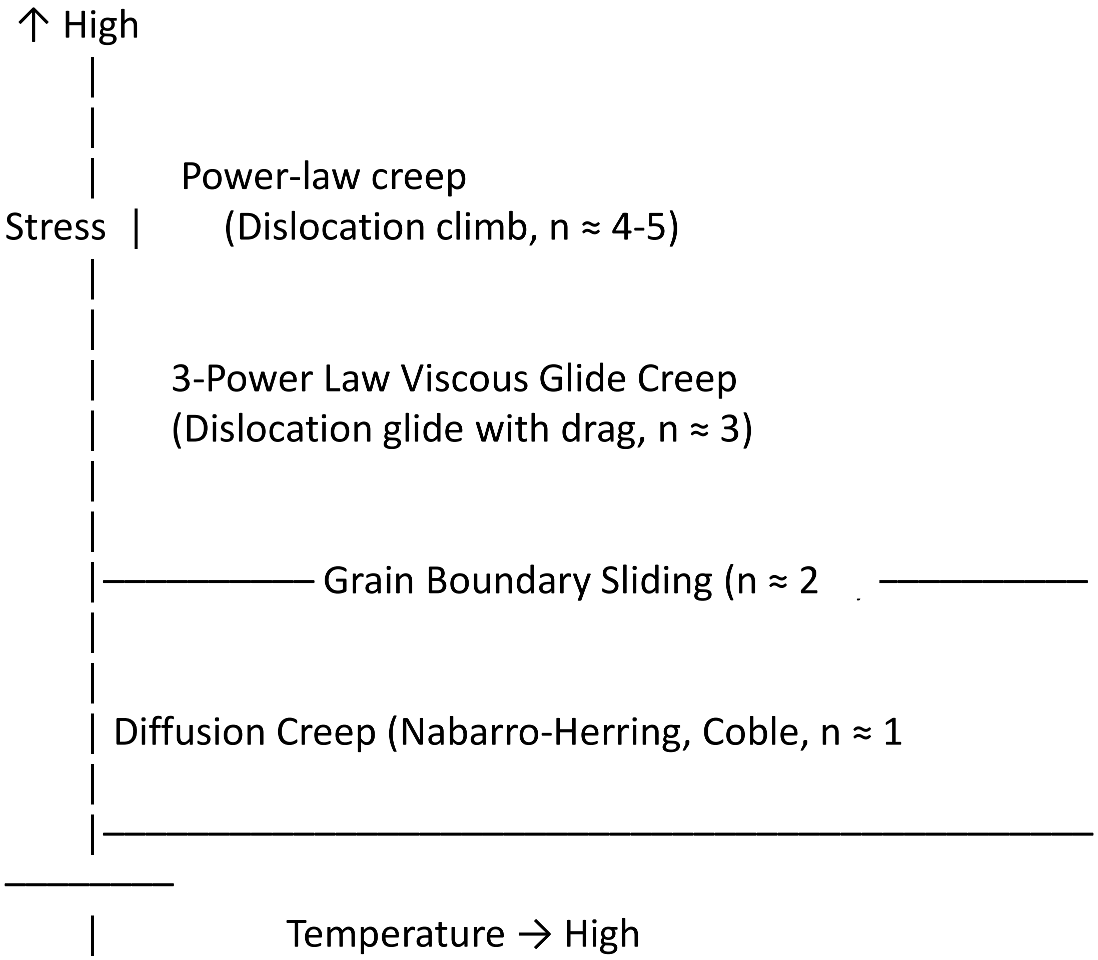
- **Friedel cutting:** In **Ni-based superalloys**, small γ' precipitates can be sheared by dislocations at high temperatures.
- **Orowan bypassing:** In **Al-Mg alloys**, strong second-phase particles cause dislocations to bow and form loops, strengthening the material.



تصویر ۱۷. تغییر مکانیزم خزشی در تنش aPM ۳۰۰ با توجه به تغییرات تنش در دمای ºC ۸۵۰ برای سوپرآلیاژ IN۷۳۸LC [۳۱].



Creep Mechanism	Dominant Process	Stress Exponent (n)	Temperature Dependence	Typical Conditions
Diffusion Creep (Nabarro-Herring, Coble)	Atom diffusion through lattice (NH) or grain boundaries (C)	1	High (Arrhenius-type)	Low stresses, high temperatures
Dislocation Climb Creep (Power-Law Creep)	Climb-controlled dislocation motion	4-5	High	Moderate to high stresses & temperatures
3-Power Law Viscous Glide Creep	Dislocations moving under viscous drag	3	Moderate	Intermediate stresses & temperatures
Grain Boundary Sliding	Grain boundary shear accommodating creep	1-2	Moderate	Fine-grained materials, moderate temperatures



↑ High

Stress

Power-law creep
(Dislocation climb, n ≈ 4-5)

3-Power Law Viscous Glide Creep
(Dislocation glide with drag, n ≈ 3)

Grain Boundary Sliding (n ≈ 2

Diffusion Creep (Nabarro-Herring, Coble, n ≈ 1

Temperature → High

Mechanism	D	n	A
Climb of edge dislocations	D_L	5	$6x10^7$
(Pure Metals and class-M alloys)	(n function of Xal structure & Γ)*		
PLB Low-temperature climb	$D_\perp$	7	$2x10^8$
Viscous glide (Class-I alloys - microcreep)	D_s	3	6
Nabarro-Herring	D_L	1	$14\,(\frac{b}{d})^2$
Coble	D_b	1	$100\,(\frac{b}{d})^3$
Harper-Dorn	D_L	1	$3x10^{-10}$
GBS (superplasticity)	D_b	2	$200\,(\frac{b}{d})^2$

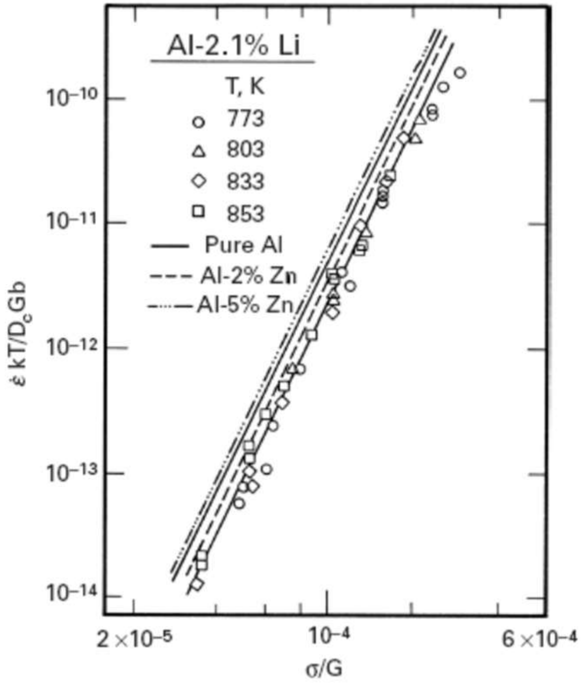
D_L = lattice diffusivity; D_s = solute diffusivity; $D_\perp$ = core diffusivity;

D_b = Grain-Boundary Diffusivity; b = Burgers vector; d = grain size;

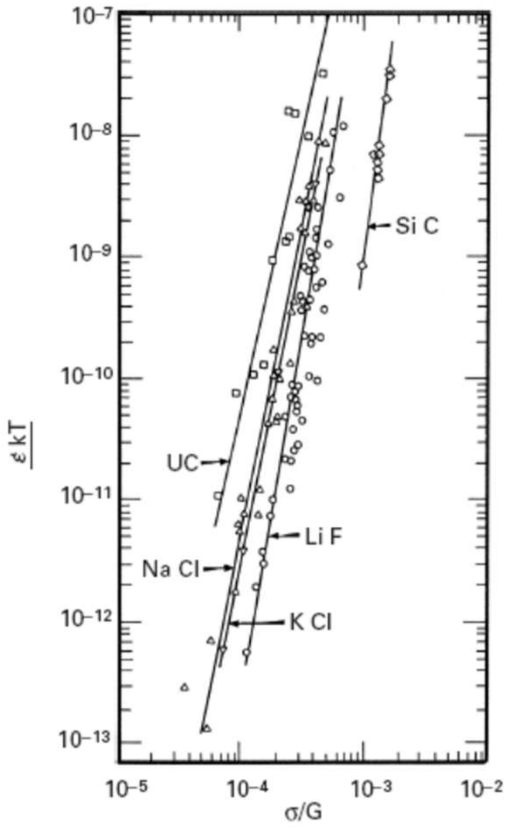
δ = subgrain size = $10\,\frac{Gb}{\tau}$ and $\rho = \frac{\sigma^2}{G^2b^2}$ where G is the shear modulus

*n increases with decreasing Γ (stacking-fault energy)

Mukherjee-Bird-Dorn Equation

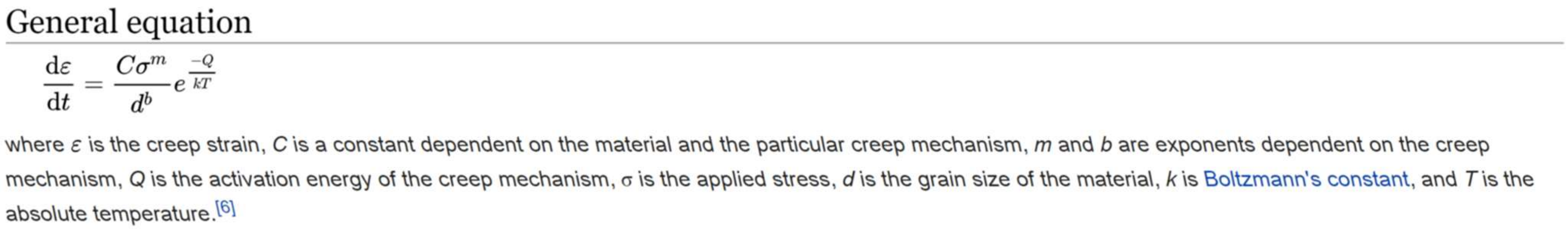


(a)



(b)

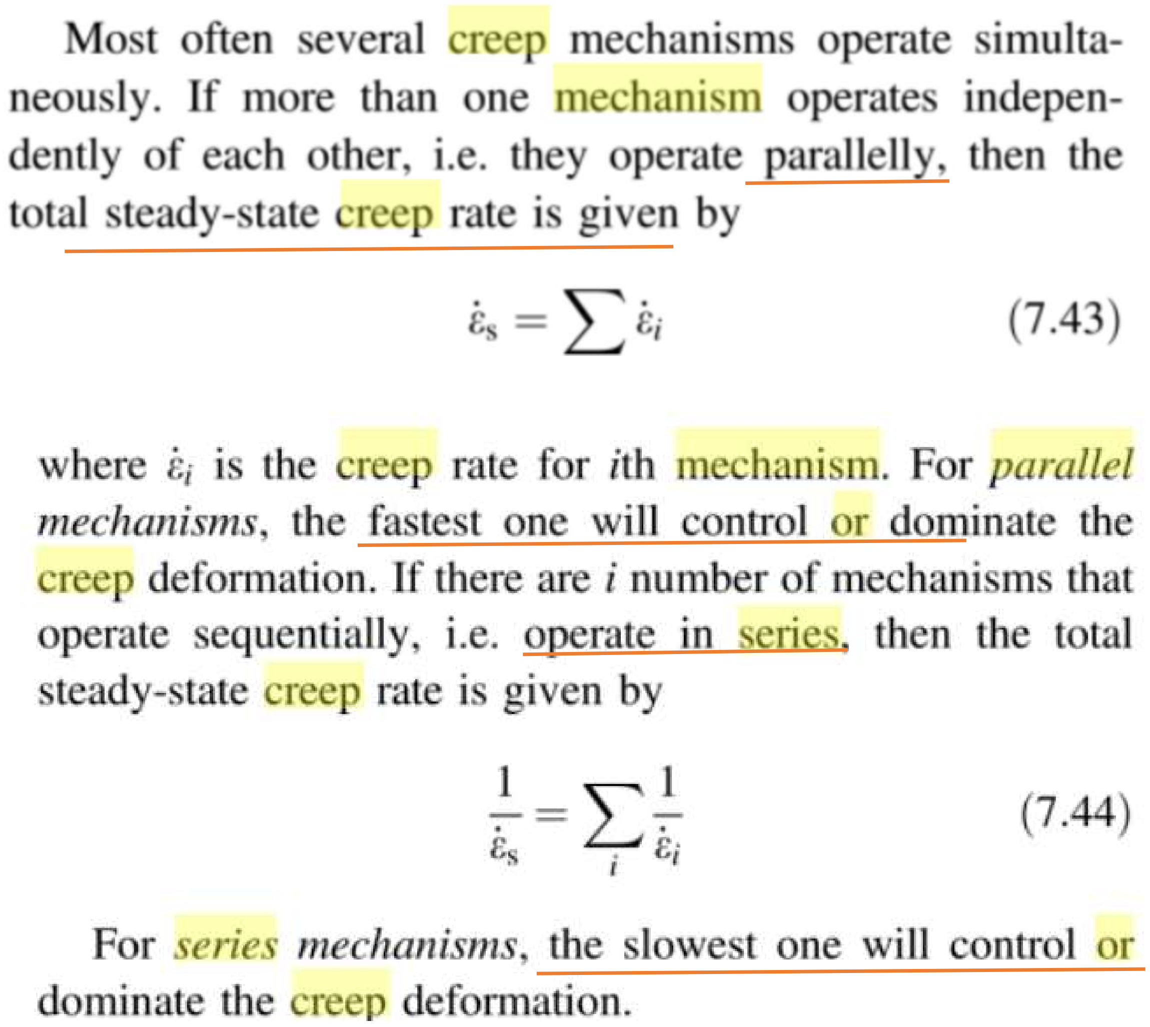
$$\dot{\varepsilon}_s = \frac{AGb}{kT} D_0 \exp(-Q_c/RT)\left(\frac{b}{d}\right)^p \left(\frac{\sigma}{G}\right)^n$$



General equation

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{C\sigma^m}{d^b} e^{\frac{-Q}{kT}}$$

where ε is the creep strain, C is a constant dependent on the material and the particular creep mechanism, m and b are exponents dependent on the creep mechanism, Q is the activation energy of the creep mechanism, σ is the applied stress, d is the grain size of the material, k is Boltzmann's constant, and T is the absolute temperature.[6]



Most often several creep mechanisms operate simultaneously. If more than one mechanism operates independently of each other, i.e. they operate parallelly, then the total steady-state creep rate is given by

$$\dot{\varepsilon}_s = \sum \dot{\varepsilon}_i \tag{7.43}$$

where $\dot{\varepsilon}_i$ is the creep rate for ith mechanism. For *parallel mechanisms*, the fastest one will control or dominate the creep deformation. If there are i number of mechanisms that operate sequentially, i.e. operate in series, then the total steady-state creep rate is given by

$$\frac{1}{\dot{\varepsilon}_s} = \sum_i \frac{1}{\dot{\varepsilon}_i} \tag{7.44}$$

For *series mechanisms*, the slowest one will control or dominate the creep deformation.

t total= t1=t2=t3

ϵ total= ϵ 1+ ϵ 2+ ϵ3

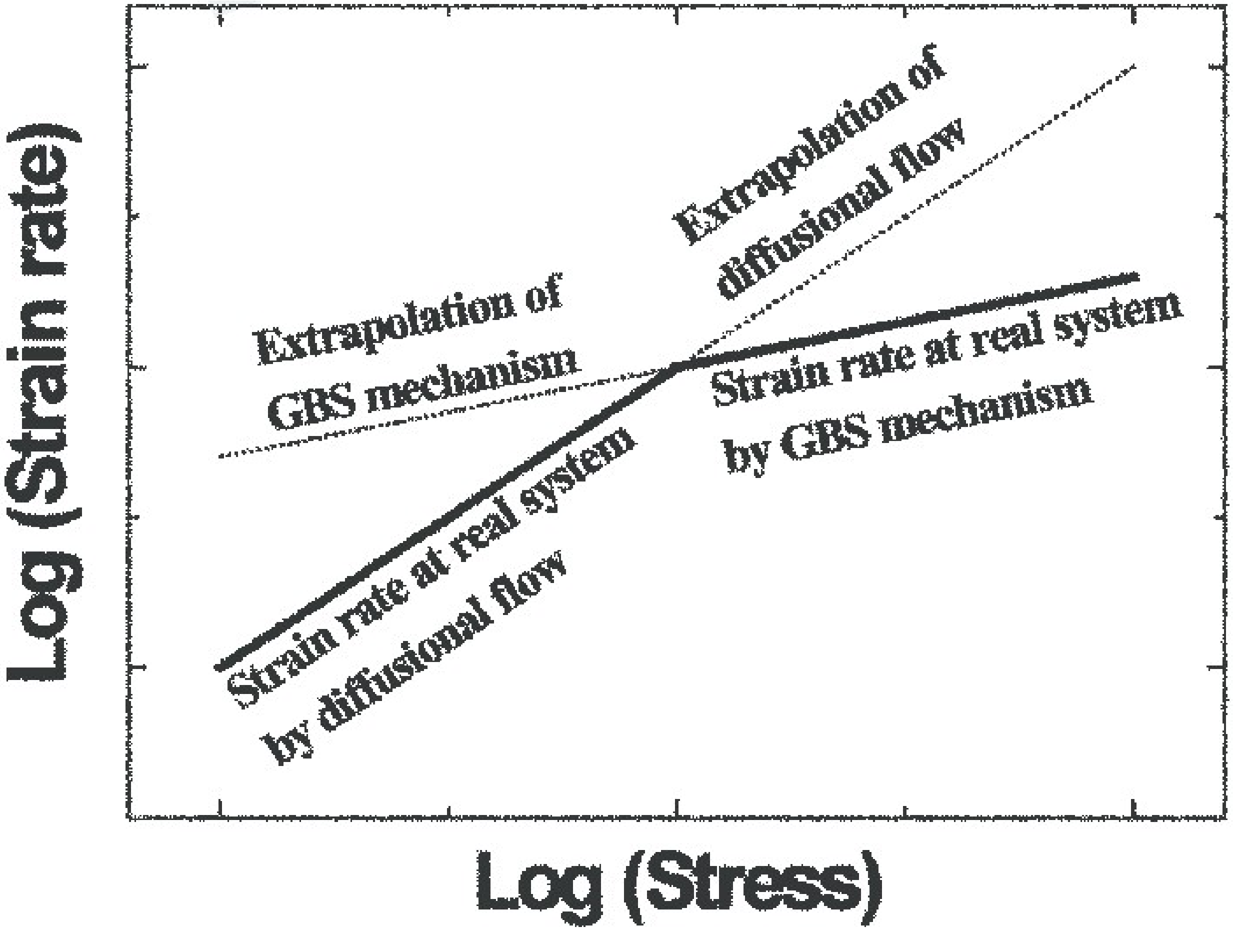
- Many different mechanisms may contribute and the total strain-rate :

parallel mechanism
(fastest controls / dominates)

$$\dot{\varepsilon} = \sum_{\mathrm{i}} \dot{\varepsilon}_{\mathrm{i}}$$

series mechanisms
(slower controls / dominates)

$$\dot{\varepsilon} = \sum \left(\frac{1}{\dot{\varepsilon}_i} \right)^{-1}$$


Log (Strain rate)
Log (Stress)
Extrapolation of diffusional flow
Extrapolation of GBS mechanism
Strain rate at real system by GBS mechanism
Strain rate at real system by diffusional flow

فرآیندهای سری: مکانیزم‌های خزشی به هم وابسته هستند

$$\dot{\varepsilon}_t^{-1} = \sum_{i=1}^{n} \frac{1}{\dot{\varepsilon}_i}$$

$$\dot{\varepsilon} = \frac{\varepsilon}{t} \longrightarrow t = \frac{\varepsilon}{\dot{\varepsilon}}$$

$$t_{total} = t_1 + t_2 + t_3$$

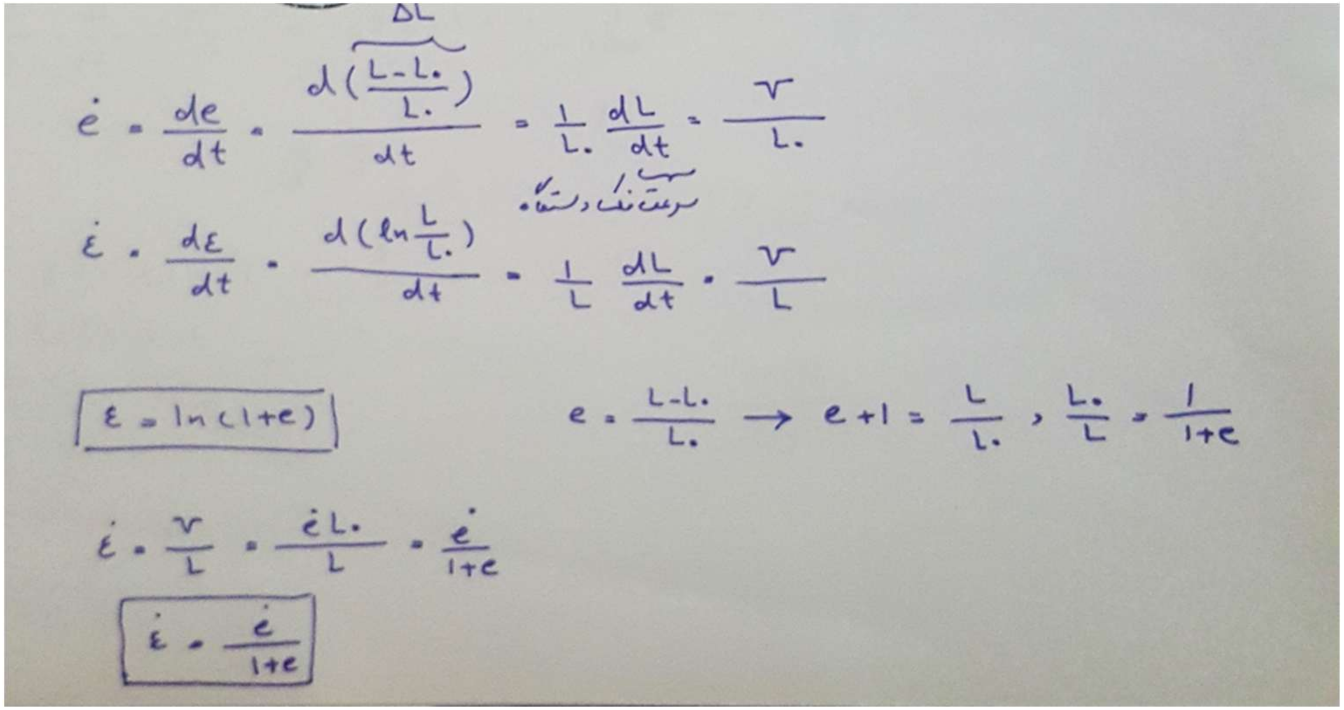
$$\frac{\varepsilon}{\dot{\varepsilon}} = \frac{\varepsilon}{\dot{\varepsilon}_1} + \frac{\varepsilon}{\dot{\varepsilon}_2} + \frac{\varepsilon}{\dot{\varepsilon}_3} \Rightarrow \frac{1}{\dot{\varepsilon}} = \frac{1}{\dot{\varepsilon}_1} + \frac{1}{\dot{\varepsilon}_2} + \frac{1}{\dot{\varepsilon}_3}$$

فرآیندهای موازی: به صورت جداگانه انجام می‌شوند و همزمان می‌توانند فعال شوند)

$$\dot{\varepsilon}_t = \sum_{i=1}^{n} \dot{\varepsilon}_i$$

$$t = t_1 = t_2 = t_3$$

$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \longrightarrow \dot{\varepsilon}\cancel{t} = \dot{\varepsilon}_1\cancel{t} + \dot{\varepsilon}_2\cancel{t} + \dot{\varepsilon}_3 t \longrightarrow \dot{\varepsilon} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2 + \dot{\varepsilon}_3$$



$$\dot{e} = \frac{de}{dt} = \frac{d\left(\frac{\overbrace{L-L_0}^{\Delta L}}{L_0}\right)}{dt} = \frac{1}{L_0}\underbrace{\frac{dL}{dt}}_{\text{سرعت فک دستگاه.}} = \frac{v}{L_0}$$

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{d\left(\ln\frac{L}{L_0}\right)}{dt} = \frac{1}{L}\frac{dL}{dt} = \frac{v}{L}$$

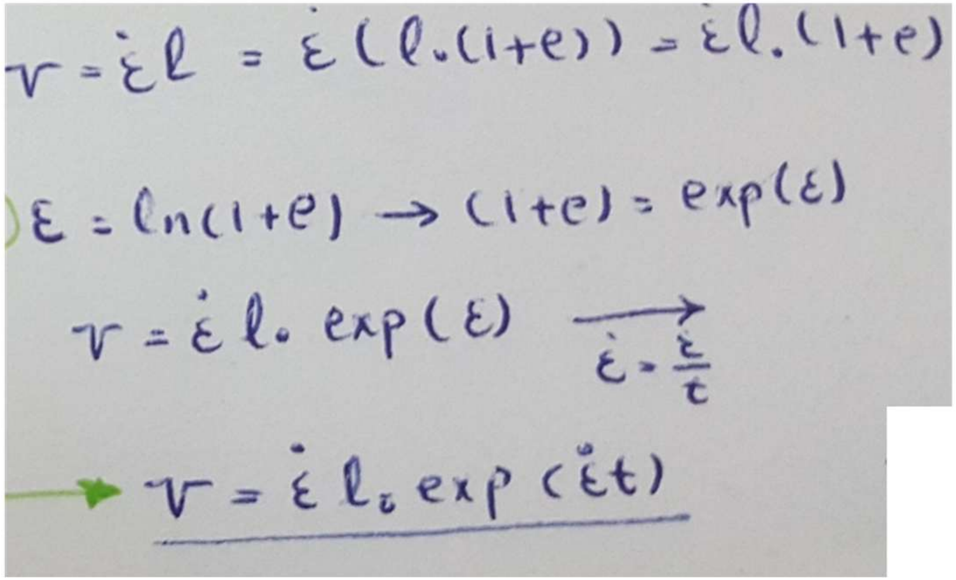
$$\boxed{\varepsilon = \ln(1+e)}$$

$$e = \frac{L-L_0}{L_0} \rightarrow e+1 = \frac{L}{L_0} \, , \; \frac{L_0}{L} = \frac{1}{1+e}$$

$$\dot{\varepsilon} = \frac{v}{L} = \frac{\dot{e}L_0}{L} = \frac{\dot{e}}{1+e}$$

$$\boxed{\dot{\varepsilon} = \frac{\dot{e}}{1+e}}$$

سرعت فک دستگاه خزشی را بر حسب پارامتر سرعت خزش و طول اولیه بیابید؟



$$v = \dot{\varepsilon} l = \dot{\varepsilon}(l_0(1+e)) = \dot{\varepsilon} l_0 (1+e)$$

$$\varepsilon = \ln(1+e) \rightarrow (1+e) = \exp(\varepsilon)$$

$$v = \dot{\varepsilon} l_0 \exp(\varepsilon) \xrightarrow[\dot{\varepsilon} = \frac{\varepsilon}{t}]{}$$

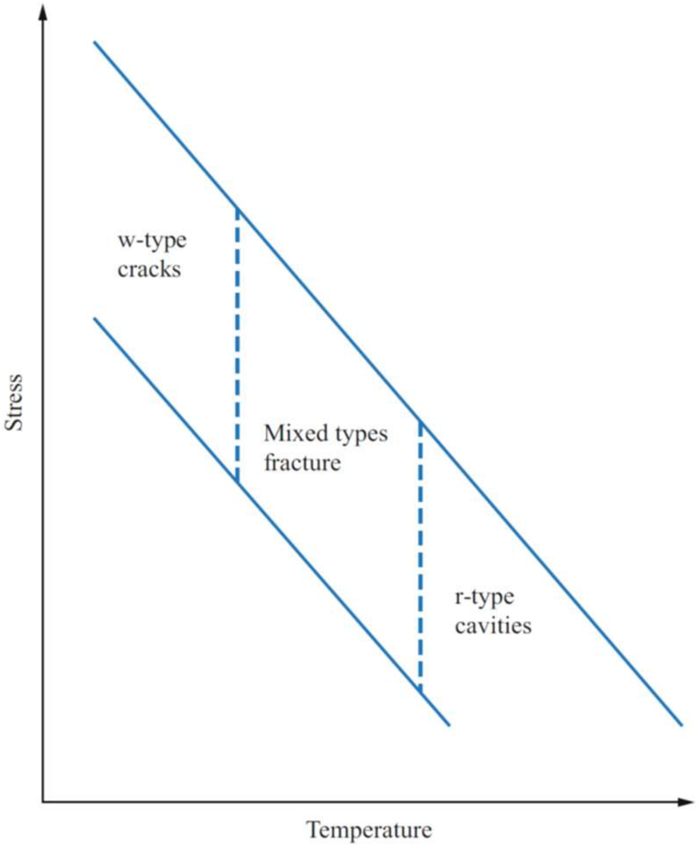
$$\rightarrow \underline{v = \dot{\varepsilon} l_0 \exp(\dot{\varepsilon} t)}$$

Chapter 10

Creep Fracture

10.1 BACKGROUND

Creep plasticity can lead to tertiary or Stage III creep and failure. It has been suggested that Creep Fracture can occur by *w* or Wedge-type cracking, illustrated in Figure 101(a), at grain-boundary triple points. Some have suggested that *w*-type cracks form most easily at higher stresses (lower temperatures) and larger grain sizes [786] when grain-boundary sliding is not accommodated. Some have suggested that the Wedge-type cracks nucleate as a consequence of grain-boundary sliding. Another mode of fracture has been associated with *r*-type irregularities or cavities illustrated in Figure 102. The Wedges may be brittle in origin or simply an accumulation of *r*-type voids [Figure 101(b)] [787]. These Wedge cracks may propagate only by *r*-type void formation [788,789]. Inasmuch as *w*-type cracks are related to *r*-type voids, it is sensible to devote this short summary of Creep Fracture to cavitation.



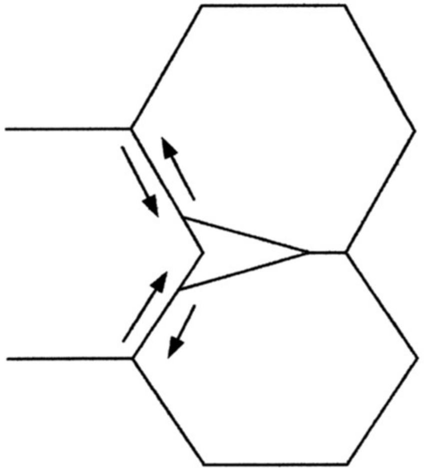
عوامل موثر بر نوع شکست

۱- دما

۲- تنش

۳- کار سرد (مرزدانه های سه تایی)

٤- تبلور مجدد

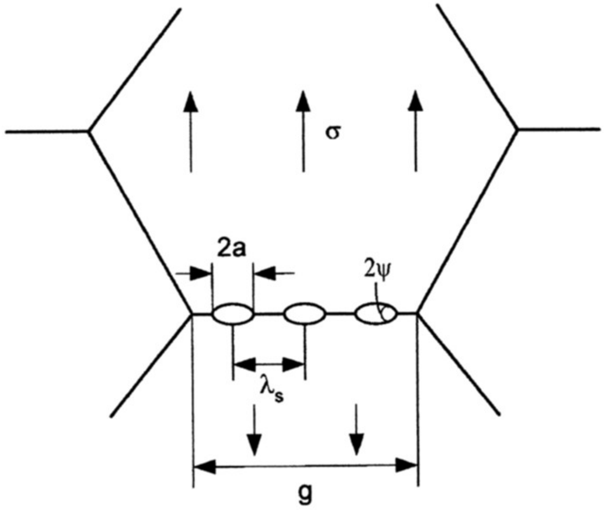


w or Wedge-type cracking

$$\sigma r_0 = 2\gamma_s, \quad \text{or,} \quad \sigma = \frac{2\gamma_s}{r_0}$$

where

γ_s the surface energy per unit area, and
r_0 the interatomic distance



Cavitation (r-type) or voids

$$\sigma_{\max} = \sqrt{\frac{L}{2\rho_t}} \cdot \tau \quad \text{for } L \gg \rho_t$$

where

τ shear stress along grain boundary, say *mn*,
L length of the sliding boundary and
ρ_t radius of curvature at the tip of the boundary

← انرژی سطحی

crack ← $\tau = \left[\frac{\gamma_{ab}\, G \quad 3\pi}{8(1-\nu)L}\right]^{1/2}$

w-type

جوانه زنی

↙ طول بزرگترین قطر دانه

↙ fid

قطر دانه

$$\tau = \frac{\pi}{2}\left(\frac{2a}{\lambda_s}\right)^{1/2}\left(\frac{\varepsilon\, \gamma_{gb} G}{(1-\nu)\, d}\right)^{1/}$$

↙ قطر دانه

↙ r-type

voids

$\tau\downarrow \quad \lambda_s\uparrow$

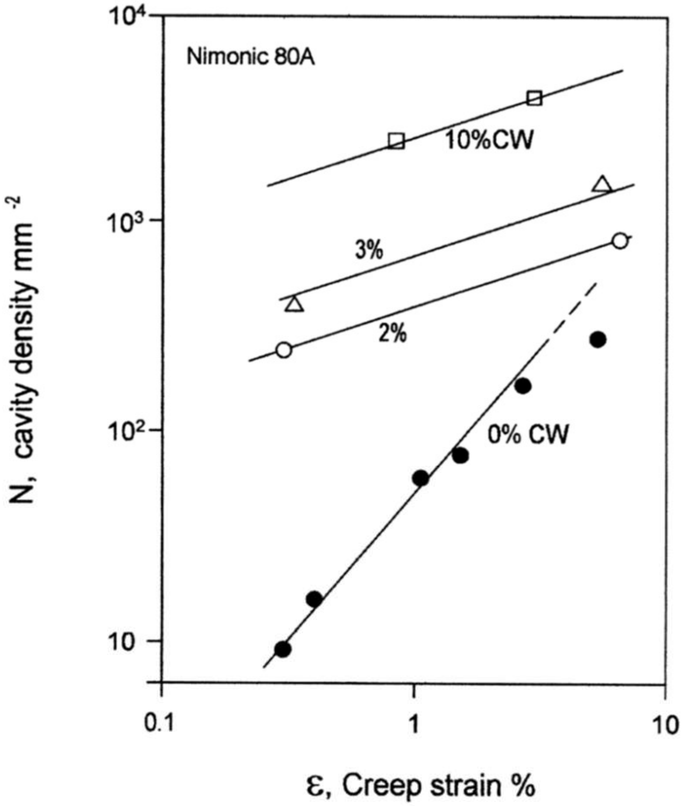


Figure 106. The variation of the cavity concentration versus creep strain in Nimonic 80A (Ni–Cr alloy with Ti and Al) for annealed and pre-strained (cold-worked) alloy. Adapted from Dyson [611]. Cavities were suggested to undergo unconstrained growth.

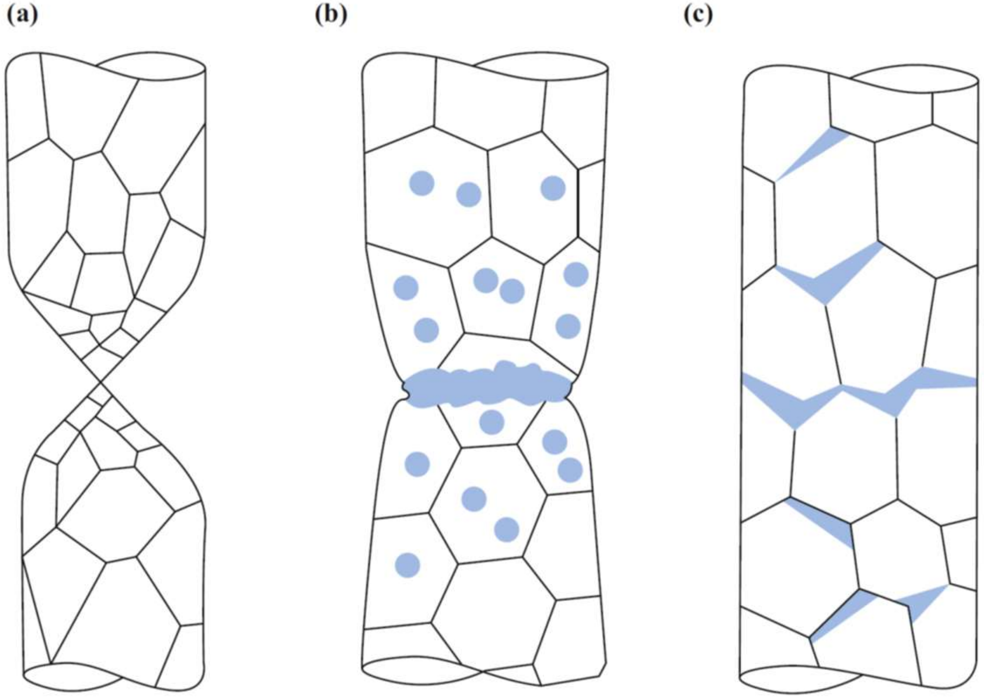
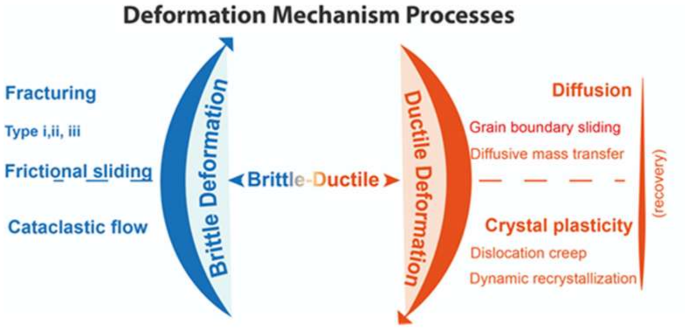


Fig. 7.22 Three modes of high temperature failure: **a** rupture; **b** transcrystalline creep fracture, in which the coloured circles represent intragranular voids that form, grow and coalescence leading to failure; **c** intercrystalline creep fracture, in which the coloured shaded regions at grain boundaries are intercrystalline voids or cracks that nucleate, grow and coalescence to some degree followed by fracture (Courtney 1990)



Deformation Mechanism Processes

Fracturing

Type i,ii, iii

Frictional sliding

Cataclastic flow

Brittle Deformation

Brittle-Ductile

Ductile Deformation

Diffusion

Grain boundary sliding

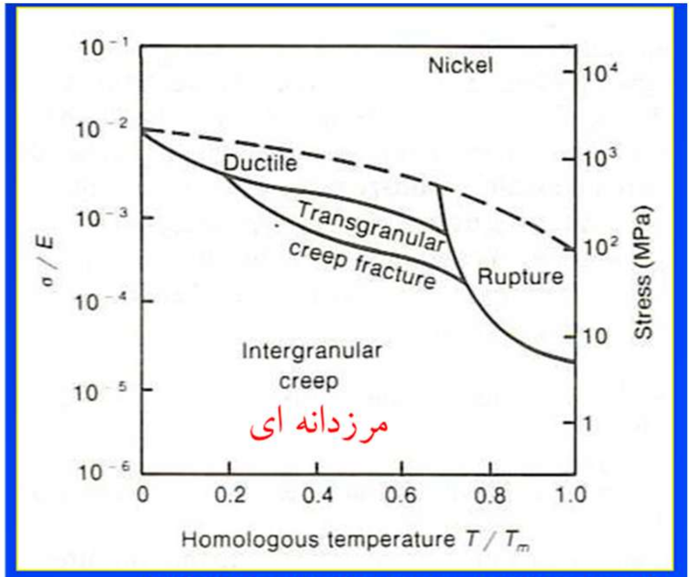
Diffusive mass transfer

Crystal plasticity

Dislocation creep

Dynamic recrystallization

(recovery)



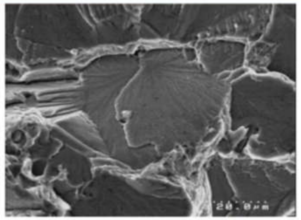
Fracture mechanism map for nickel

Fracture at elevated temperature

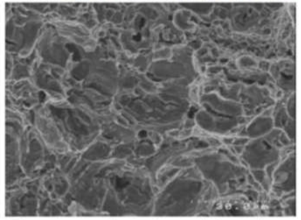
Transgranular fracture → Temp → **Intergranular fracture**

Slip planes are weaker than grain boundaries

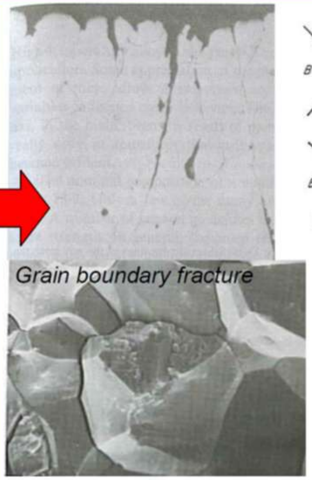
Grain boundaries are weaker than slip planes.



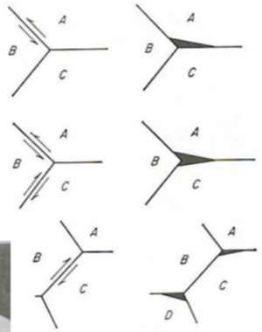
Transgranular cleavage fracture



Transgranular microvoid coalescence



Grain boundary fracture



The formation of intergranular crack by grain boundary sliding

Note: at T just below T_{recrys}, ductility drops due to grain boundary sliding → intergranular failure.

Ductile fracture:

Ductile fracture is characterized by extensive plastic deformation and absorbs significant energy before fracture. A crack, formed as a result of the ductile fracture, propagates slowly and when the stress is increased.

Brittle fracture:

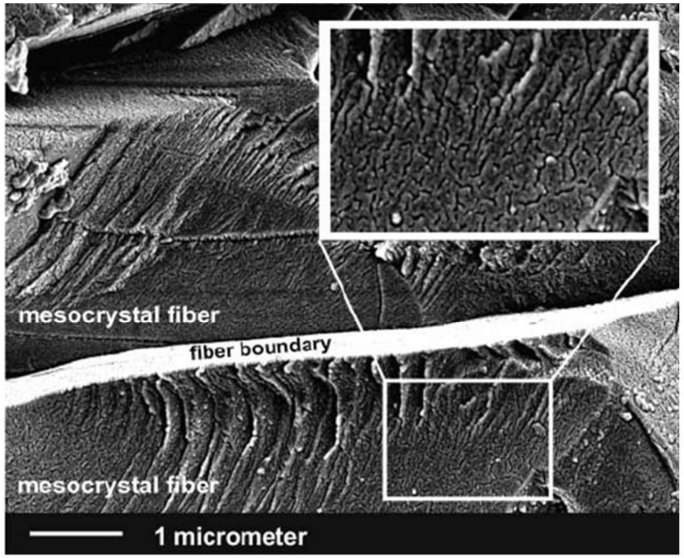
Brittle fracture is characterized by very low plastic deformation and low energy absorption prior to breaking. A crack, formed as a result of the brittle fracture, propagates fast and without increase of the stress applied to the material.

Generally fracture can be divided into 2 types such

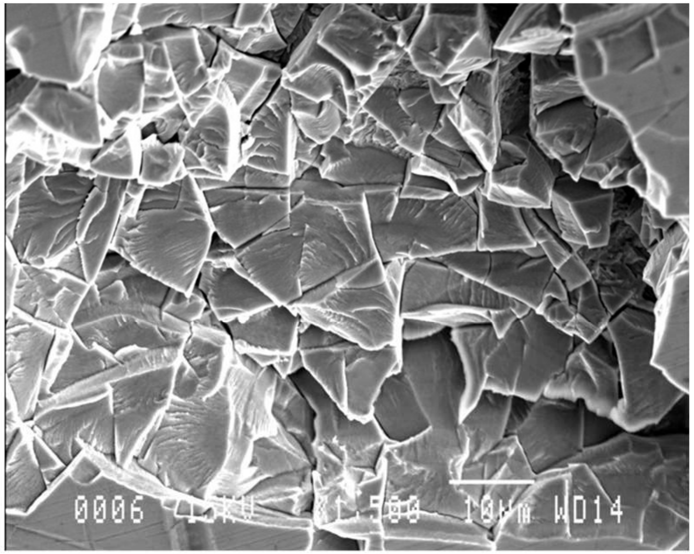
- Brittle fracture (eg. Cast iron)
- Ductile fracture (eg. Mild steel)

Further it can e classified,

Depends on the appearance as 1.shearing fracture and 2.cleavage fracture and crystallographic nature as1. fibrous and 2.granular fracture



Fibrous fracture



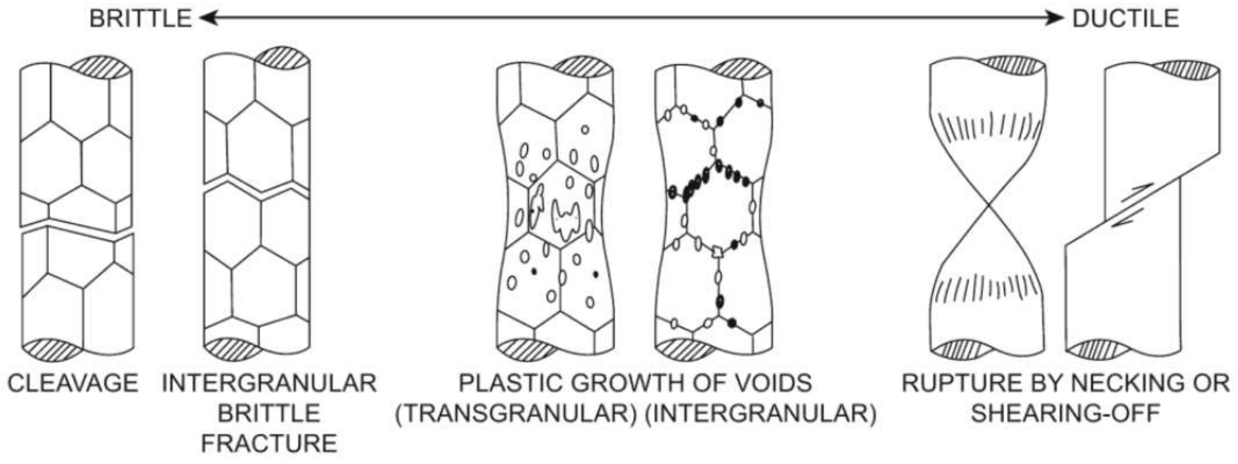
cleavage fracture

Define cleavage fracture.

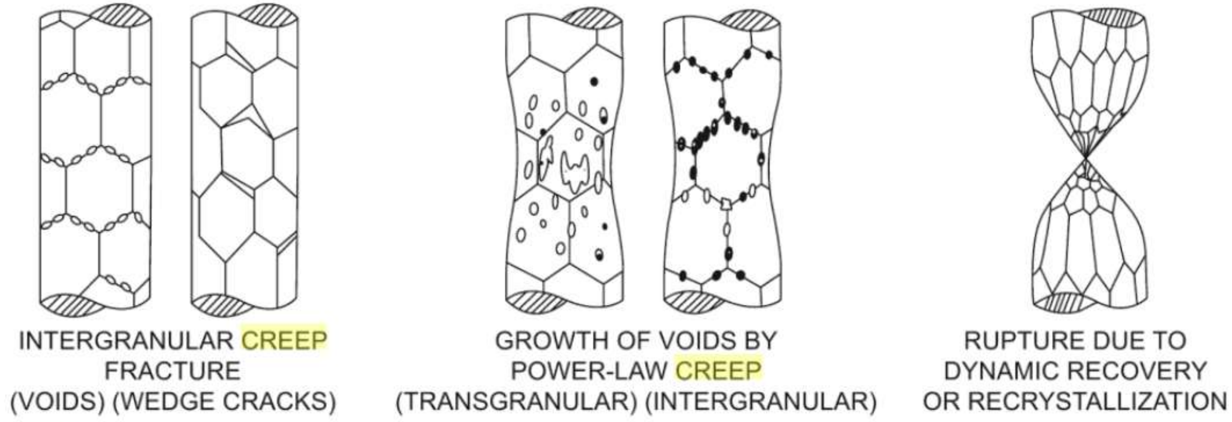
In brittle crystalline materials, fracture can occur by *cleavage* as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes). After the formation of micro crack described above, if the crack propagates along a weak crystallographic plane it is known as cleavage fracture.

7. Distinguish between ductile fracture and brittle fracture?

Ductile fracture	*Brittle fracture*
Materials fractures after plastic deformation and slow propagation of crack.	Materials fractures with very little or no plastic deformation, e.g. in a china clay, glass etc
Fractured surfaces are dull or fibrous in appearance.	Fractured surfaces are crystalline in appearance
Percentage elongation is about 30% prior to fracture occurs.	Percentage elongation is about 0.5% or almost nil prior to fracture occurs.
There is reduction in cross-sectional area of the specimen.	There is virtually no change in the cross sectional area.
Fracture takes place after necking with little sound.	Fracture occurs rapidly often accompanied by a Loud noise.



(a) Low-temperature ($T<0.3T_m$) fracture



(b) Creep temperature ($T>0.3T_m$)

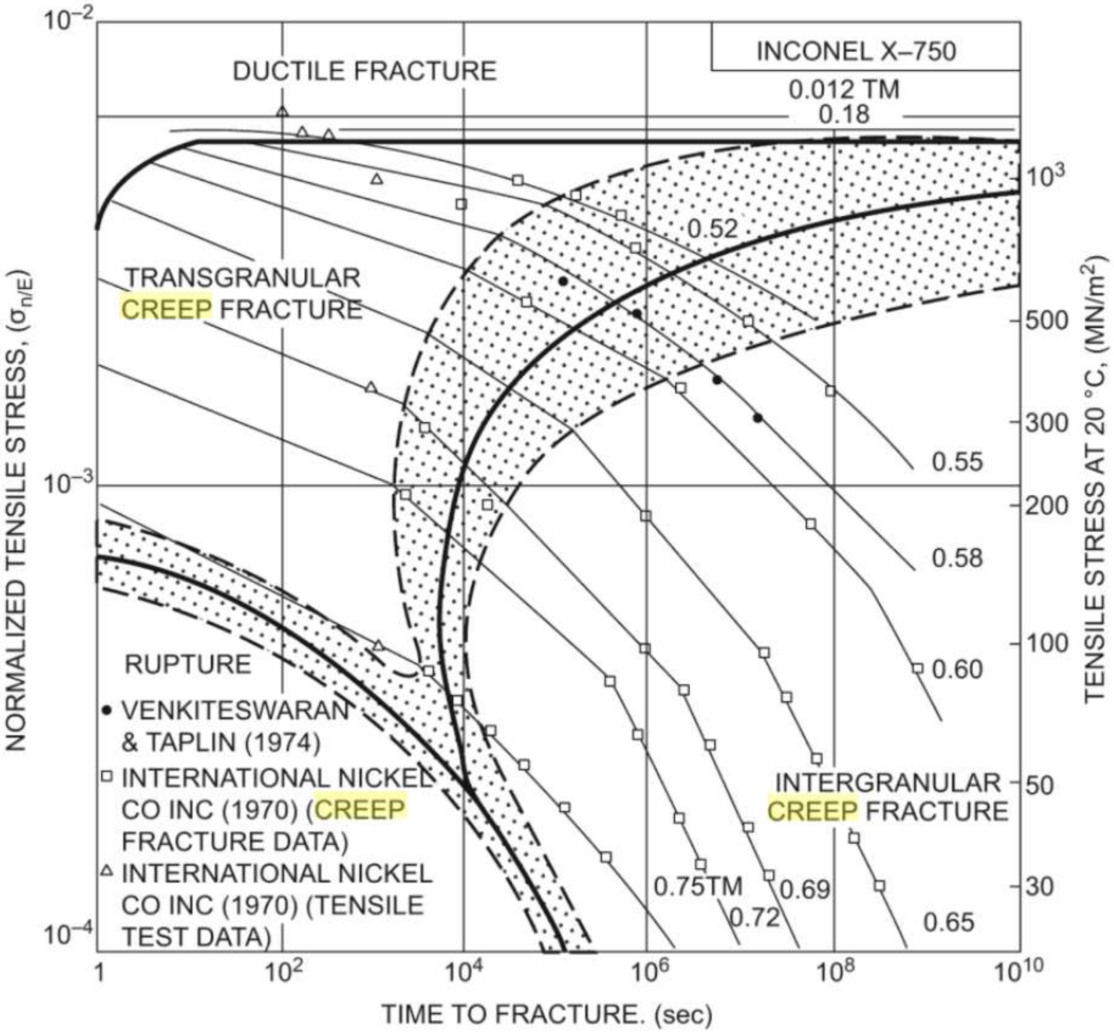


Fig. 2.3 Fracture mechanism map for Inconel X-750. Source: Ref 2.1

تفاوت و شباهت حالت های rupture و ductile

۱- rupture در دماهای بالا و تنش پایین تر از حالت ductile اتفاق می افتد.

۲- در rupture بازیابی دینامیکی داریم در صورتی که در ductile اتفاق نمی افتد

۱- هر دو می توانند پدیده necking را تجربه کنند.

۲- هر دو می توانند جز شکست نرم محسوب شوند.

Creep Testing Methods

Overview of standard creep testing procedures: constant load and constant stress tests

Creep testing methods include constant load tests (where the load is held constant to observe deformation over time) and constant stress tests (where stress is maintained while observing how material gradually deforms).

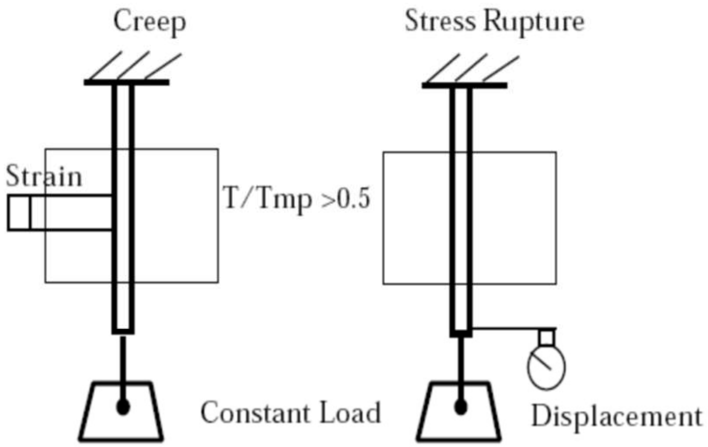
Discussion of the significance of test environments (e.g., vacuum or inert atmosphere)

Testing environments such as vacuum or inert atmospheres are crucial to avoid oxidation and other reactions that can influence creep behavior, ensuring more accurate results.

Importance of durability and reproducibility in testing

Ensuring that creep tests yield durable and reproducible results is essential for validating material performance and reliability in real-world applications.

Creep vs. Stress Rupture Test

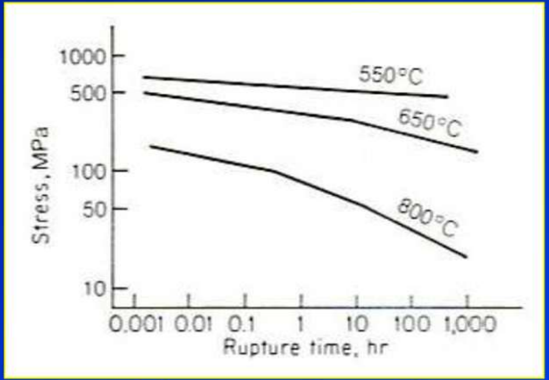


- Low Loads	- High Loads
- Precision Strain Measurement ($\varepsilon_f<0.5\%$)	- Gross Strain Measurement (ε_f up to 50%)
- Long term (2000-10,000 h)	- Short term (<1000 h)
- Expensive equipment	- Less expensive equipment
Emphasis on minimum strain rate at stress and temperature	Emphasis on time to failure at at stress and temperature

Stress Rupture Tests

- Determines the time necessary for material to result in failure under a overload.
- Useful in materials selection where dimensional tolerances are acceptable, but rupture cannot be tolerated.
- Generally performed at elevated temperatures.
- Smooth, notched, flat specimens or samples of any combination can be tested.

The ***rupture test*** in carried out in a similar manner to the ***creep test*** but at a ***higher stress level*** until the specimen fails and the ***time at failure*** is measured.



Stress rupture- time data on log-log scale

- ***Rupture strength*** and ***failure time*** are plotted, normally showing a ***straight line***.
- ***Changing of the slope*** indicates ***structural changes in the material***, i.e., transgranular → intergranular fracture, oxidation, recrystallisation, grain growth, spheroidization, precipitation.
- Direct application in ***design***.

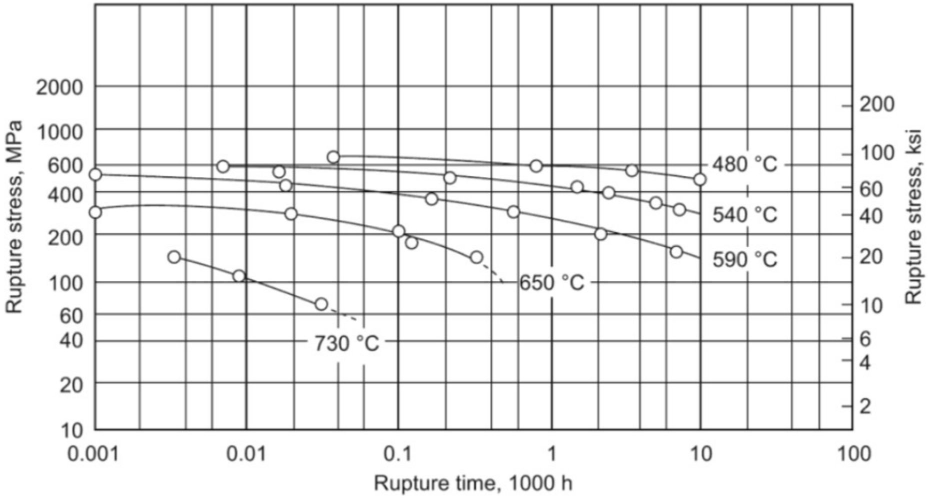


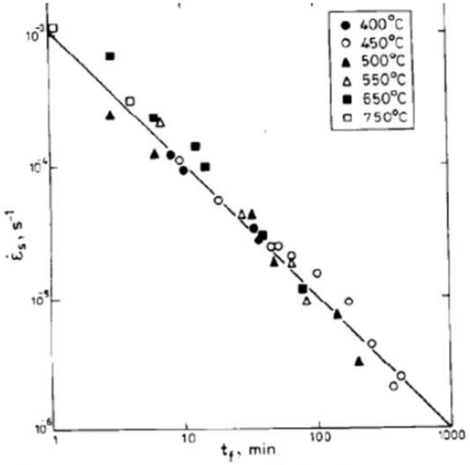
Fig. 2.2 Example of time-temperature-rupture data of 1Cr-1Mo-0.25V steel

Table 2.1 Some stress-rupture time-temperature parameters developed in the 1950s

Authors' names and year	Reference	Form of parameter
Larson and Miller (1952)	Ref 2.3	$T(C_{LM} + \log t)$
Manson and Haferd (1952)	Ref 2.5	$(\log t - \log t_a)/(T - T_a)$
Manson and Brown (1953)	Ref 2.8	$(\log t - \log t_a)/(T - T_a)^n$
Orr et al. (1954)	Ref 2.6	$\log t - \Delta H/RT$
Manson and Succop (1956)	Ref 2.9	$(\log t + C_{MS}T)$

- Monkman-Grant : $\dot{\varepsilon}_s t_r = \mathrm{K}$

  Eq. 13-24



Demonstration of Monkman-Grant Relationship in Cu (Feltham and Meakin 1959)

Monkman-Grant relationship predicts time of failure due to creep mechanisms.

Monkman-Grant relationship relates minimum strain rate and time to failure

$$\dot{\varepsilon}_{min} t_f = C \approx \varepsilon_f$$

$$\varepsilon^{\cdot} = \frac{d\varepsilon}{dt} = Aexp\left(-\frac{Q}{RT}\right)\sigma^{n} = A^{*}$$

$\varepsilon^{\cdot}\ dt$=A^{*}

$\varepsilon^{\cdot}t$=MGP

Modified Monkman-Grant relation (MMGR)

$$\dot{\varepsilon}_{\mathrm{m}} \cdot \frac{\mathrm{t}_{\mathrm{r}}}{\varepsilon_{\mathrm{f}}} = constant = C_{MMG} \, .$$

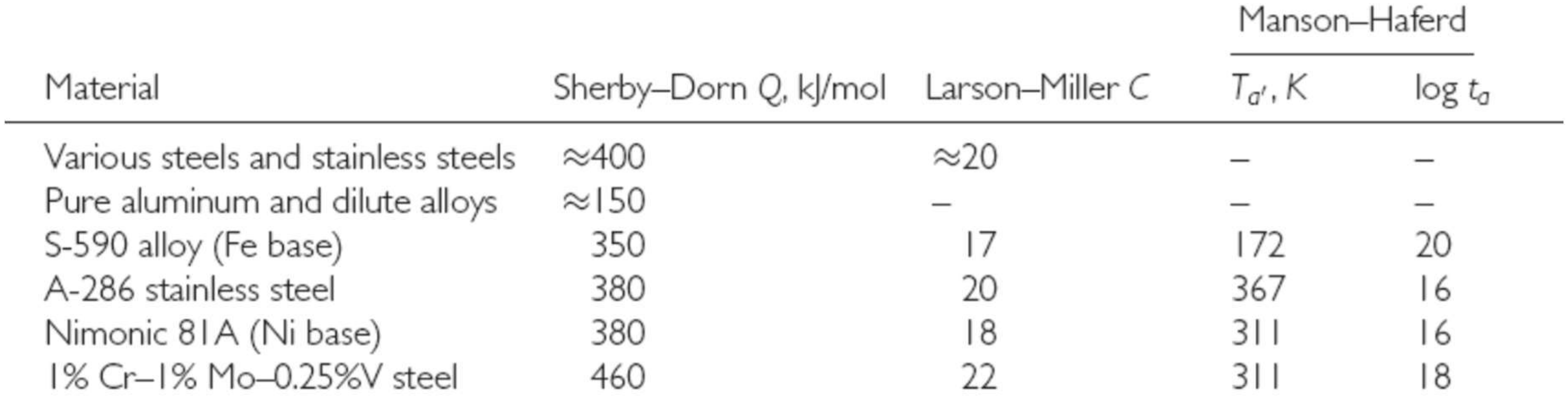
where ε_f is the strain to failure

- Larson-Miller Parameter : $\boxed{P_{L\text{-}M} = T\,(\log t + C)}$

- Sherby-Dorn Parameter : $\boxed{P_{S\text{-}D} = t\,e^{-Q/RT}}$

- Manson-Haferd Parameter : $\boxed{P_{M\text{-}H} = \dfrac{T - T_a}{\log t - \log t_a}}$

Material Parameters



Material	Sherby–Dorn Q, kJ/mol	Larson–Miller C	Manson–Haferd	
			$T_{a'}$, K	$\log t_a$
Various steels and stainless steels	≈400	≈20	–	–
Pure aluminum and dilute alloys	≈150	–	–	–
S-590 alloy (Fe base)	350	17	172	20
A-286 stainless steel	380	20	367	16
Nimonic 81A (Ni base)	380	18	311	16
1% Cr–1% Mo–0.25%V steel	460	22	311	18

Larson Miller Parameter

- Model based on Arrhenius rate equation.

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

Where T = temperature (K)

t_r = time before failure (hours)

C= material specific constant

- Predicts rupture lives given certain temperature and stress.
- First used by General Electric in the 50's to perform research on turbine blades.

dϵ/dt =A exp(-Q/PT)

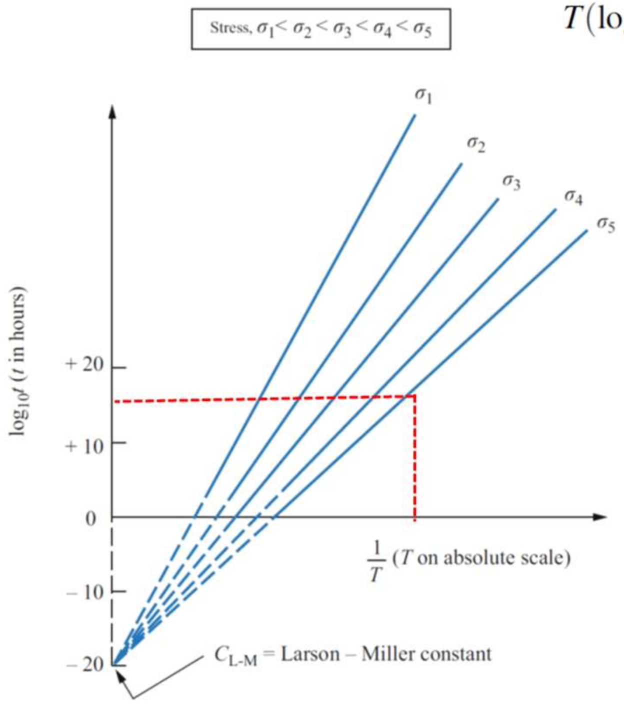
$$\int_0^{\varepsilon} \mathrm{d}\varepsilon = A_1 \mathrm{e}^{-Q/RT} \int_0^{t} \mathrm{d}t$$

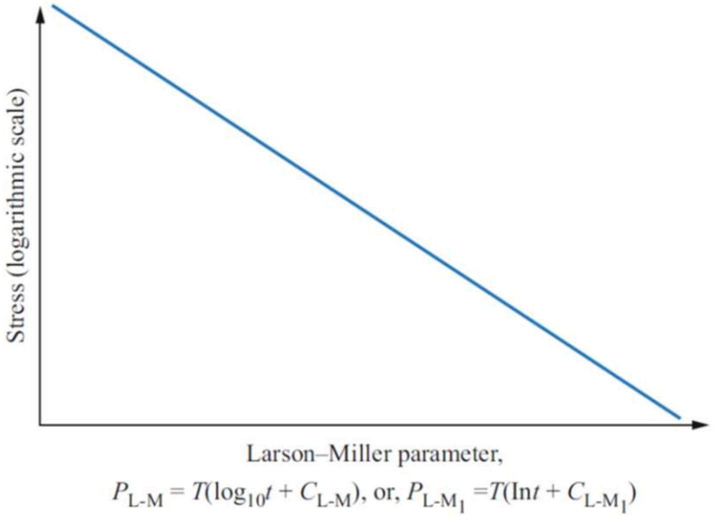
$$\therefore t = \frac{\varepsilon}{A_1} \mathrm{e}^{Q/RT} = \theta \mathrm{e}^{Q/RT}$$

$$\log_{10} t + C_{\mathrm{L-M}} = m\left(\frac{1}{T}\right)$$

$$T(\log_{10} t + C_{\mathrm{L-M}}) = m = \text{function of stress } (\sigma)$$

$$T(\log_{10} t + C_{\mathrm{L-M}}) = m = \text{function of stress } (\sigma)$$





3) Hertzberg, 5.8

If the Larson-Miller parameter for a given elevated temperature alloy was found to be 26,000, by how much would the rupture life of a sample be estimated to decrease if the absolute temperature of the test were increased from 1100 to 1250K? Assume that the Larson-Miller constant is equal to 20.

Solution:

1100K:

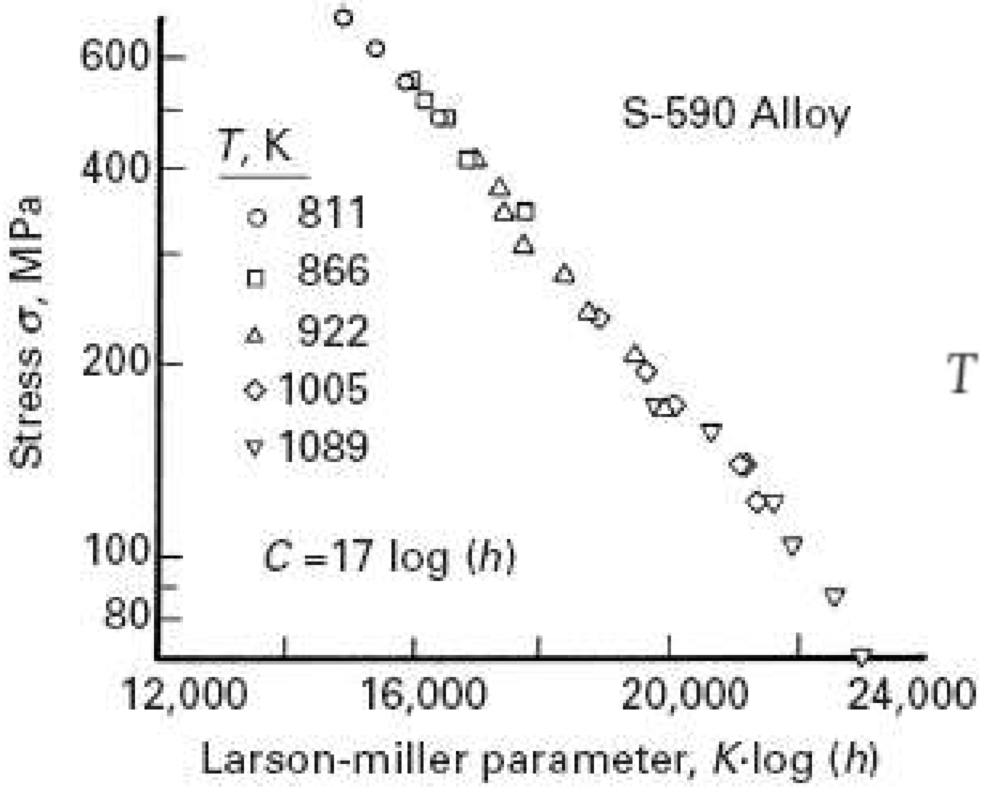
$$26000 = 1100(20 + \log t_1)$$
$$t_1 = 4329hr$$

1250K:

$$26000 = 1250(20 + \log t_2)$$
$$t_2 = 6.3hr$$

The rupture life will decrease from 4329*hr* to 6.3 *hr*.

Larson-Miller Parameter



$$T(\log t_r + C) = m.$$

Master plot for Larson–Miller parameter for S-590 alloy (an Fe-based alloy) (*C* = 17).

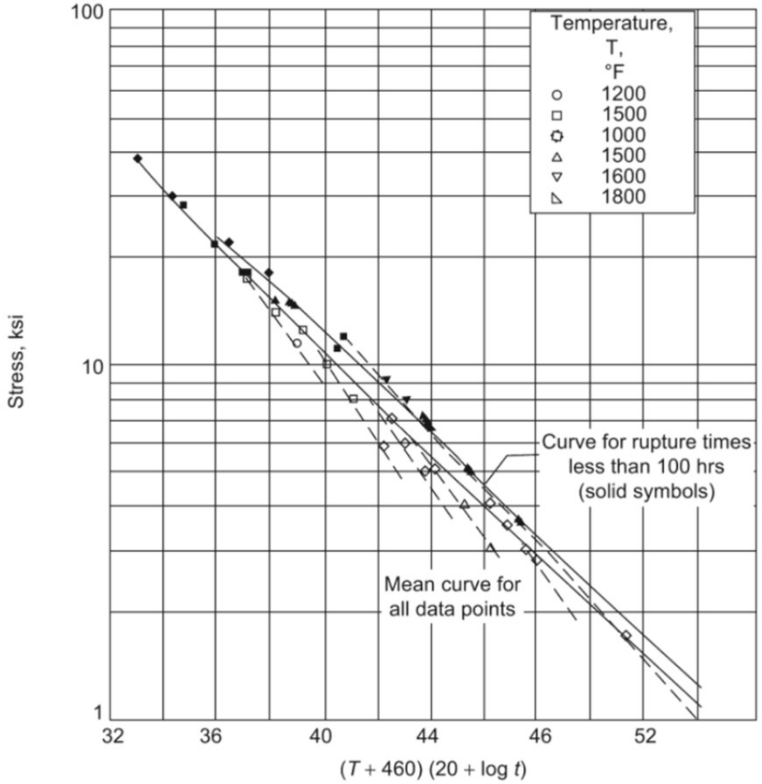
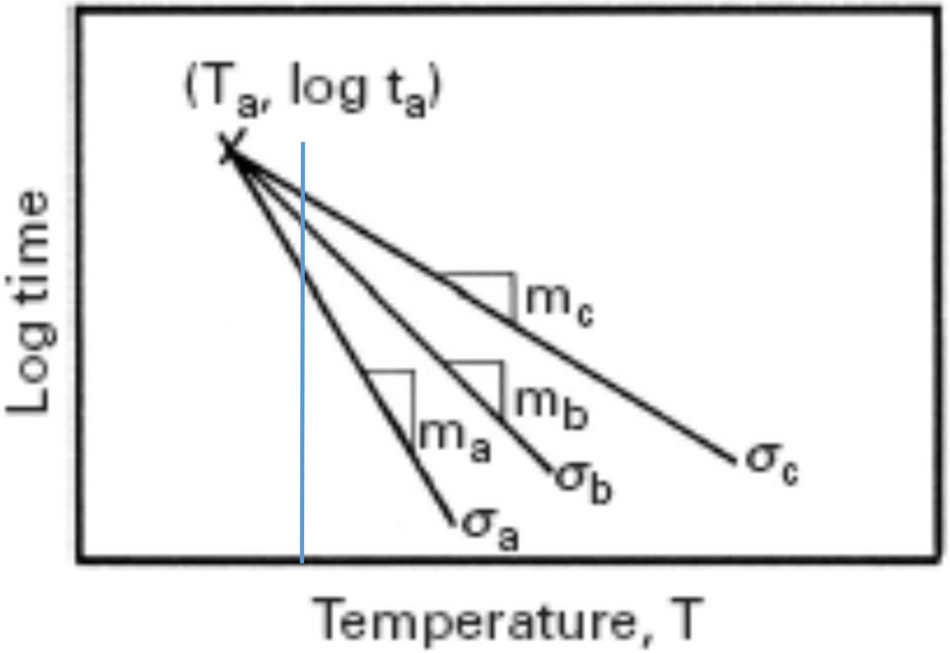


Fig. 2.4 "Peeling onion-skin" appearance of master rupture curves for 18-8 stainless steel using the Larson-Miller parameter $(T + 460) \times (20 + \log t)$

Manson-Hafered Parameter

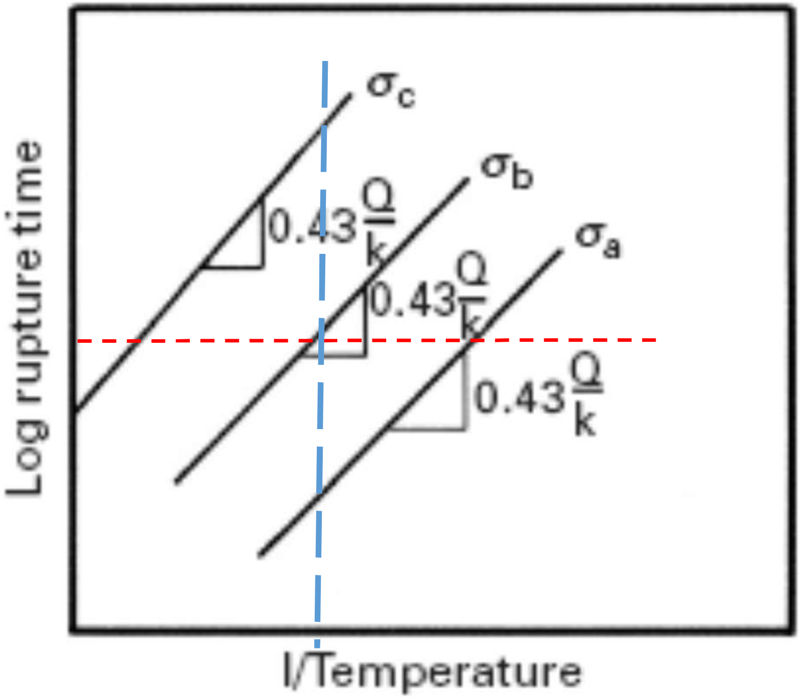


$$\frac{\log t_r - \log t_a}{T - T_a} = m$$

Relationship between time rupture and temperature at three levels of stress, *σa*, *σb*, and *σc*, using Manson–Haferd parameter (*σa > σb > σc*).

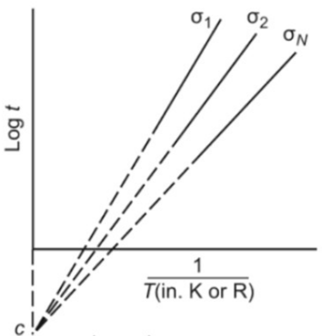
Sherby-Dorn Parameter

- Sherby-Dorn Parameter : $\boxed{P_{S\text{-}D} = t\, e^{-Q/RT}}$



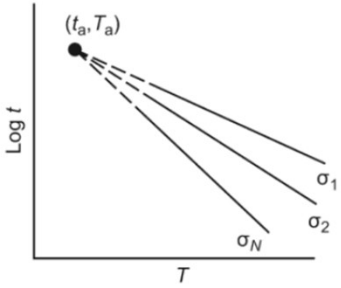
$$\log t_r - m = 0.43 \frac{Q_c}{kT}$$

Relationship between time to rupture and temperature at three levels of stress, *σa > σb > σ*c, using Sherby–Dorn parameter.



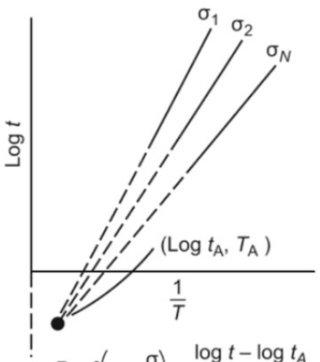
$P = f\left(\sigma \ or\ \frac{\sigma}{E}\right) = (T)(\log t + C_{LM})$

(a) **Larson-Miller**



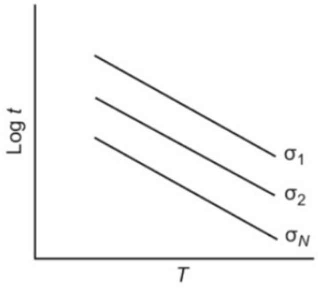
$P = f\left(\sigma \ or\ \frac{\sigma}{E}\right) = \frac{\log t - \log t_a}{T - T_a}$

(b) **Manson-Haferd**



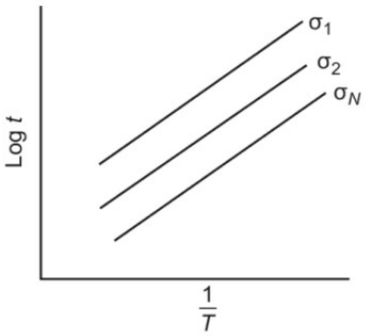
$P = f\left(\sigma \ or\ \frac{\sigma}{E}\right) = \frac{\log t - \log t_A}{1/T - 1/T_A}$

(c) **Goldhoff-Sherby**



$P = f\left(\sigma \ or\ \frac{\sigma}{E}\right) = \log t - TC_{MS}$

(d) **Manson-Succop**



$P = f\left(\sigma \ or\ \frac{\sigma}{E}\right) = \log t - \Delta H/\mathrm{RT})$

(e) **Orr-Sherby-Dorn**

Example :

Calculate the time to rupture at 650°C and 100MPa stress for a 1%Cr-1% Mo-0.25%V steel, according to the Larson-Miller , Sherby--Dorn, and Manson--Haferd methods, if this alloy underwent rupture in 20hrs when tested in tension at the same stress level at a temperature of 750°C.

Solution:

The Larson-Miller equation is $T(\log t_r + C) = m$.
At 750°C, $T = 750 + 273 = 1{,}023^0$ K and $t_r = 20$ hours. Therefore,
$m = 1023 \times (\log 20 + 22) \approx 2.4 \times 10^4$
At 650°C, $T = 650 + 273 = 923^0$K, and we have
$923(\log t_r + 22) = 2.4 \times 10^4$, so that $\log t_r = (2.4 \times 10^4/923) - 22$
$t_r = 6.7 \times 10^3$ hours.

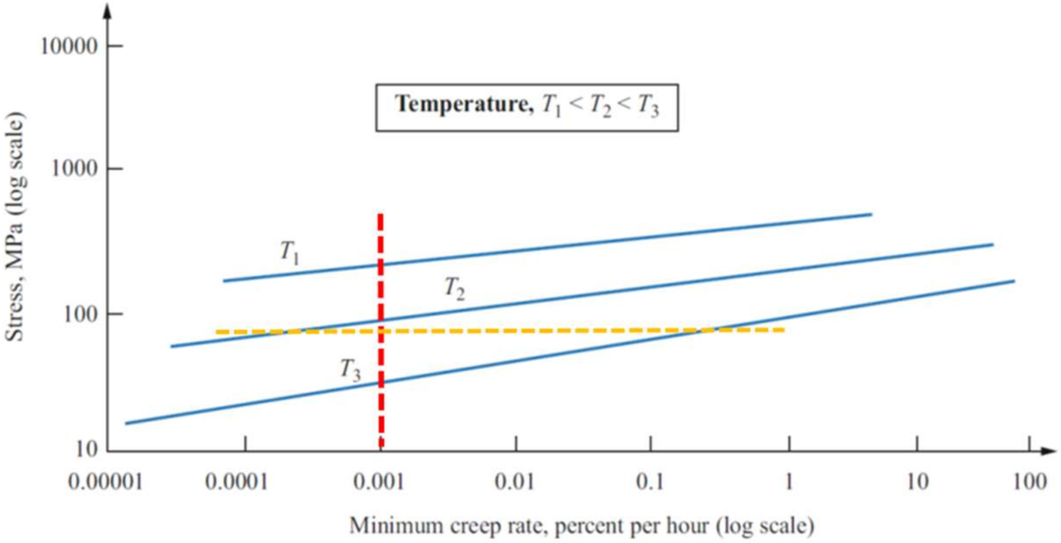
The Sherby-Dorn equation is $\log t_r - Q/(kT) = m$. From Table 1, $Q = 460$ kJ/mol. Because Q here involves moles, we must use R instead of k. At 750°C, $T = 1{,}023^0$ K and $t_r = 20$ hours. Thus, $m = \log 20 - (460 \times 10^3/8.314 \times 1023)$
At 650°C, $T = 923^0$ K, and we obtain $\log t_r = m + 0.43(Q/kT)$
so that **$t_r = 6 \times 10^3$ hours.**

The Manson-Haferd equation is $(\log t_r - \log t_a)/(T - T_a) = m$. From Table 1, $Ta = 311$ K, and $\log t_a = 18$. At 750°C, $T = 1{,}023^0$ K, and it follows that $t_r = 20$ hours.
Therefore, $m = (\log 20 - 18)/(1{,}023 - 311) = -0.023$.
At 650°C, $T = 923^0$ K, and we have $(\log t_r - \log t_a)/(T - T_a) = m$
$(\log t_r - 18)/(923 - 311) = -0.023$,
$\log t_r = 3.924$,

t_r = 8.4 × 103 hours.

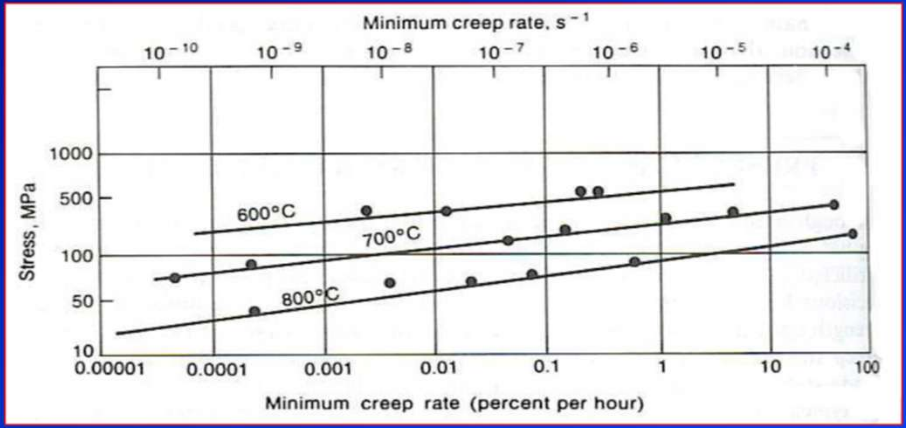
Prediction of Creep Strength

Fig. 7.30 Variation of minimum creep rate with stress at various temperatures for a given material (schematic)



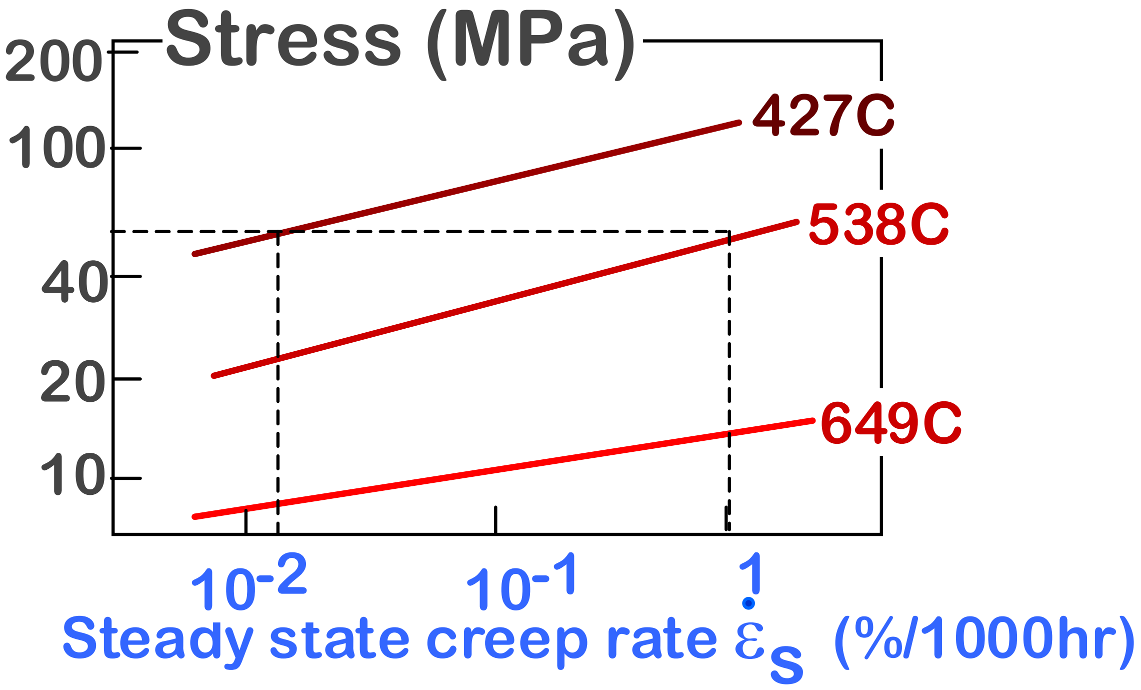
Presentation of engineering creep data

Creep strength is defined as the stress at a given temperature, which produces a ***steady-state creep rate*** (10^{-11} to 10^{-8} s^{-1}.)



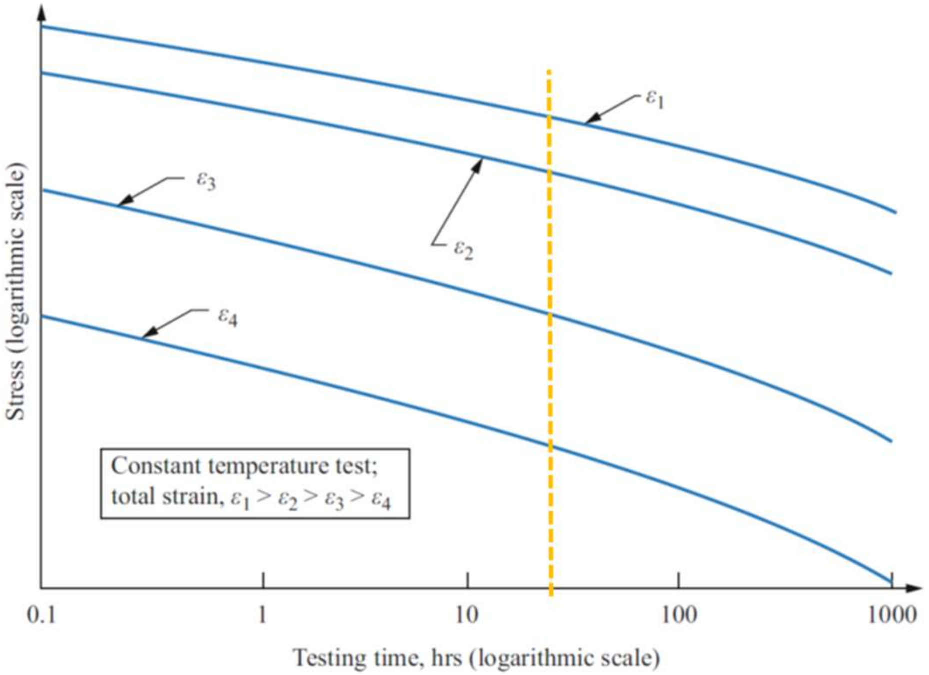
Stress vs minimum creep rate

- ***Log-log plot*** is used so that the extrapolation of one log-cycle represents a ***tenfold change***.


Stress (MPa)
200
100
40
20
10
427C
538C
649C
10^{-2}
10^{-1}
1
Steady state creep rate $\dot{\varepsilon}_s$ (%/1000hr)

Prediction of Creep Strength

Fig. 7.28 Stress versus testing time on log-log plot for different amounts of total strain for a given material at a constant temperature (schematic)



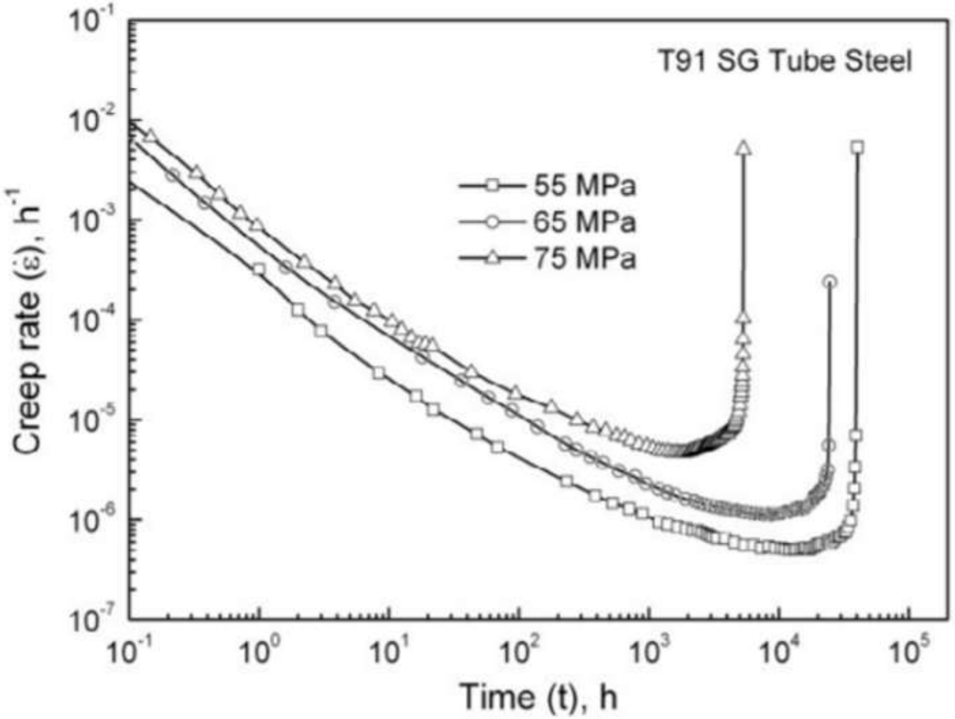
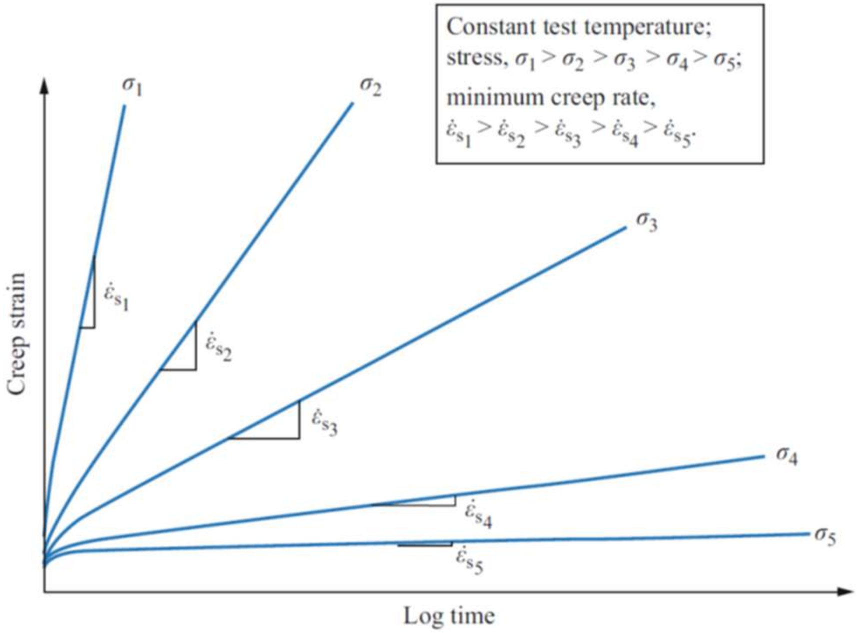


Fig. 4. Typical creep curves showing creep rate-time plots for stress levels 55, 65 and 75 MPa at 923 K.

Prediction of Creep Strength

Fig. 7.29 Family of schematic creep strain–time curves at various stress levels for a given material tested at the same temperature, showing minimum creep rates



Low temperature Creep $T < 0.3T_m$

Creep deformation Medium temperature Creep $0.3T_m < T < 0.8T_m$

High temperature Creep $T > 0.8T_m$

LOW TEMPERATURE CREEP

Creep at low temperatures (< 0.25Tmp) is generally transient, achieving creep exhaustion during stage 1 (primary creep) and never reaching stage 2 (secondary creep). Thermal energy required for dynamic recovery is not available in the temperature ranges of interest; therefore, the material experiences creep exhaustion or creep saturation.

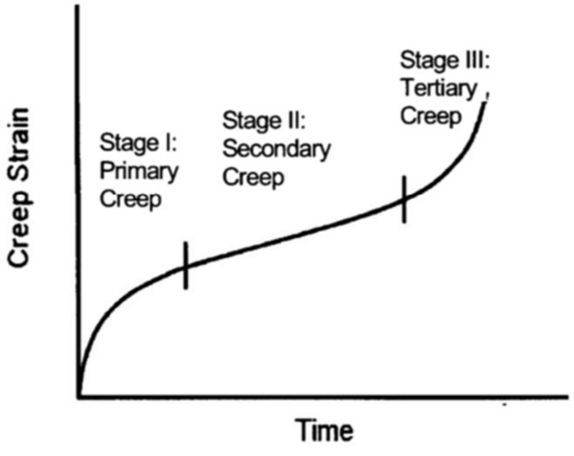
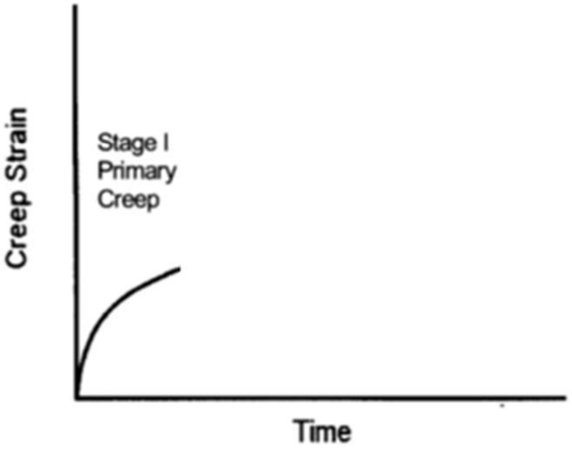


Figure 2-1. Typical Creep Curve Showing the Three Stages of Creep



Primary or transient creep is often described by the following empirical power law equation

$$\varepsilon = At^{n}$$

$$\boxed{\varepsilon^{\cdot} = A(n-1)t^{n-1} = \mathrm{B}t^{n-1}}$$

where

ε — strain
A — a constant
n — time exponent
t — time

The constant A is reportedly dependent on microstructure and temperature

Andrade Law

$$\boxed{\varepsilon = \varepsilon_0 + \beta t^{1/3}}$$

$$\boxed{\varepsilon^{\cdot} = At^{-2/3}}$$

where $\boldsymbol{\varepsilon}_0$ is the instantaneous strain, β isa constant and t is time. Equation is in accordance with the time law of creep proposed by Andrade,[1] known as Andrade's β-flow.

Creep mechanisms can be visualized by using superposition of various strain-time curves as shown in Fig. 8.5. An empirical relation which describes the strain-time relation is:

$$\boxed{\varepsilon = \varepsilon_i \left(1 + \beta t^{1/3}\right) \exp(kt)} \qquad (8.2)$$

$$\varepsilon = \varepsilon_0 (1 + \beta t^{1/3})\, e^{kt}$$

Transient creep may also follow a logarithmic fit of the type

$$\varepsilon = A' + B\ln(t)$$

where

ε — instantaneous plastic and creep strain
A' and B — creep constants
t — time measured in hours

In comparison to the normal creep equation, the logarithmic creep behavior is usually described by

$$\boxed{\varepsilon = \varepsilon_0 + \alpha \ln(1 + \gamma t),}$$

where **α** and **γ** are constants. This equation indicates that over a long period of time, the strain rate of deformation tends to become zero. Such an equation, as discussed in the previous section, would be useful for describing exhaustion creep.

primary or transient creep :

- Andrade-β flow (or 1/3 rd law) : $\varepsilon_p = \beta t^{1/3}$ $\Leftrightarrow$ problem as $t \rightarrow 0$
- Garofalo / Dorn Equation : $\varepsilon_p = \varepsilon_t (1 - e^{-rt})$, r is related to $\dfrac{\dot{\varepsilon}_i}{\dot{\varepsilon}_s}$

Medium TEMPERATURE CREEP

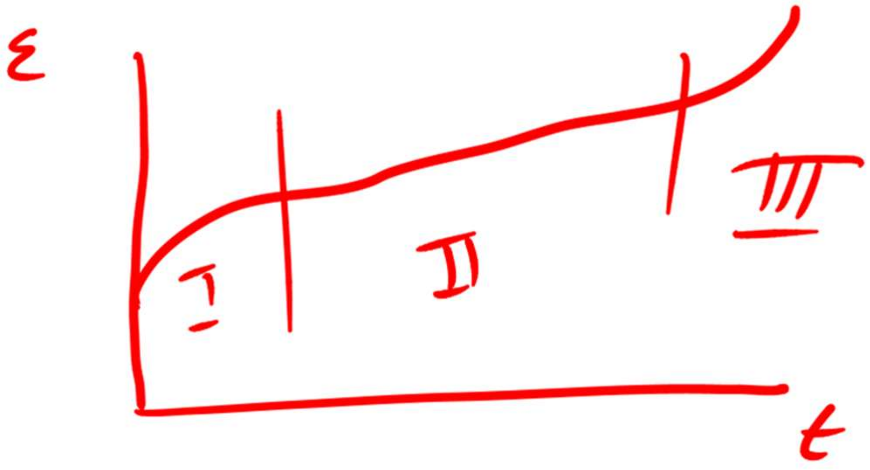
The Bailey–Orowan equation

$$\dot{\varepsilon}_s = R/H$$

$$R = -(\partial\sigma/\partial t)_{\varepsilon}$$

$$H = (\partial\sigma/\partial\varepsilon)_{\mathrm{t}}$$

Medium TEMPERATURE CREEP



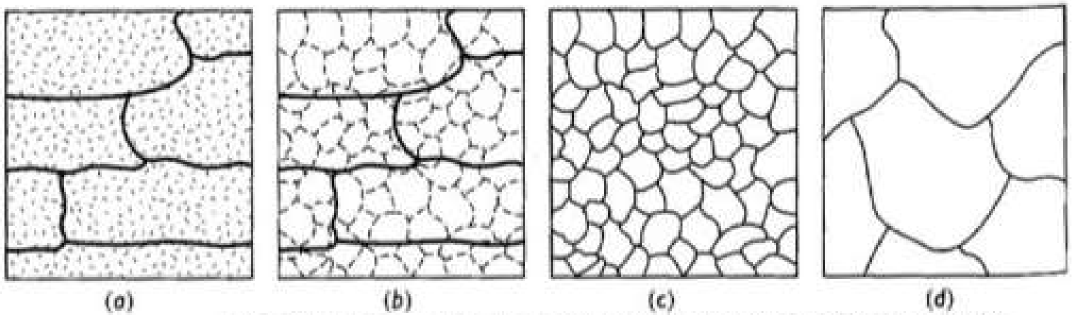
Chapter 7

Recrystallization

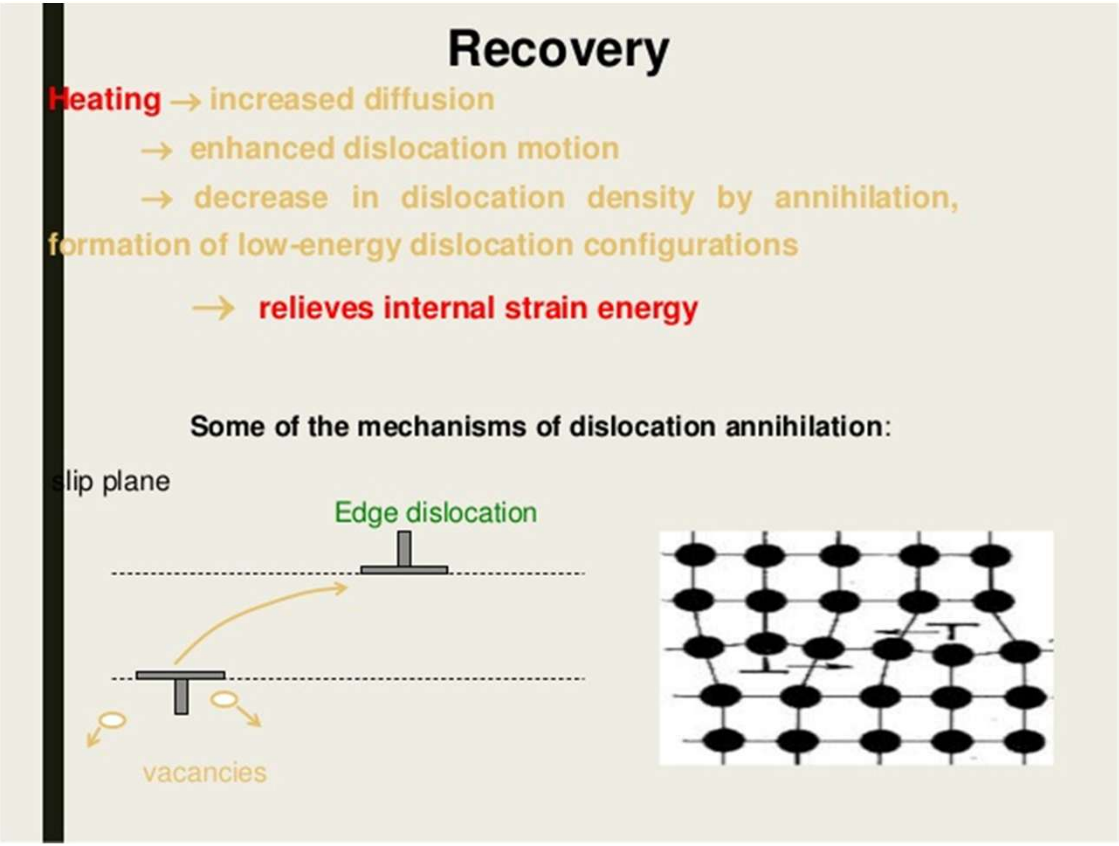
Dynamic recrystallization

Annealing is a heat treatment designed to eliminate the effects of cold working. The properties of a metal may revert back to the precold-worked states by Annealing, through recovery, recrystallization and grain growth.

Recovery: the relief of some of the internal strain energy of a previously cold-worked material.
Recrystallization: the formation of a new set of strain-free grains within a previously cold-worked material.
Grain Growth: the increase in average grain size of a polycrystalline material. An elevated temperature heat treatment (annealing) is needed for these 3-processes.



The effect of annealing temperature on the microstructure of cold-worked metals: (a) cold worked, (b) after recovery, (c) after recrystallization, and (d) after grain growth.



Recovery

Heating → **increased diffusion**

→ **enhanced dislocation motion**

→ **decrease in dislocation density by annihilation, formation of low-energy dislocation configurations**

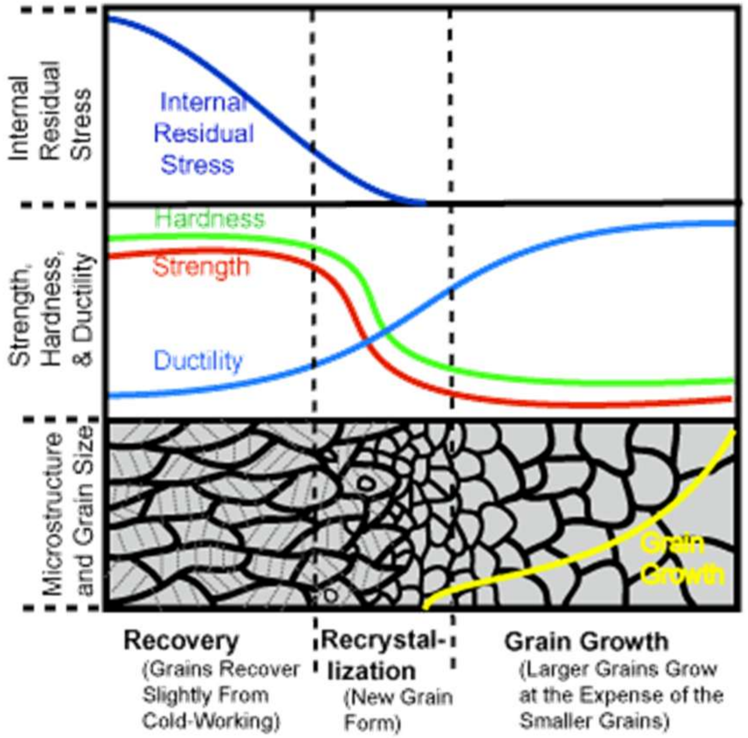
→ **relieves internal strain energy**

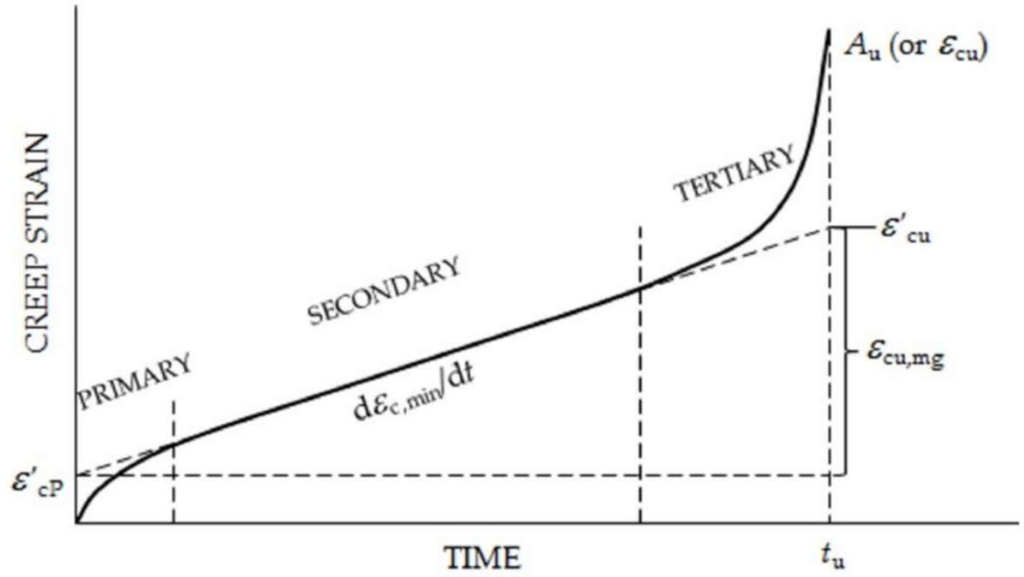
Some of the mechanisms of dislocation annihilation:

slip plane

Edge dislocation

vacancies




A_u (or ε_{cu})
CREEP STRAIN
TERTIARY
ε'_{cu}
SECONDARY
$\varepsilon_{cu,mg}$
PRIMARY
$d\varepsilon_{c,min}/dt$
ε'_{cP}
TIME
t_u

During this stage, the steady state is achieved because of an approximate balance between two opposing factors: the strain hardening that tends to reduce the creep rate and the softening or recovery process that tends to increase it

σ=cte , σ=f(t, ϵ) →

$$\mathrm{d}\sigma = \frac{\partial\sigma}{\partial t}\partial t + \frac{\partial\sigma}{\partial\varepsilon}\partial\varepsilon = 0, \quad \text{or,} \quad \frac{\partial\sigma}{\partial\varepsilon}\partial\varepsilon = -\frac{\partial\sigma}{\partial t}\partial t;$$

$$\therefore \dot{\varepsilon}_{\mathrm{s}} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = -\frac{\partial\sigma/\partial t}{\partial\sigma/\partial\varepsilon} = \frac{r}{h}$$

Microstructural softening due to recovery process in the low-temperature region includes cross-slip of screw dislocations while that at a homologous temperature above 0.5 includes rearrangement and annihilation of dislocations and climbing of edge dislocations.

تبلور مجدد

استاتیک : در حین یک تغییر شکل پلاستیکی، هنگام تبلور کردن، دما نیز تبلور کرده یک جسم که تغییر شکل پلاستیک سرد داده است.

دینامیکی : در حضور تغییر شکل : مانند خزش

$$r = -\frac{\partial\sigma}{\partial t} = A\left(\frac{\sigma}{E}\right)^{p} \cdot D_{sf}$$

① بازیابی متناسب با میزان تنش است.

② متناسب با ضریب نفوذ است.

$P = 3$ برای اکثر فلزات

و

$$\dot{\varepsilon}_s = \frac{r}{h} = \frac{A\left(\frac{\sigma}{E}\right)^{p} D_{sf}}{c\left(\frac{\sigma}{E}\right)} = \frac{A}{c}\left(\frac{\sigma}{E}\right)^{p-1} D_{sf}$$

$$\dot{\varepsilon}_{ss} = \underbrace{\beta}\left(\frac{\sigma}{E}\right)^{n} \cdot \underbrace{D_{sf}} = A'\left(\frac{\sigma}{E}\right)^{n}$$

پس اجسامی دارای نرخ خزش کمی هستند که ضریب نفوذ کمتری داشته باشند.

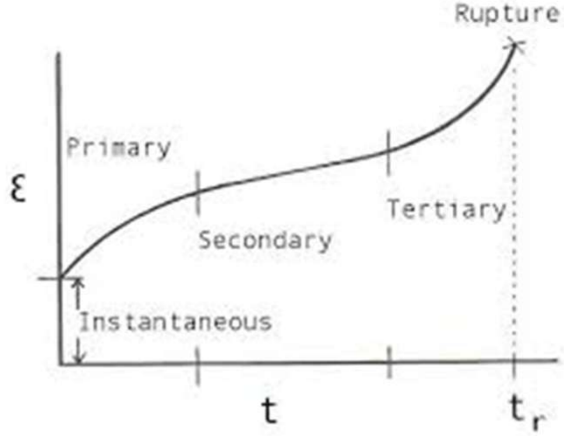
- total creep curve : $\varepsilon = \varepsilon_o + \varepsilon_p + \varepsilon_s$

ε_o = instantaneous strain at loading (elastic, anelastic and plastic)

ε_s = steady-state creep strain (constant-rate *viscous creep*) = $\dot{\varepsilon}_s t$

ε_p = primary or transient creep : Andrade-β flow (or 1/3 rd law) : $\beta t^{1/3}$

$$\boxed{\varepsilon = \varepsilon_0 + \beta t^{1/3} + \varepsilon^{\cdot} t}$$



Garofalo equation:

$$\boxed{\varepsilon = \varepsilon_0 + \varepsilon_t\left(1 - e^{-rt}\right) + \dot{\varepsilon}_s t}$$

$$\varepsilon = \varepsilon_i + \varepsilon_t(1 - \exp(rt)) + t\dot{\varepsilon}_{ss}$$

$$\boxed{\varepsilon = \varepsilon_0 + \beta t^{1/3} + \dot{\varepsilon}_s t + \gamma t^3,}$$

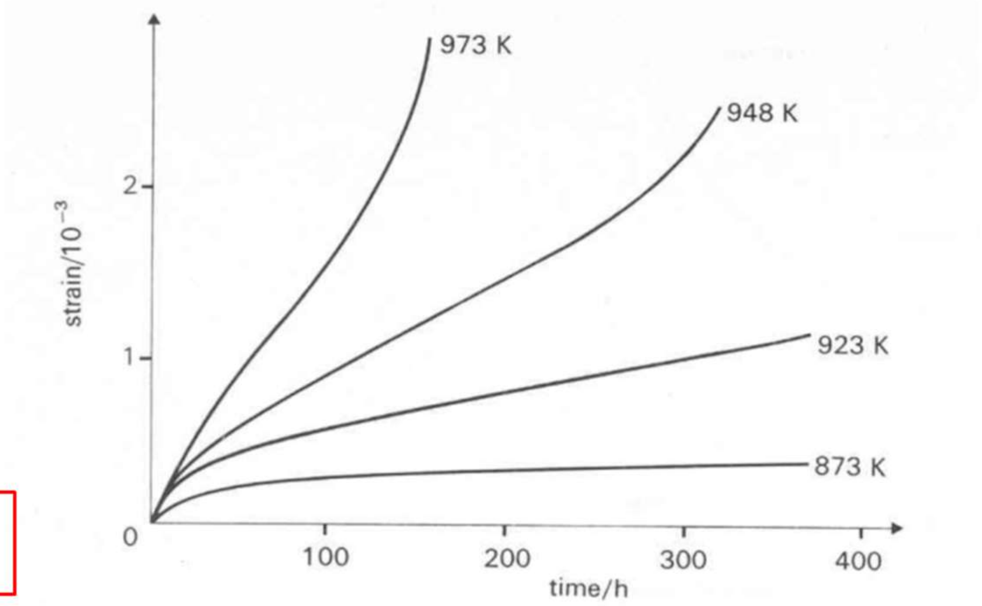
where $\boldsymbol{\gamma} t^3$ describes the tertiary component of the creep curve

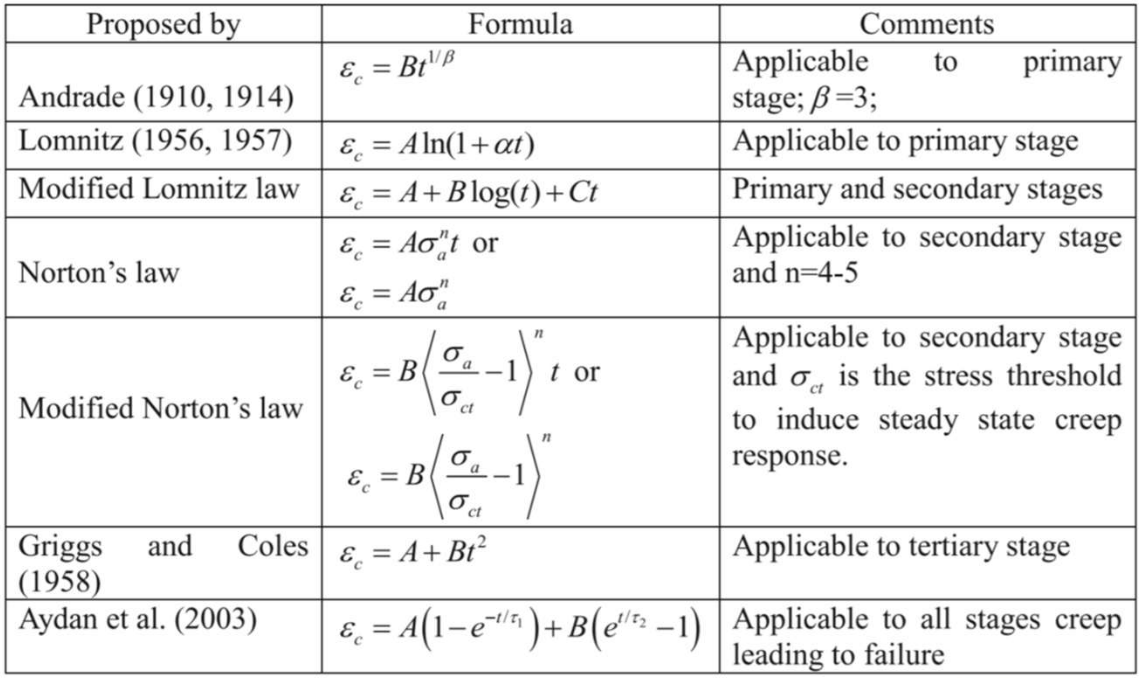
$$\boxed{\varepsilon = \varepsilon_i + B\sigma^m t + D\sigma^\alpha(1 - \exp(\beta t))}$$

High TEMPERATURE CREEP

$$\boxed{\varepsilon = \varepsilon_0 + \gamma t^n}$$

$$\boxed{\varepsilon = B + C \exp(\gamma t)}$$



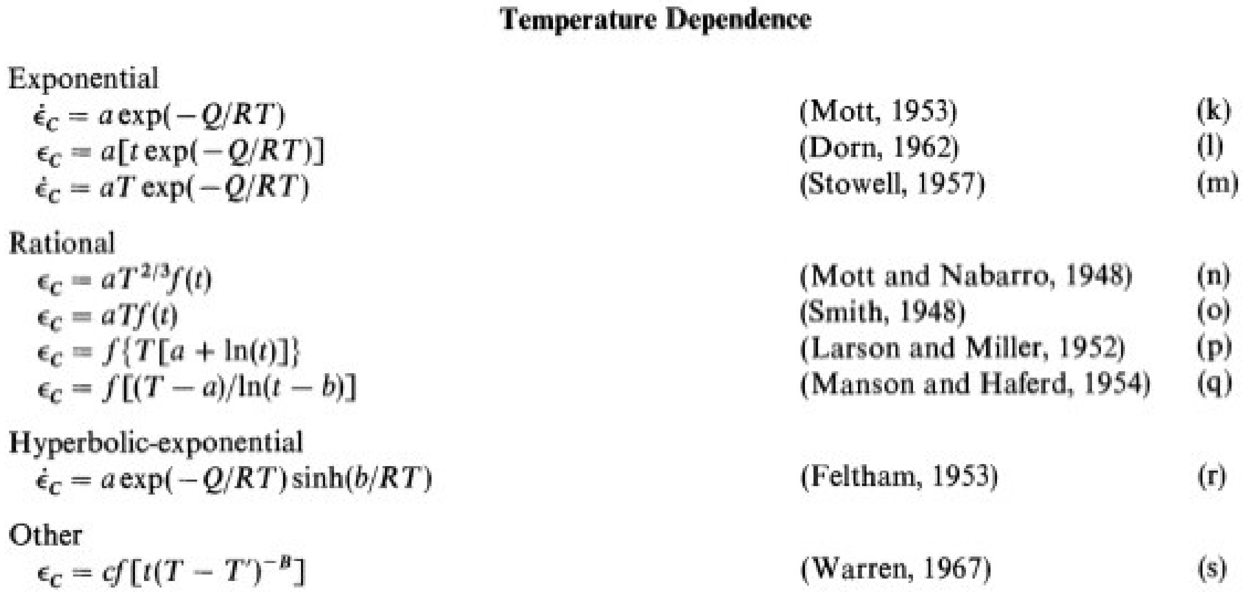


Proposed by	Formula	Comments
Andrade (1910, 1914)	$\varepsilon_c = Bt^{1/\beta}$	Applicable to primary stage; β =3;
Lomnitz (1956, 1957)	$\varepsilon_c = A\ln(1+\alpha t)$	Applicable to primary stage
Modified Lomnitz law	$\varepsilon_c = A + B\log(t) + Ct$	Primary and secondary stages
Norton's law	$\varepsilon_c = A\sigma_a^n t$ or $\varepsilon_c = A\sigma_a^n$	Applicable to secondary stage and n=4-5
Modified Norton's law	$\varepsilon_c = B\left\langle \dfrac{\sigma_a}{\sigma_{ct}} - 1 \right\rangle^n t$ or $\varepsilon_c = B\left\langle \dfrac{\sigma_a}{\sigma_{ct}} - 1 \right\rangle^n$	Applicable to secondary stage and σ_{ct} is the stress threshold to induce steady state creep response.
Griggs and Coles (1958)	$\varepsilon_c = A + Bt^2$	Applicable to tertiary stage
Aydan et al. (2003)	$\varepsilon_c = A\left(1 - e^{-t/\tau_1}\right) + B\left(e^{t/\tau_2} - 1\right)$	Applicable to all stages creep leading to failure

$A, B, C, \alpha, \tau_1, \tau_2$, and n are constants to be determined from experimental results. σ_a, ε_c, $\dot{\varepsilon}_c$, and t are the applied stress, creep strain, strain rate, and time, respectively, hereafter

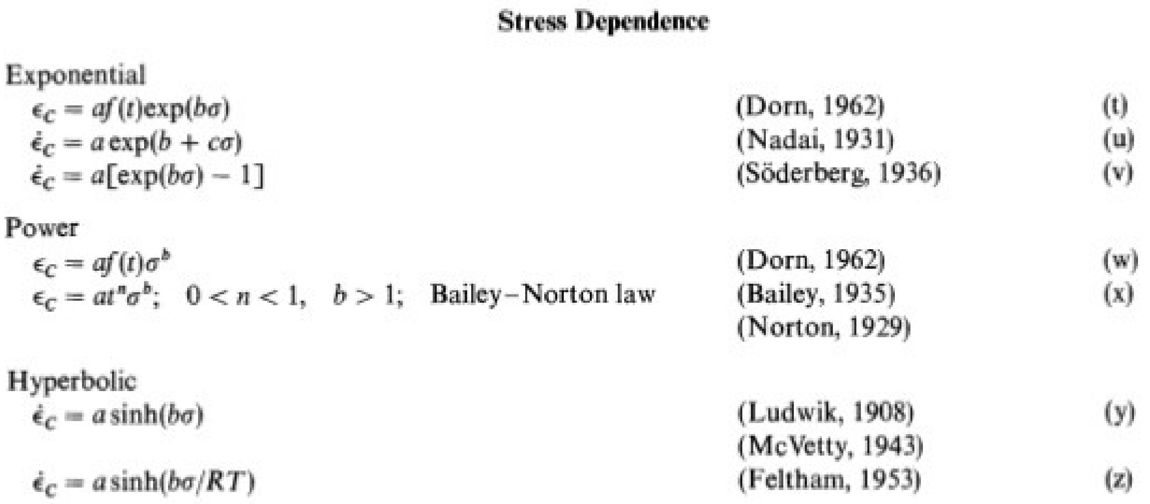
Equation Form	References	Equation
Time Dependence		
Rational		
$\epsilon_C = at/(1 + bt)$	(Freundenthal, 1936)	(a)
Logarithmic		
$\epsilon = a + b\ln(t)$	(Phillips, 1905)	(b)
$\epsilon = a + b\ln(1 + ct)$	Modification of (b)	(c)
Exponential		
$\epsilon = a + bt - c\exp(-dt)$	(McVetty, 1934)	(d)
$\epsilon_C = at + b[1 - \exp(-ct)]$	(McVetty, 1934) (Söderberg, 1936)	(e)
Power		
$\epsilon_C = bt^n; \quad 1/3 < n < 1/2$	(Bailey, 1935)	(f)
Power series		
$\epsilon_C = at^m + bt^n; \quad m > 1, \quad 0 < n < 1$	(de Lacombe, 1939)	(g)
$\epsilon_C = at_m + bt_n + ct_p \cdots$	(Graham, 1953)	(h)

- The temperature dependency of creep is often related to thermodynamics and rate processes of solid-state physics, the temperature dependency is often of exponential form.



Temperature Dependence

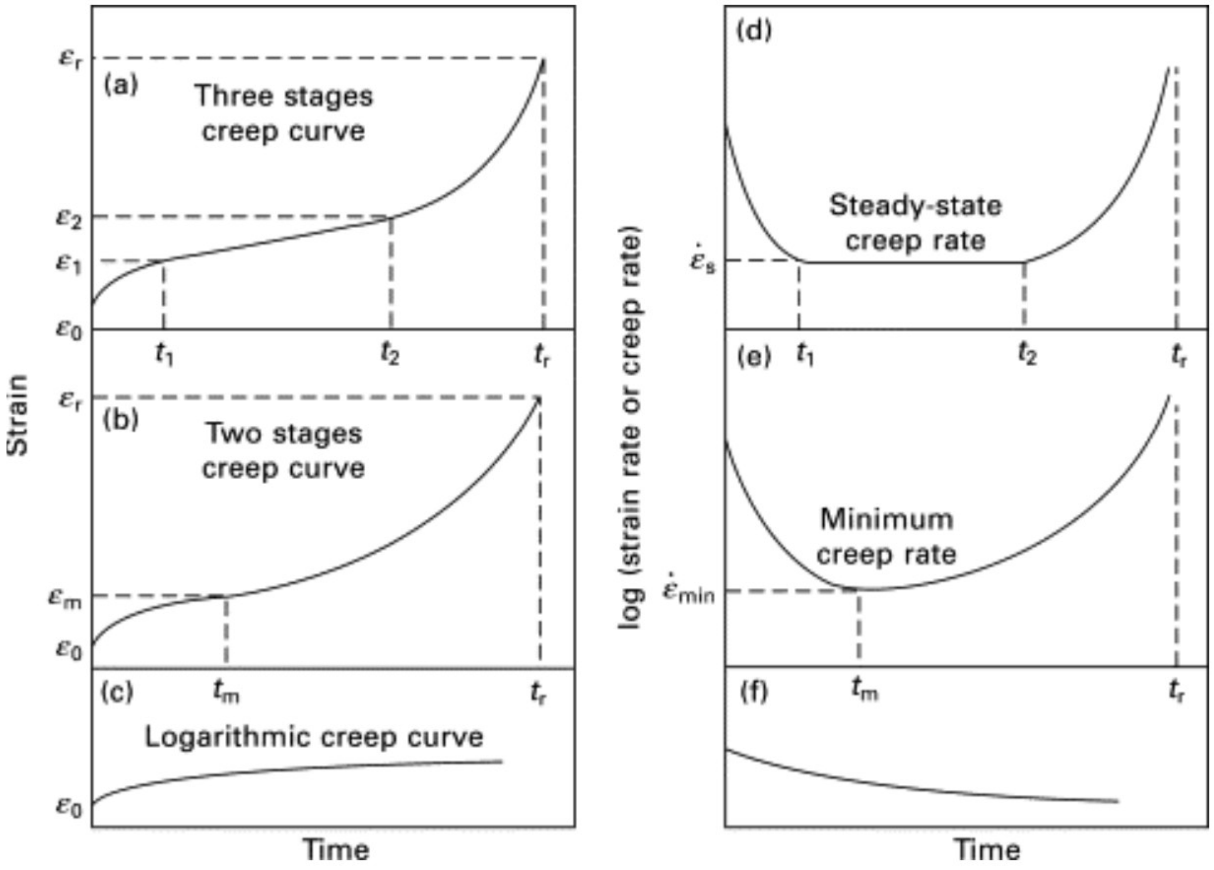
Exponential		
$\dot{\epsilon}_C = a\exp(-Q/RT)$	(Mott, 1953)	(k)
$\epsilon_C = a[t\exp(-Q/RT)]$	(Dorn, 1962)	(l)
$\dot{\epsilon}_C = aT\exp(-Q/RT)$	(Stowell, 1957)	(m)
Rational		
$\epsilon_C = aT^{2/3}f(t)$	(Mott and Nabarro, 1948)	(n)
$\epsilon_C = aTf(t)$	(Smith, 1948)	(o)
$\epsilon_C = f\{T[a + \ln(t)]\}$	(Larson and Miller, 1952)	(p)
$\epsilon_C = f[(T - a)/\ln(t - b)]$	(Manson and Haferd, 1954)	(q)
Hyperbolic-exponential		
$\dot{\epsilon}_C = a\exp(-Q/RT)\sinh(b/RT)$	(Feltham, 1953)	(r)
Other		
$\epsilon_C = cf[t(T - T')^{-B}]$	(Warren, 1967)	(s)



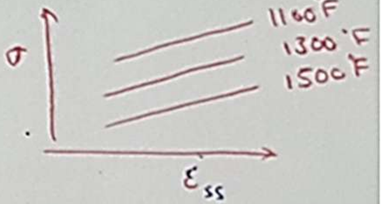
Stress Dependence

Exponential		
$\epsilon_c = af(t)\exp(b\sigma)$	(Dorn, 1962)	(t)
$\dot{\epsilon}_c = a\exp(b + c\sigma)$	(Nadai, 1931)	(u)
$\dot{\epsilon}_c = a[\exp(b\sigma) - 1]$	(Söderberg, 1936)	(v)
Power		
$\epsilon_c = af(t)\sigma^b$	(Dorn, 1962)	(w)
$\epsilon_c = at^n\sigma^b$; $0 < n < 1$, $b > 1$; Bailey–Norton law	(Bailey, 1935) (Norton, 1929)	(x)
Hyperbolic		
$\dot{\epsilon}_c = a\sinh(b\sigma)$	(Ludwik, 1908) (McVetty, 1943)	(y)
$\dot{\epsilon}_c = a\sinh(b\sigma/RT)$	(Feltham, 1953)	(z)

ϵ denotes total strain, ϵ_c creep strain, $\boldsymbol{\sigma}$ stress, T temperature, t time, ln the natural logarithm, exp the exponential e, and a, b, c,..., A, B, C,... parameters that may be functions of $\boldsymbol{\sigma}$, t, T or they may be constants. Time derivative is denoted by a dot over a symbol (e.g.,$\in^{o}$). The notation f(x) denotes a function of x.

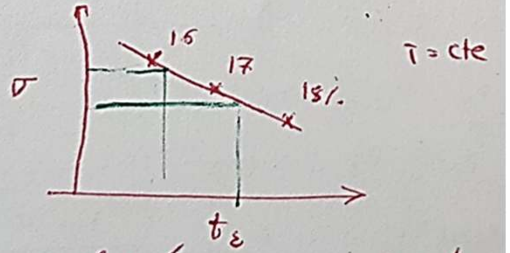

(a)
Three stages creep curve
ε_r
ε_2
ε_1
ε_0
t_1
t_2
t_r
(b)
Two stages creep curve
ε_r
ε_m
ε_0
(c)
t_m
t_r
Logarithmic creep curve
ε_0
Strain
Time
(d)
Steady-state creep rate
$\dot{\varepsilon}_s$
(e)
t_1
t_2
t_r
Minimum creep rate
$\dot{\varepsilon}_{min}$
(f)
t_m
t_r
log (strain rate or creep rate)
Time

$\log \sigma - \log \dot{\varepsilon}_{ss}$



316 فولاد زنگ نزن

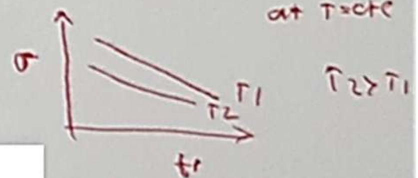
$\sigma - \log t$ (t at $\varepsilon = \varepsilon$ valued)



در یک تنش ثابت برای رسیدن به کرنش بیشتر زمان بیشتری لازم است

$\log \sigma - \log t_r$

at T=cte



تغییر در شیب در یک دمای ثابت

نشان دهنده تغییر مکانیزم شکست یا خزش است

نشان دهنده زمان شکست بر مبنای آهنگ خزش

مرحله دوم

طول موثر ترک

$$t_r = \frac{1}{\varepsilon_0}\left[\frac{\overset{\uparrow}{L}\,\gamma\,8\pi\,(1-\nu)}{\sigma \underset{\text{قطر دانه}}{d^2}}\right]^{1/2}$$

خزش دمای پایین

قطر دانه ∝ طول موثر ترک

Creep Under Multiaxial Loading

(text 14-14)

Use Levy-Mises Equations in plasticity

$$\sigma_{eff} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}$$

and $d\varepsilon_1 = \frac{d\varepsilon_{eff}}{\sigma_{eff}} \left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right]$,

since creep is plastic deformation 1/2 appears as in plasticity.

Similarly, $d\varepsilon_2$ and $d\varepsilon_3$.

Dividing by dt, get the corresponding creep-rates,

$$\dot{\varepsilon}_1 = \frac{\dot{\varepsilon}_{eff}}{\sigma_{eff}} \left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right], \text{ etc.}$$

One first determines the uniaxial creep-rate equation,

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

and assume the same for effective strain-rate : $\dot{\varepsilon}_{eff} = A\,\sigma_{eff}^{n}\, e^{-Q/RT}$

so that $\boxed{\dot{\varepsilon}_1 = A\,\sigma_{eff}^{n-1}\, e^{-Q/RT} \left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right]}$ etc.

Stress Relaxation

(1) Elastic strain, ε_e;
(2) Time-independent plastic strain, ε_p, that occurs on loading;
(3) Time-dependent creep strain, ε_c.

The total strain after loading is therefore given as:

$$\varepsilon_t = \varepsilon_e + \varepsilon_p + \varepsilon_c = \text{constant} \tag{7.72}$$

$$0 = \frac{d\varepsilon_e}{dt} + 0 + \frac{d\varepsilon_c}{dt}; \quad \text{or,} \quad \frac{d\varepsilon_e}{dt} = -\frac{d\varepsilon_c}{dt}$$

But for a linear elastic material, $\varepsilon_e = \sigma/E$, where σ is the instantaneous stress, which is a function of time, and E is the elastic modulus. Hence,

$$\frac{d\varepsilon_e}{dt} = \frac{1}{E}\frac{d\sigma}{dt} \tag{7.74}$$

Substituting (7.74) into (7.73) and then integrating with respect to time t, one obtains

$$\int_{\varepsilon_p}^{\varepsilon_c} \frac{d\varepsilon_c}{dt} dt = -\frac{1}{E}\int_{\sigma_i}^{\sigma} \frac{d\sigma}{dt} dt$$

$$\therefore \varepsilon_c - \varepsilon_p = \frac{\sigma_i - \sigma}{E} \tag{7.75}$$

where ε_p is the time-independent plastic strain at time $t = 0$, when relaxation begins, and σ_i is the initial stress at the same instant. Equation (7.75) shows that as σ decreases ε_c increases. Creep therefore occurs under conditions of decreasing stress.

$$\frac{d\varepsilon_c}{dt} = \dot{\varepsilon}_s = A_2'\sigma^n$$

$$\frac{1}{E}\frac{d\sigma}{dt} = -A_2'\sigma^n \tag{7.77}$$

Equation (7.77) is the differential equation for the idealized case of stress relaxation where steady-state creep at a low stress level and a fixed total strain, ε_t, are assumed. Integrating (7.77), we get

$$\begin{aligned} \int \frac{d\sigma}{\sigma^n} &= -A_2'E \int dt \\ -\frac{1}{(n-1)\sigma^{n-1}} &= -A_2'Et + C \end{aligned} \tag{7.78}$$

where C is the integration constant. At the start of testing, i.e. at time $t = 0$, the initial stress $\sigma = \sigma_i$. From this condition, C can be evaluated from (7.78):

$$C = -\frac{1}{(n-1)\sigma_i^{n-1}} \tag{7.79}$$

Substitution of the value of C from (7.79) into (7.78) gives the relation between stress and time in stress relaxation as follows:

$$\frac{1}{\sigma^{n-1}} = \frac{1}{\sigma_i^{n-1}} + A_2'E(n-1)t \tag{7.80}$$

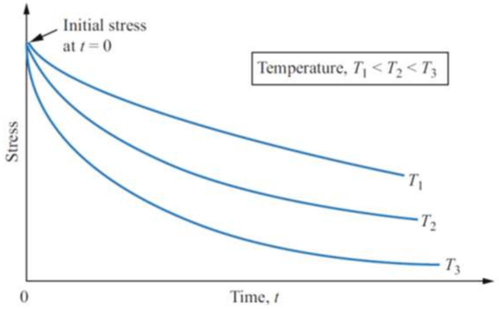


Fig. 7.41 Schematic stress-relaxation curves for a given material at various temperatures for the same initial stress, showing the rate of decrease of stress increases with increasing temperature

$$\sigma_t = \frac{F_t}{A}$$

$$\varepsilon_e = \frac{\sigma_t}{E}$$

$$\varepsilon_i = \varepsilon_e + \varepsilon_p = cte$$

$$\varepsilon_i = \frac{\sigma_t}{E} + \varepsilon_p = cte$$

مشتق میگیریم

$$\frac{d\varepsilon_i}{dt} = \frac{1}{E}\frac{d\sigma_t}{dt} + \frac{d\varepsilon_p}{dt} = 0$$

$$\frac{1}{E}\frac{d\sigma_t}{dt} = -\frac{d\varepsilon_p}{dt} \xrightarrow[T=cte \quad \dot{\varepsilon} = C\sigma^n]{\dot{\varepsilon} = BD_s(\sigma/E)^n \exp(-Q/RT)}$$

$$\frac{1}{E}\frac{d\sigma_t}{dt} = -C\sigma^n$$

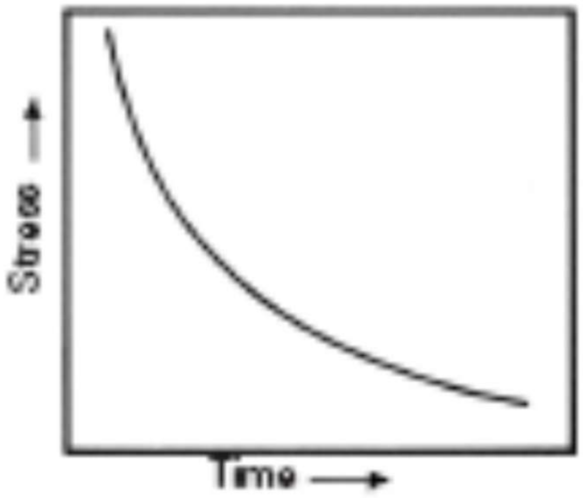
$$\int \frac{d\sigma_t}{\sigma^n} = \int -E\,C\,dt$$

$$\frac{-1}{(n-1)\sigma^{n-1}} = -ECt + k$$

$$\left|\begin{array}{l} t=0 \\ \sigma=\sigma_i \end{array}\right. \rightarrow k = \frac{-1}{(n-1)\sigma^{n-1}}$$

$$\frac{1}{\sigma^{n-1}} = \frac{1}{\sigma_i^{n-1}} + CE(n-1)t$$

Stress Relaxation



7.16.2. A steel bolt clamping two rigid plates together is kept over a period of 5 years at a constant temperature of 650 °C. It is found that the stress (σ in MPa) dependence of steady-state creep rate ($\dot{\varepsilon}_s$ in s^{-1}) for this steel at 650 °C is given by $\dot{\varepsilon}_s = \text{constant}\,(\sigma)^5$. Test of the bolt steel at this temperature indicates that $\dot{\varepsilon}_s = 7 \times 10^{-9}\ s^{-1}$ at a stress of 41 MPa. If Young's modulus of the steel at 650 °C is 124 GPa and the stress in the bolt must not drop below 3 MPa during the 5 years, determine the initial stress to which the bolt must be tightened.

Solution

Given that $\dot{\varepsilon}_s = \text{constant}\,(\sigma)^5$, at 650 °C. Further, it is indicated that when the stress is $\sigma = 41$ MPa, the steady-state creep rate is $\dot{\varepsilon}_s = 7 \times 10^{-9}\ s^{-1}$, therefore

$$\text{Constant, say, } A'_2 = \frac{\dot{\varepsilon}_s}{\sigma^5} = \frac{7 \times 10^{-9}}{(41)^5}\ \text{MPa}^{-5}\ s^{-1}$$
$$= 6.04197 \times 10^{-17}\ \text{MPa}^{-5}\ s^{-1}$$

Since it is given that the dependence of steady-state creep rate ($\dot{\varepsilon}_s$) on stress (σ) is governed by power relation, so the relation between stress and time in stress relaxation will be given by (7.80), which is:

$$\frac{1}{\sigma^{n-1}} = \frac{1}{\sigma_i^{n-1}} + A'_2 E(n-1)t$$

where

σ	the stress remaining after 5 years = 3 MPa;
n	the power index of stress (σ) in the relation between steady-state creep rate ($\dot{\varepsilon}_s$) and stress (σ) = 5;
σ_i	the initial stress in MPa, which is to be determined;
A'_2	the constant in the relation between steady-state creep rate ($\dot{\varepsilon}_s$) and stress (σ) = $6.04197 \times 10^{-17}\ \text{MPa}^{-5}\ s^{-1}$;
E	Young's modulus of the steel at 650 °C = 124×10^3 MPa;
t	the time in seconds = $(5 \times 365.25 \times 24 \times 3600)$ s = 157.788×10^6 s;

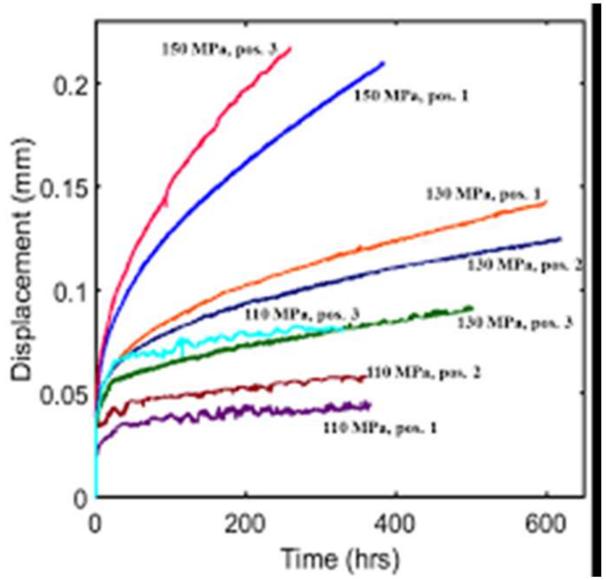
Hence, substituting the above values into (7.80), we get:

$$\frac{1}{\sigma_i^{5-1}} = \frac{1}{(3)^{5-1}} - (6.04197 \times 10^{-17}) \times (124 \times 10^3) \times (5-1) \times (157.788 \times 10^6)$$
$$= 7.617 \times 10^{-3}\ \text{MPa}^{-4}.$$

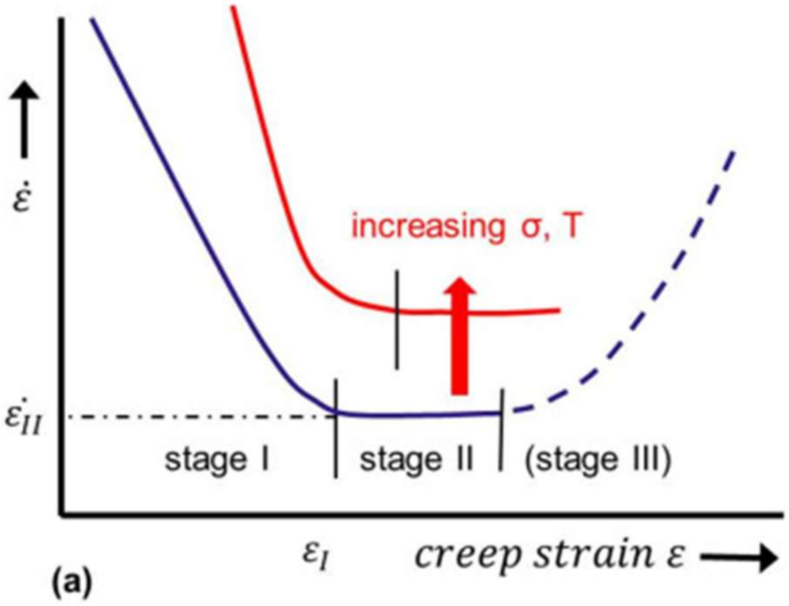
$$\text{Or,}\quad \sigma_i^4 = \frac{1}{7.617 \times 10^{-3}} = 131.285\ \text{MPa}^4;$$

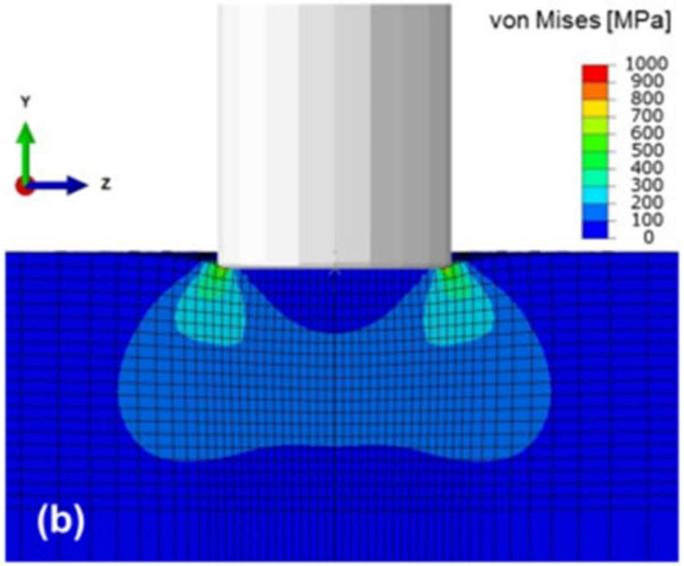
$$\therefore \sigma_i = (131.285)^{\frac{1}{4}}\text{MPa} = \underline{\mathbf{3.385\ MPa}}.$$

Impression Creep–New Creep Test



New flat-punch indentation creep testing





factors that influencing functional life of components at elevated temp?

1) Creep
2) Corrosion
3) High temperature fracture
4) Thermo mechanical Fatigue
5) Micro structural changes
6) Metallurgical ageing and metallurgical stability
7) Interaction of all above with each other

Common Materials and Their Creep Properties

Materials commonly studied for creep (metals, ceramics, polymers)

Creep behavior is studied in various materials, with metals like steel and nickel being common due to their applications in high-temperatures; ceramics and polymers also exhibit unique creep properties under prolonged stress.

Comparison of creep resistance in different materials

Generally, metals exhibit higher creep resistance under high stresses and temperatures, while ceramics show better stability but can be brittle. Polymers often have high creep rates due to their molecular structure.

Case studies of materials with notable creep characteristics

Case studies include superalloys in jet engines that withstand high temperatures while maintaining their strength, and polymer blends that showcase increased longevity in automotive applications.

۳- آزمایش‌های مورد استفاده در دمای بالا

Co, Si, Al و Cr

۱- خزش

۲- خوردگی oxidation, hot corrosion

۳- پایداری فازی و ساختار ← استحاله فازی و دکربوره شدن

۴- ثبات خواص مکانیکی مثل استحکام

۵- خستگی حرارتی thermal fatigue or thermomechanical fatigue

شکست در اثر تنش سیکلی در حین تکرار تنش کشش اتفاق می‌افتد - ترک خستگی از سطح شروع می‌شود پس ناصافی سطح مهم است

$\varepsilon = \alpha E \Delta T$

کرنش ناشی از دما
کرنش ناشی از دما و تنش

۶- پارامترهای شوک حرارتی (حضور فازهای ترد سولفیدی)

Design Considerations to avoid Creep

- Reduce the effect of grain boundaries:
  - Use single crystal material with large grains.
  - Addition of solid solutions to eliminate vacancies.
- Employ materials of high melting temperatures.
- Consult Creep Test Data during materials Selection
  - Type of service application
  - Set adequate inspection intervals according to life expectancy.

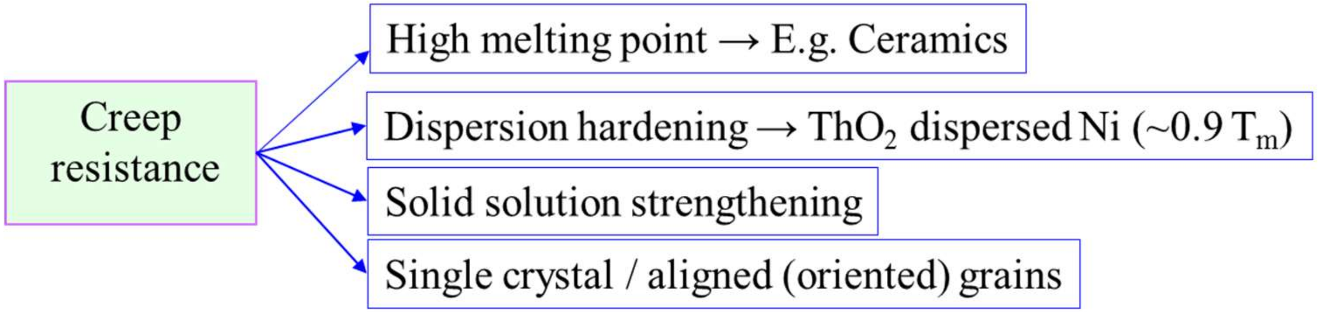
- High Temp Behavior of Materials:

Mechanical degradation

Chemical Degradation

- Gas Turbine and jet Turbine
- Nuclear reactors
- Power plants
- Spacecraft
- Chemical processing

$$\varepsilon_{ss}^{ceramics} < \varepsilon_{ss}^{metals} << \varepsilon_{ss}^{polymers}$$



Creep resistance

- High melting point → E.g. Ceramics
- Dispersion hardening → ThO_2 dispersed Ni (~0.9 T_m)
- Solid solution strengthening
- Single crystal / aligned (oriented) grains

Rules for Increasing Creep Resistance

- Large Grain Size
  (directionally solidified superalloys)

- Low Stacking Fault Energy
  (Cu vs Cu-Al alloys)

- Solid Solution Alloying
  (Al vs Al-Mg alloys)

- Dispersion Strengthening
  (Ni vs TD-Ni)

Parameters affects the creep

1- Microstructure (grain size, columnar grain)

2- Chemical composition (solid solution and precipitates)and purity

3- Melting temperature

4- Production technique

عوامل مؤثر بر خزش   دانه جهت دار ستونی → D optimum   دانه های ستونی مرحله سوم گسترده تری دارند .

۱- اندازه دانه   ① $Q = f(D)$: افزایش اندازه دانه مقاومت به خزش با ε را بالا می برد ② نقش مرزدانه ای ، ③ حفره ها و ترک ها ، ④ حضور ناخالصی ها در مرزدانه و تجمع

۲- تبلور مجدد $\varepsilon \propto \frac{2}{h}$ با کار موفقی (٢) میزان ε افزایش می یابد.

۳- اثر پیش کرنش یا کار سختی   پیش کرنش مضراتش فقط اگر کرنش ی وجود داشته باشد

باید آزادسازی تنش باید اتفاق می افتد .

حد خزش بر حسب کار سرد

تنش هایی که کمتر از آن خزش اتفاق می افتد

Effect of structure and properties on creep resistance:

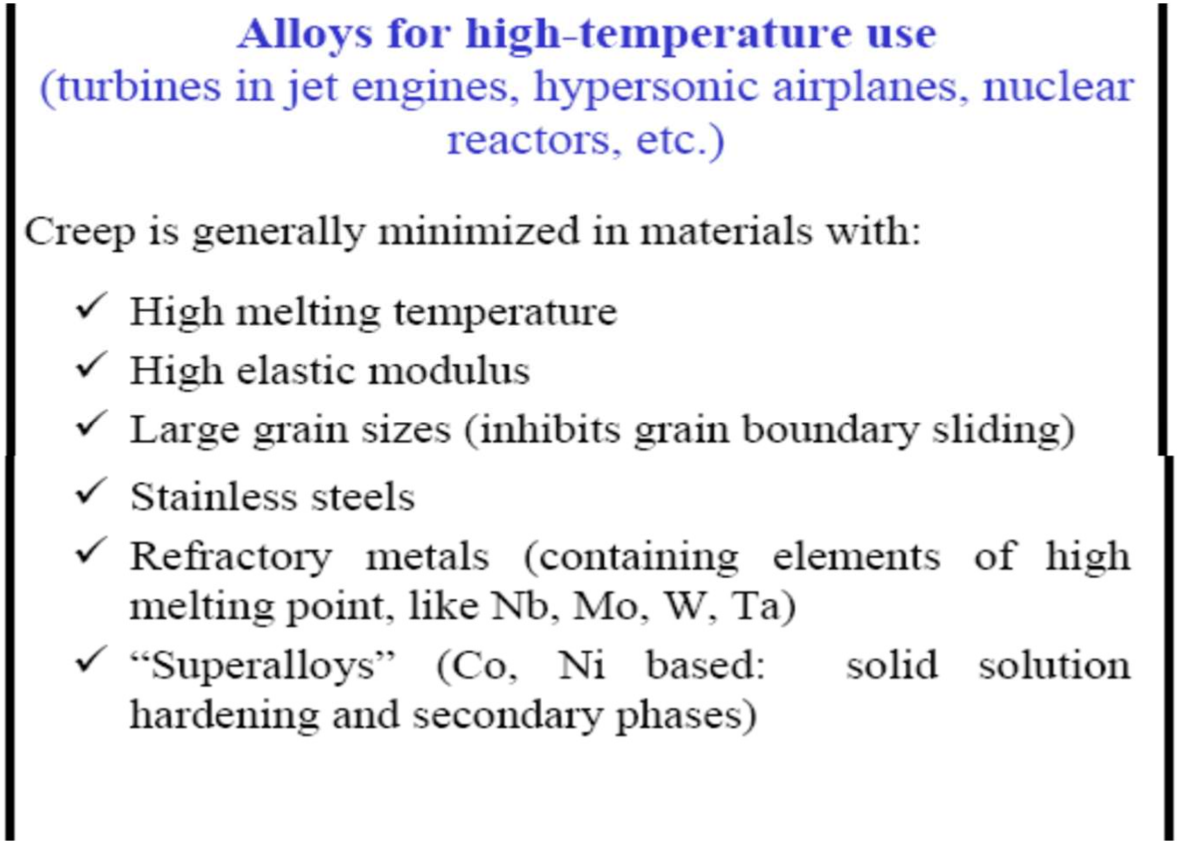
- ε• ↑ with: ↑ applied stress, ↑ diffusivity (↓ activation energy), ↓ grain size
- For a given application T, use of higher T_{mp} material will ↓diffusivity and correspondingly ↓ ε_{ss}
- In general:

- Diffusivities in bcc metals >> diffusivities in fcc metals
- if we have a bcc metal and an fcc metal with the same T_{mp}, then

  ε• *bcc* > ε• *fcc*

- ↑ grain size, ↓ ε• for diffusion controlled creep but does not have any influence on the dislocation creep mechanism.

- For dislocation glide mechanism: ↑ in grain size will ↑ε•



Alloys for high-temperature use

(turbines in jet engines, hypersonic airplanes, nuclear reactors, etc.)

Creep is generally minimized in materials with:

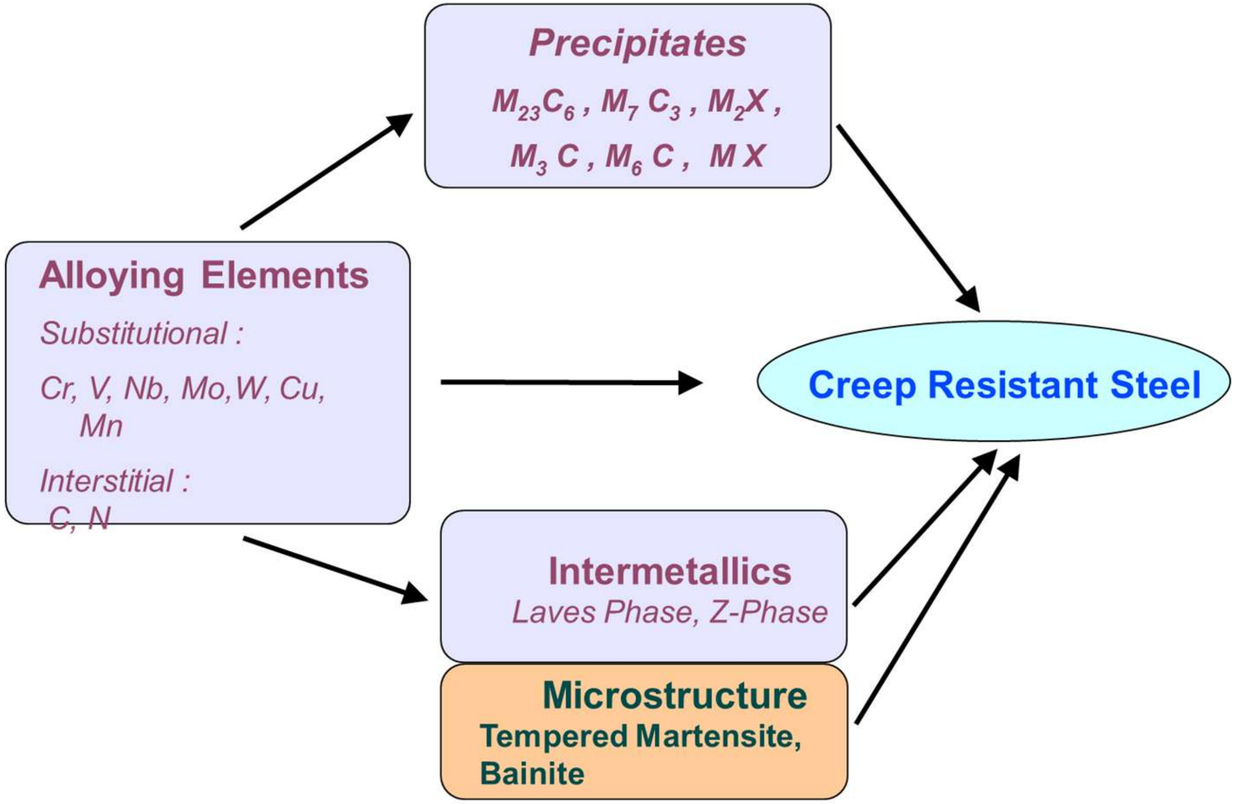
- ✓ High melting temperature
- ✓ High elastic modulus
- ✓ Large grain sizes (inhibits grain boundary sliding)
- ✓ Stainless steels
- ✓ Refractory metals (containing elements of high melting point, like Nb, Mo, W, Ta)
- ✓ "Superalloys" (Co, Ni based: solid solution hardening and secondary phases)

2477 ºC
2896 ºC
3695 ºC
3290 ºC

Resistance to Creep

- ⇒ Solid solution hardening
- ⇒ Precipitate hardening
- ⇒ Microstructure

Heat Resisting Steel



Precipitates

$M_{23}C_6$, M_7C_3 , M_2X ,

M_3C , M_6C , MX

Alloying Elements

Substitutional :

Cr, V, Nb, Mo,W, Cu, Mn

Interstitial :

C, N

Creep Resistant Steel

Intermetallics

Laves Phase, Z-Phase

Microstructure

Tempered Martensite, Bainite

Creep resistance alloys

1- superalloy

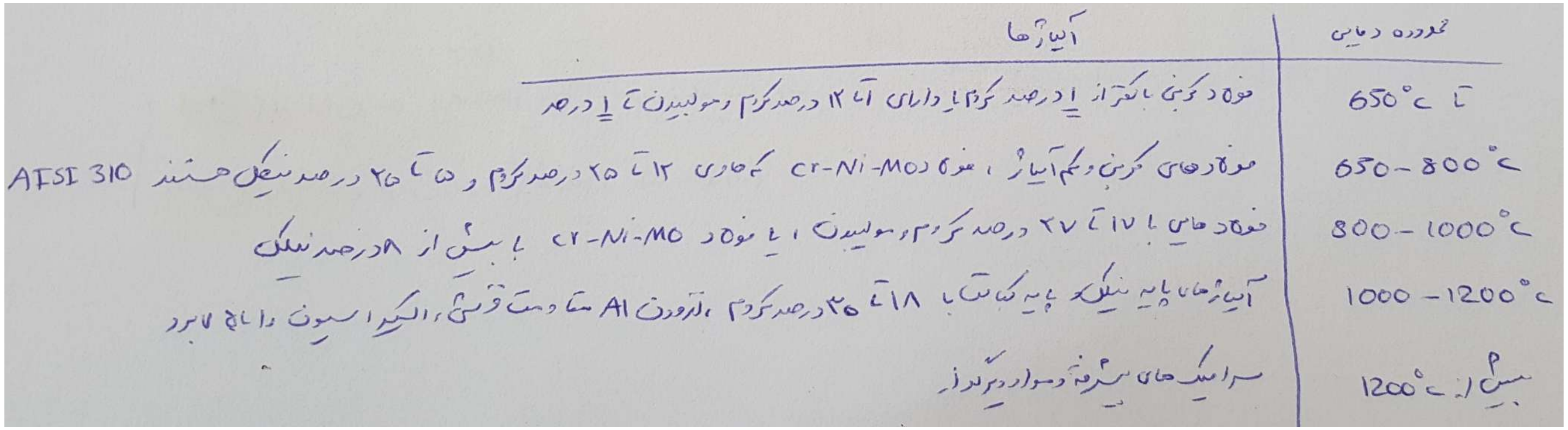
2- stainless steel (ferritic and austenitic matrix): 9-12 % Cr, Mo, V (9Cr-1Mo-0.2V steel)

with temperature up to 550 °C and 650 °C, respectively

3- high melting point metals

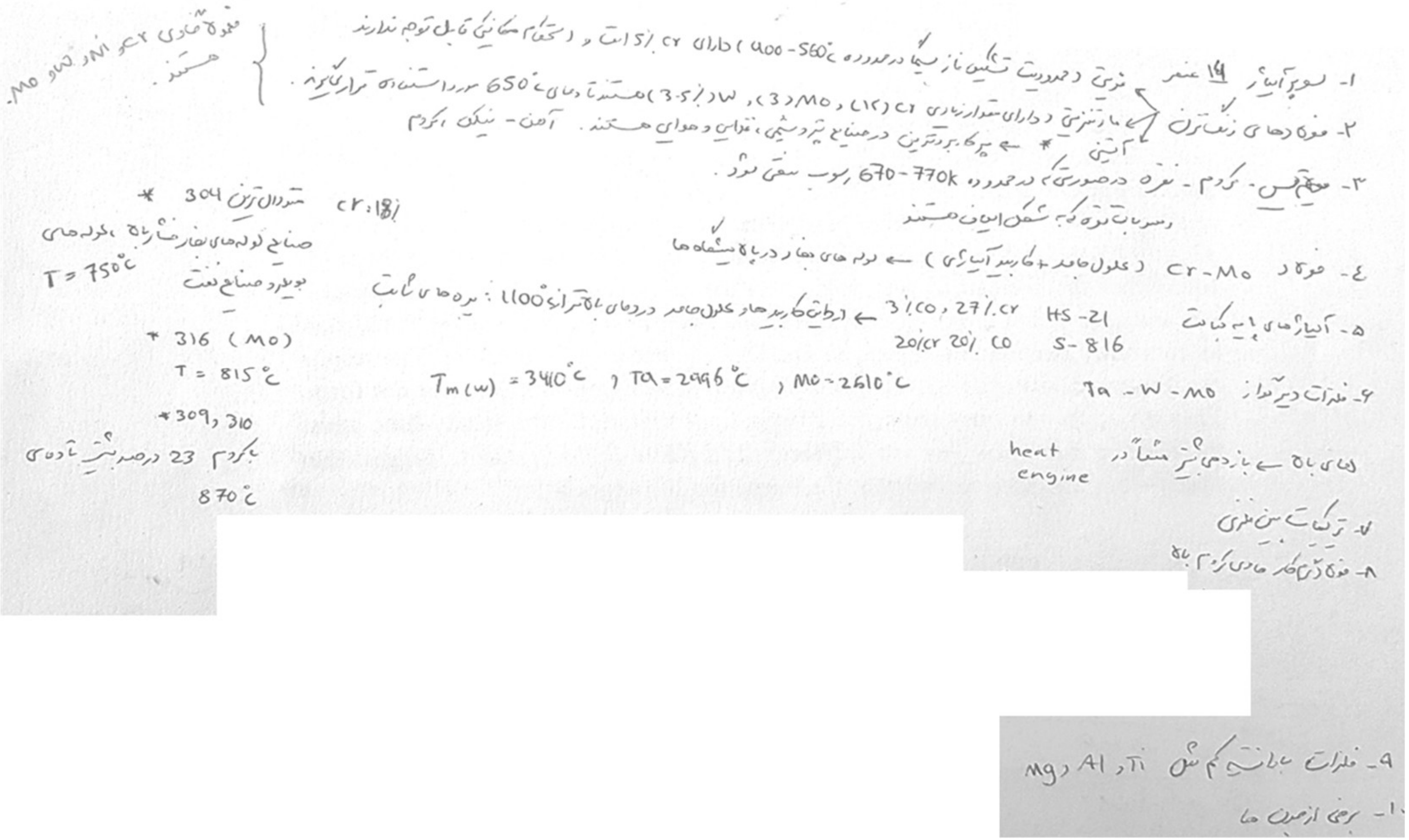
4- cast-iron

5-aluminum



محدوده دمایی	آلیاژها
تا 650°C	فولاد کربنی با کمتر از ½ درصد کروم یا دارای ۱ تا ۱۲ درصد کروم و مولیبدن تا ½ درصد
650-800°C	فولادهای کربنی و کم آلیاژ، فولاد Cr-Ni-Mo که حاوی ۱۲ تا ۲۵ درصد کروم و ۵ تا ۲۵ درصد نیکل هستند AISI 310
800-1000°C	فولادهایی با ۱۷ تا ۲۷ درصد کروم و مولیبدن، یا فولاد Cr-Ni-Mo با بیش از ۸ درصد نیکل
1000-1200°C	آلیاژهای پایه نیکل و پایه کبالت با ۱۸ تا ۳۵ درصد کروم، افزودن Al مقاومت خزشی، اکسیداسیون را بالا می‌برد
بیش از 1200°C	سرامیک‌های پیشرفته و مواد دیرگداز

Creep resistance alloys



۱- سوپرآلیاژ ۱۴ عنصر

۲- فولادهای زنگ نزن
- فریتی (محدودیت تشکیل فاز سیگما در محدوده 400-560°c) دارای cr ۱۵٪ است و استحکام مکانیکی قابل توجه ندارند
- مارتنزیتی دارای مقدار زیادی cr (۱۲)، Mo (۳)، W (۳-۵٪) هستند تا دمای 650°c مورد استفاده قرار می‌گیرند.
- آستنیتی * ← پرکاربردترین در صنایع پتروشیمی، غذایی و هوایی هستند. آهن - نیکل - کروم

معمولاً حاوی ۲cr و ۸Ni و گاهی Mo هستند.

* 304 متداول‌ترین cr: 18٪
صنایع لوله‌های تحت فشار، لوله‌های بویلر و صنایع نفت
T = 750°c

* 316 (Mo)
T = 815°c

* 309, 310
با کروم 23 درصد بیشتر تا دمای
870°c

۳- مس - کروم - نقره در صورتی که در محدوده 670-770k رسوب سختی شود.
رسوبات نقره که به شکل [illegible] هستند

۴- فولاد Cr-Mo (محلول جامد + کاربید آلیاژی) ← لوله‌های بخار در پالایشگاه‌ها

۵- آلیاژهای پایه کبالت
HS-21 ٪27 cr، ٪3 co ← در اثر کاربیدها و محلول جامد در دماهای بالاتر از 1100°: پره‌های ثابت
S-816 ٪20 cr ٪20 co

۶- فلزات دیرگداز Ta - W - Mo
$T_{m(W)} = 3410°c$ ، $Ta = 2996°c$ ، $Mo = 2610°c$

دمای بالا ← بازدهی بیشتر مثلاً در heat engine

۷- ترکیبات بین فلزی

۸- فولاد ابزار کار داغ گروه H

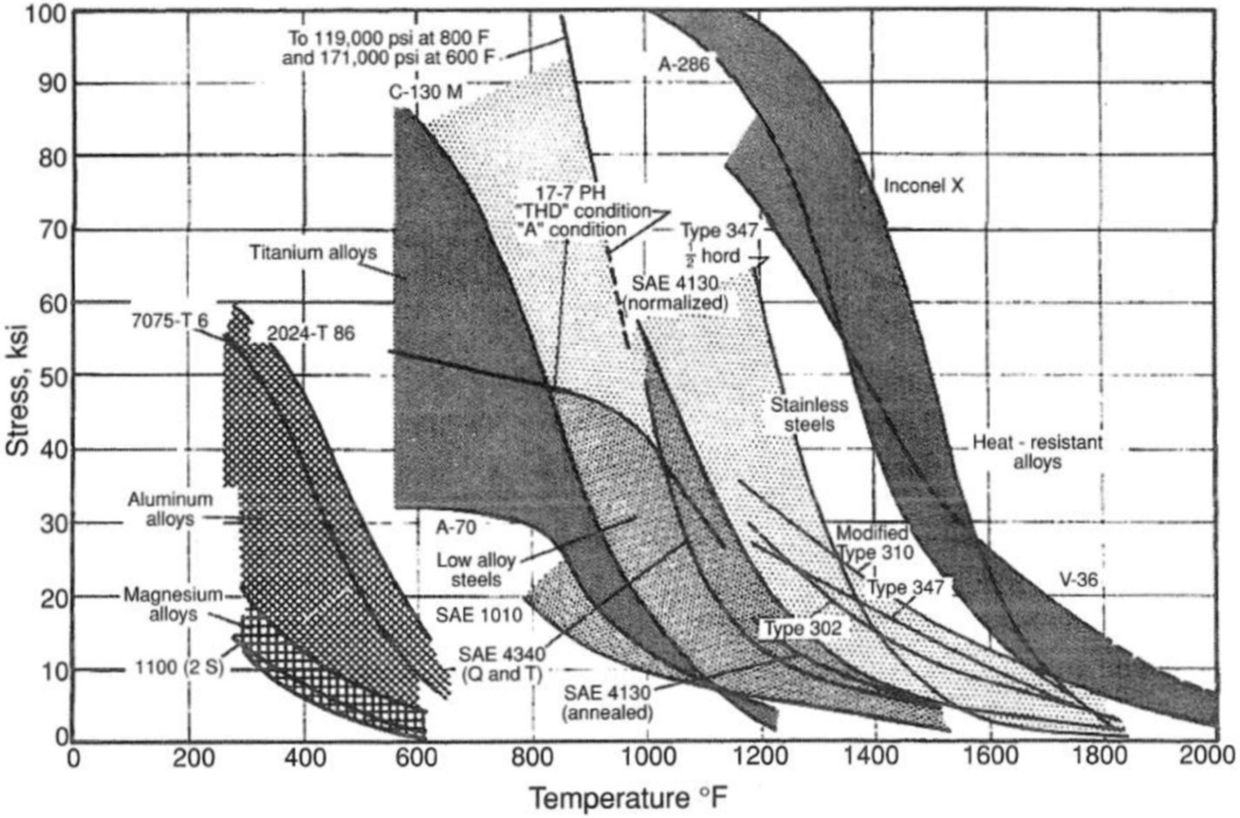
۹- فلزات سبک مثل Ti، Al و Mg

۱۰- برخی از چدن‌ها

Creep Resist Materials

400 to 575°C	Low alloy ferritic steels Titanium alloys (up to 450°C) Inconels and nimonics	Heat exchangers Steam turbines Gas turbine compressors
575 to 650°C	Iron-based super-alloys Ferritic stainless steels Austenitic stainless steels Inconels and nimonics	Steam turbines Superheaters Heat exchangers
650 to 1000°C	Austenitic stainless steels Nichromes, nimonics Nickel based super-alloys Cobalt based super-alloys	Gas turbines Chemical and petrochemical reactors Furnace components Nuclear construction
Above 1000°C	Refractory metals: Mo, W, Ta Alloys of Nb, Mo, W, Ta Ceramics: Oxides Al_2O_3, MgO etc. Nitrides, Carbides: Si_3N_4, SiC	Special furnaces Experimental turbines

Alloys for high temperature applications



A **superalloy**, or **high-performance alloy**, is an alloy with the ability to operate at a high fraction of its melting point.

Several key characteristics of a superalloy are excellent mechanical strength, resistance to thermal creep deformation, and resistance to corrosion or oxidation.

The crystal structure is typically face-centered cubic (FCC) austenitic.

Superalloys develop high temperature strength through solid solution strengthening and precipitation strengthening from secondary phase precipitates such as gamma prime and carbides.

Oxidation or corrosion resistance is provided by elements such as aluminium and chromium.

1- **Ni-based superalloys** have emerged as the material of choice for these applications.

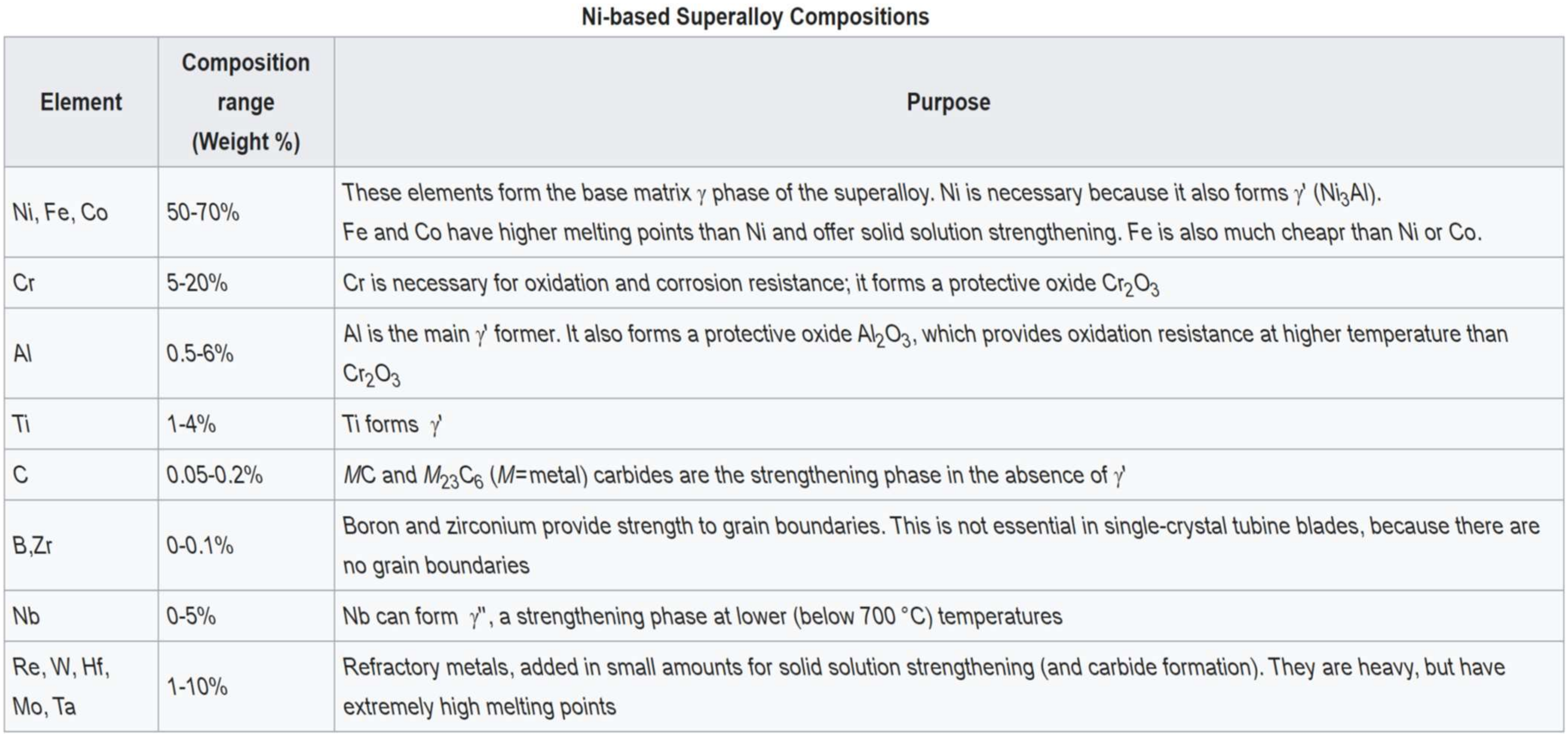
2- **Co-based superalloys** potentially possess superior hot corrosion, oxidation, and wear resistance as compared to Ni-based superalloys.

3-**Fe-based superalloy**

The use of steels in superalloy applications is of interest because certain steel alloys have showed creep and oxidation resistance similar to that of Ni-based superalloys, while being far less expensive to produce.

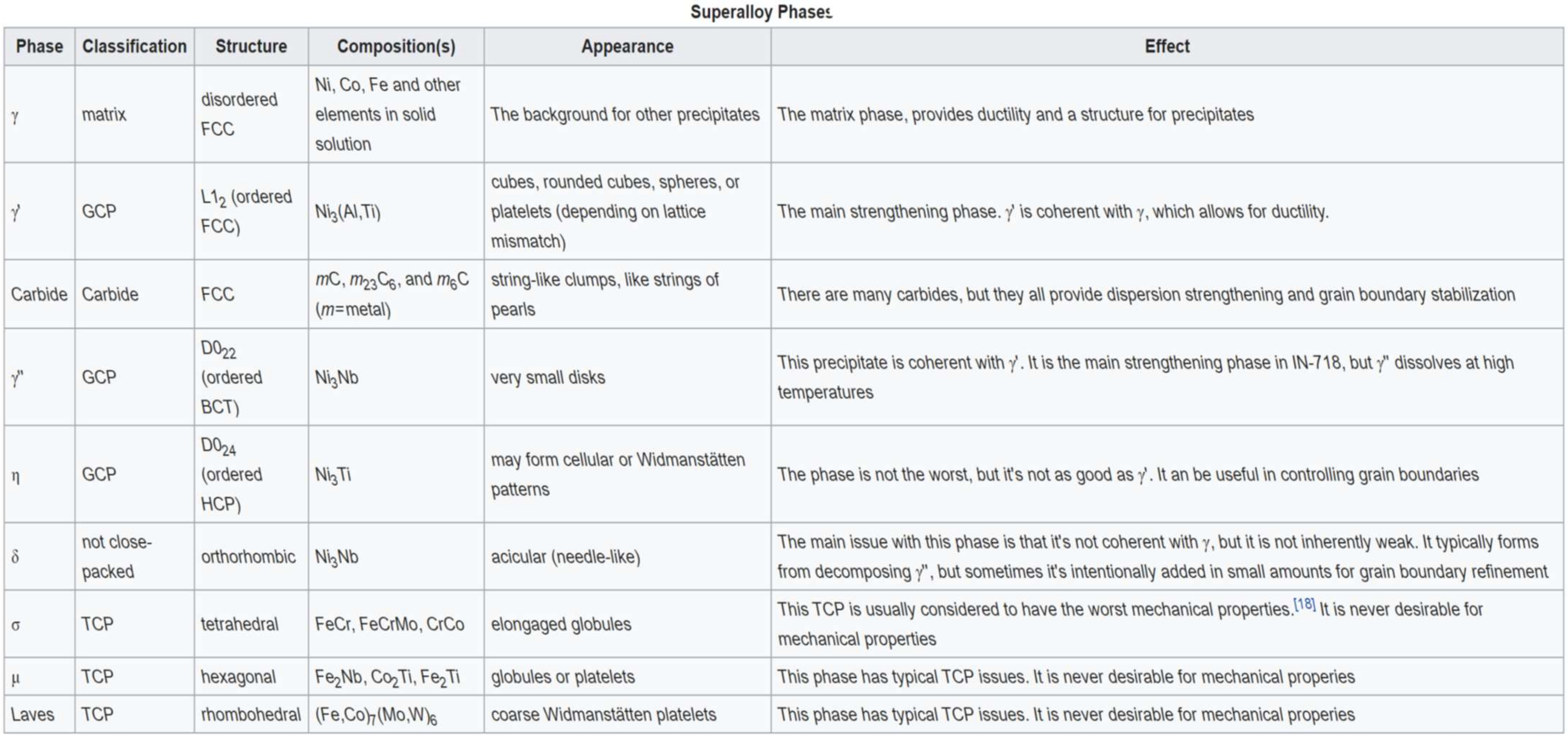
Super alloys including not only metals, but also nonmetals; chromium, iron, cobalt, molybdenum, tungsten, tantalum, aluminium, titanium, zirconium, niobium, rhenium, yttrium, vanadium, carbon, boron or hafnium are some examples of the alloying additions used.

Each of these additions has been chosen to serve a particular purpose in optimizing the properties for high temperature application.



Ni-based Superalloy Compositions

Element	Composition range (Weight %)	Purpose
Ni, Fe, Co	50-70%	These elements form the base matrix γ phase of the superalloy. Ni is necessary because it also forms γ' (Ni_3Al). Fe and Co have higher melting points than Ni and offer solid solution strengthening. Fe is also much cheapr than Ni or Co.
Cr	5-20%	Cr is necessary for oxidation and corrosion resistance; it forms a protective oxide Cr_2O_3
Al	0.5-6%	Al is the main γ' former. It also forms a protective oxide Al_2O_3, which provides oxidation resistance at higher temperature than Cr_2O_3
Ti	1-4%	Ti forms γ'
C	0.05-0.2%	MC and $M_{23}C_6$ (M=metal) carbides are the strengthening phase in the absence of γ'
B,Zr	0-0.1%	Boron and zirconium provide strength to grain boundaries. This is not essential in single-crystal tubine blades, because there are no grain boundaries
Nb	0-5%	Nb can form γ'', a strengthening phase at lower (below 700 °C) temperatures
Re, W, Hf, Mo, Ta	1-10%	Refractory metals, added in small amounts for solid solution strengthening (and carbide formation). They are heavy, but have extremely high melting points



Superalloy Phases

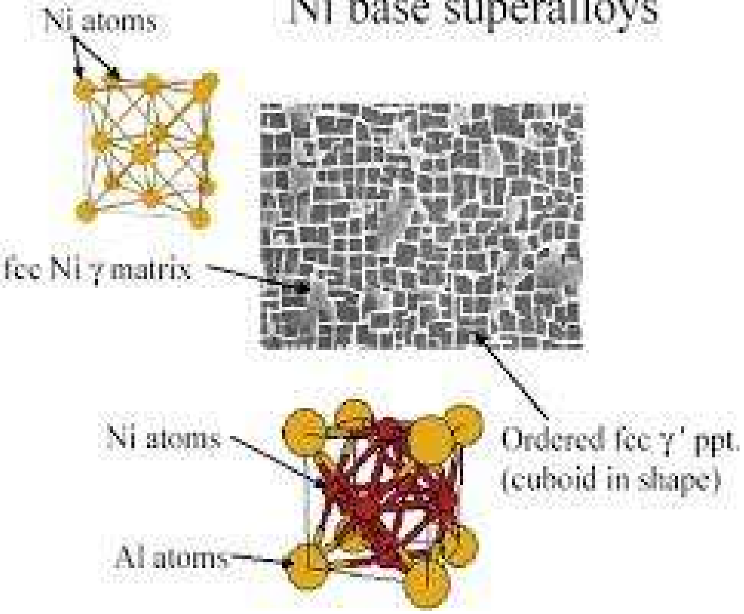
Phase	Classification	Structure	Composition(s)	Appearance	Effect
γ	matrix	disordered FCC	Ni, Co, Fe and other elements in solid solution	The background for other precipitates	The matrix phase, provides ductility and a structure for precipitates
γ'	GCP	$L1_2$ (ordered FCC)	$Ni_3(Al,Ti)$	cubes, rounded cubes, spheres, or platelets (depending on lattice mismatch)	The main strengthening phase. γ' is coherent with γ, which allows for ductility.
Carbide	Carbide	FCC	mC, $m_{23}C_6$, and m_6C (m=metal)	string-like clumps, like strings of pearls	There are many carbides, but they all provide dispersion strengthening and grain boundary stabilization
γ''	GCP	$D0_{22}$ (ordered BCT)	Ni_3Nb	very small disks	This precipitate is coherent with γ'. It is the main strengthening phase in IN-718, but γ'' dissolves at high temperatures
η	GCP	$D0_{24}$ (ordered HCP)	Ni_3Ti	may form cellular or Widmanstätten patterns	The phase is not the worst, but it's not as good as γ'. It an be useful in controlling grain boundaries
δ	not close-packed	orthorhombic	Ni_3Nb	acicular (needle-like)	The main issue with this phase is that it's not coherent with γ, but it is not inherently weak. It typically forms from decomposing γ'', but sometimes it's intentionally added in small amounts for grain boundary refinement
σ	TCP	tetrahedral	FeCr, FeCrMo, CrCo	elongaged globules	This TCP is usually considered to have the worst mechanical properties.[18] It is never desirable for mechanical properties
μ	TCP	hexagonal	Fe_2Nb, Co_2Ti, Fe_2Ti	globules or platelets	This phase has typical TCP issues. It is never desirable for mechanical properies
Laves	TCP	rhombohedral	$(Fe,Co)_7(Mo,W)_6$	coarse Widmanstätten platelets	This phase has typical TCP issues. It is never desirable for mechanical properies

-The γ’ phase is a cubic L12-structure Ni3(Al, Ti, Ta, Nb) phase that produces cuboidal precipitates. Superalloys often have a high (60-75%) volume fraction of γ’ precipitates. γ’ precipitates are coherent with the parent γ phase, and are resistant to shearing due to the development of an anti-phase boundary when the precipitate is sheared.

-The γ” phase is a tetragonal Ni3Nb or Ni3V structure. The γ” phase, however, is unstable above 650 °C, so γ” is less commonly used as a strengthening phase in high temperature applications.

-Carbides are also used in polycrystalline superalloys to inhibit grain boundary sliding.

Ni base superalloys



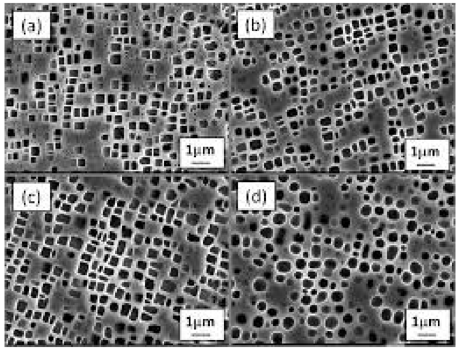
Ni atoms

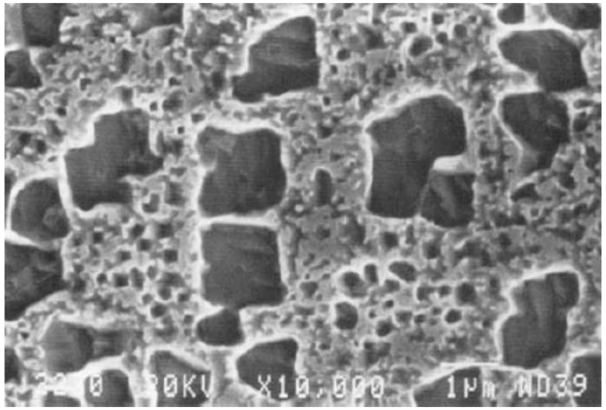
fcc Ni γ matrix

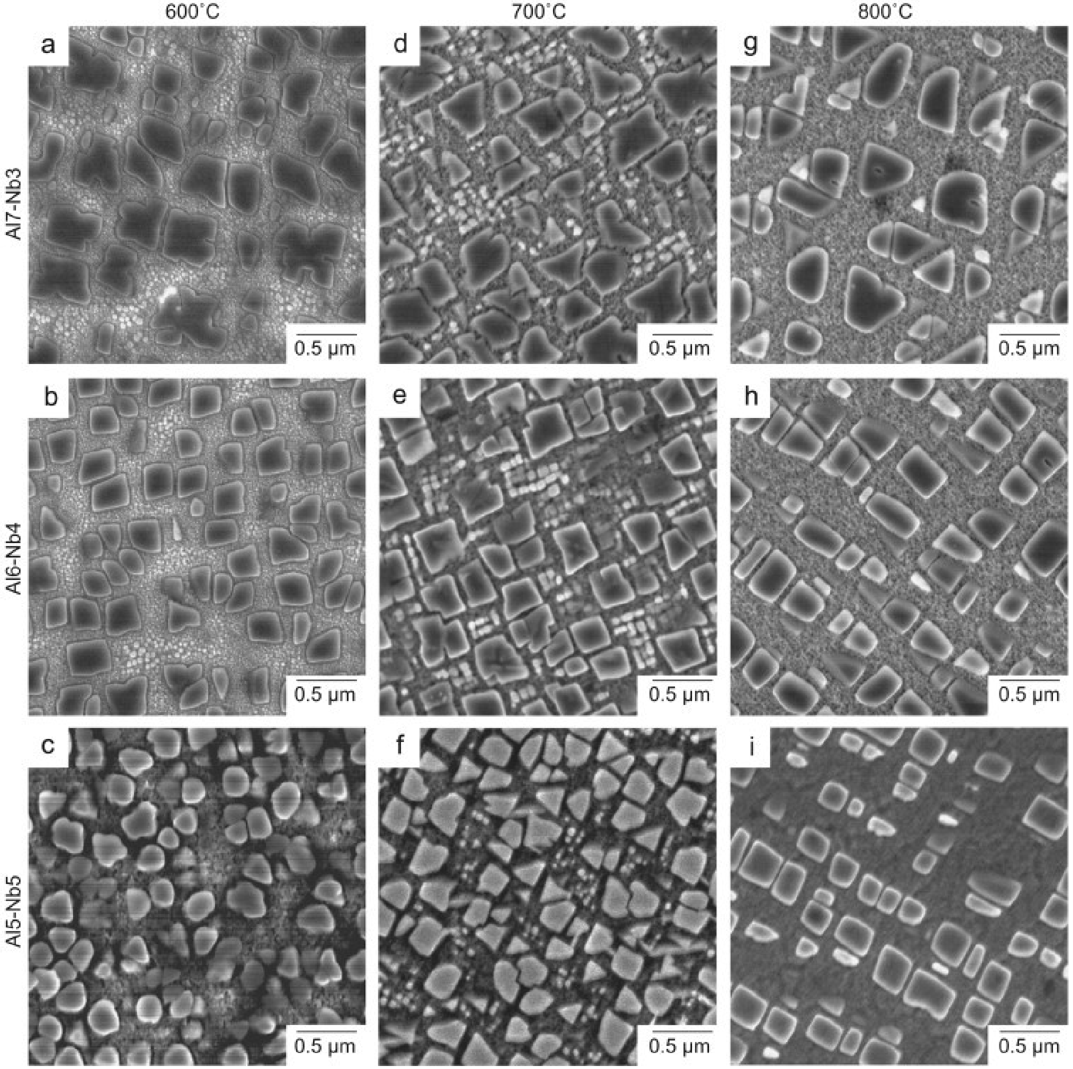
Ni atoms

Al atoms

Ordered fcc γ' ppt.
(cuboid in shape)





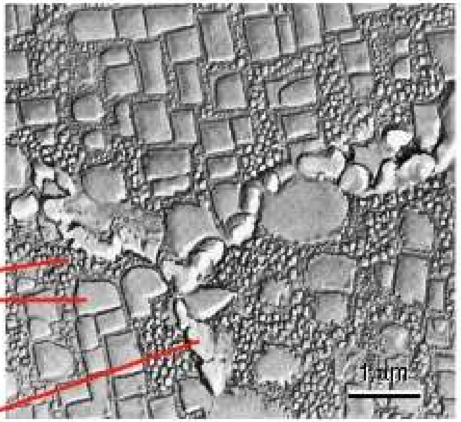

600˚C
700˚C
800˚C
Al7-Nb3
Al6-Nb4
Al5-Nb5
a
b
c
d
e
f
g
h
i
0.5 µm

SUPERALLOYS

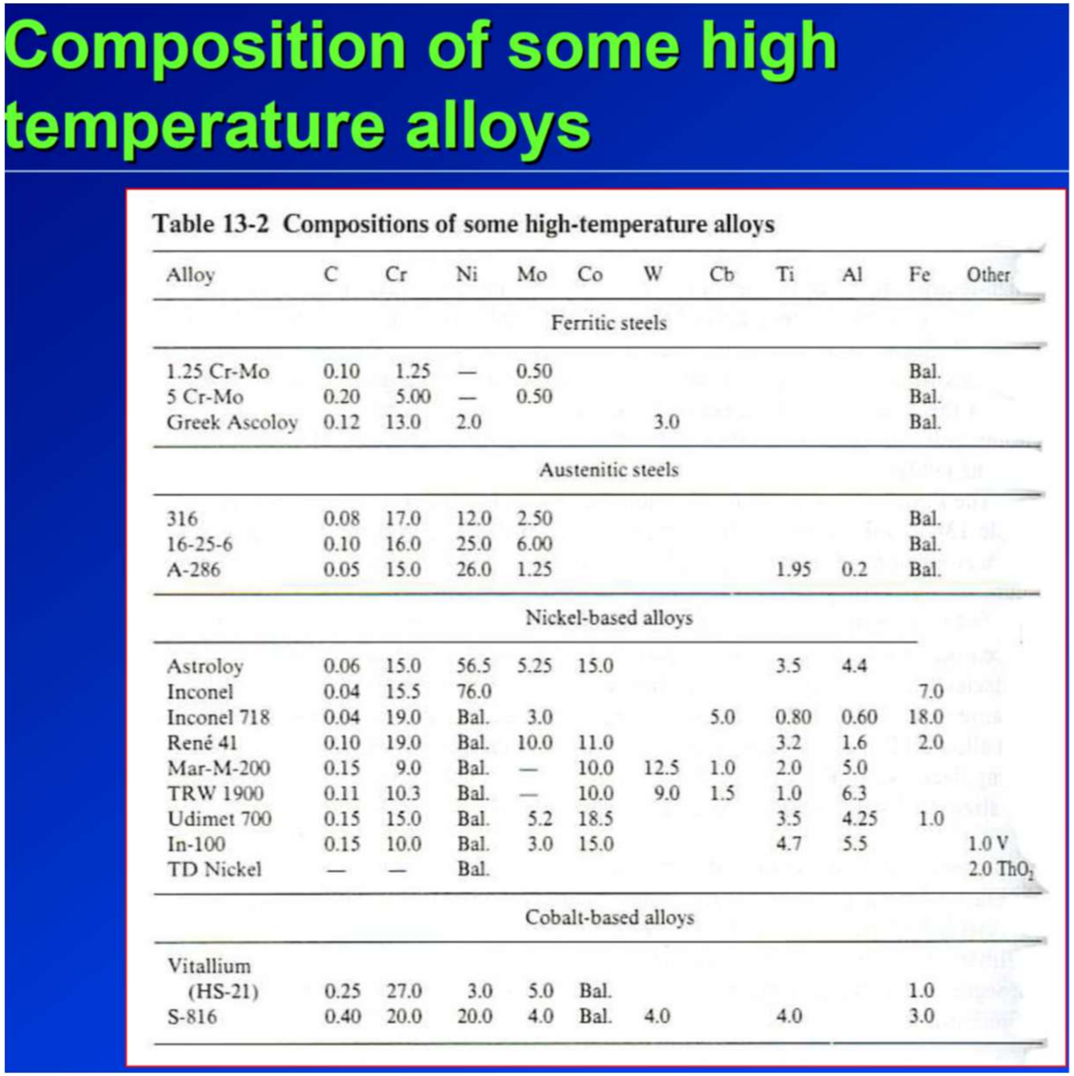
STRENGTHENING MECHANISM

Three strengthening mechanisms are used in Ni superalloys:

- **Solid solution hardening**
- **Coherent precipitate hardening**
- **Carbide phases on grain boundaries**



Examples of such alloys are Hastelloy, Inconel, Waspaloy, Rene alloys, Incoloy, MP98T, TMS alloys, and CMSX single crystal alloys.



Composition of some high temperature alloys

Table 13-2 Compositions of some high-temperature alloys

Alloy	C	Cr	Ni	Mo	Co	W	Cb	Ti	Al	Fe	Other
Ferritic steels											
1.25 Cr-Mo	0.10	1.25	—	0.50						Bal.	
5 Cr-Mo	0.20	5.00	—	0.50						Bal.	
Greek Ascoloy	0.12	13.0	2.0			3.0				Bal.	
Austenitic steels											
316	0.08	17.0	12.0	2.50						Bal.	
16-25-6	0.10	16.0	25.0	6.00						Bal.	
A-286	0.05	15.0	26.0	1.25				1.95	0.2	Bal.	
Nickel-based alloys											
Astroloy	0.06	15.0	56.5	5.25	15.0			3.5	4.4		
Inconel	0.04	15.5	76.0							7.0	
Inconel 718	0.04	19.0	Bal.	3.0			5.0	0.80	0.60	18.0	
René 41	0.10	19.0	Bal.	10.0	11.0			3.2	1.6	2.0	
Mar-M-200	0.15	9.0	Bal.	—	10.0	12.5	1.0	2.0	5.0		
TRW 1900	0.11	10.3	Bal.	—	10.0	9.0	1.5	1.0	6.3		
Udimet 700	0.15	15.0	Bal.	5.2	18.5			3.5	4.25	1.0	
In-100	0.15	10.0	Bal.	3.0	15.0			4.7	5.5		1.0 V
TD Nickel	—	—	Bal.								2.0 ThO_2
Cobalt-based alloys											
Vitallium (HS-21)	0.25	27.0	3.0	5.0	Bal.					1.0	
S-816	0.40	20.0	20.0	4.0	Bal.	4.0		4.0		3.0	

Phase Formation

Adding new elements is usually good because of solid solution strengthening, but engineers need to be careful about which phases precipitate.

Precipitates can be classified as geometrically close-packed (GCP), topologically close-packed (TCP), or carbides. GCP phases are usually good for mechanical properties, but TCP phases are often deleterious. Because TCP phases are not truly close packed, they have few slip systems and are very brittle. They are additionally bad because they "scavenge" elements away from GCP phases.

Many elements that are good for forming γ' or have great solid solution strengthening may precipitate TCPs.

Engineers need to find the balance.

An area of the alloy with TCP phase formation will be weak because

- the TCP phase has inherently poor mechanical properties
- the TCP phase is incoherent with the γ matrix
- the TCP phase is surrounded by a "depletion zone" where there is no γ'
- the TCP phase usually forms sharp plate or needle-like morphologies which easily nucleate cracks