

# 3. CREEP OF METALS

**Lecturer:**

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# High temperature applications

- Steel power plants
- Oil refineries
- Chemical plants

High operating temperatures

Engine jet ----1400°C

Steam turbine power plants: pipes carry steam  
(~566°C, pressure ~ 3500 psi)

surface reentry temperature ~ 2800°C (e.g. Apollo rocket)  
...Temperatures generated within the hottest area during  
ballistic reentry may exceed 11,100 °C



## What happen to the strength at elevated temperature

Strength becomes.....

very dependent to strain rate and time of  
exposure

Called

# Creep

# MECHANICAL FAILURE - CREEP



# MECHANICAL FAILURE – CREEP

## ISSUES TO ADDRESS...

- Creep curve
- Revisit dislocations
- Revisit diffusion
- Creep testing
- Creep failure
- Larson-Miller parameter



- Many engineering components are exposed to high temperature for a long period of time.
- Changes within the component due to this (at constant stress) is called Creep.
- e.g. Turbine blade within a jet engine, steam generator.

World trade center, WTC collapsed, due to creep

## WHAT IS CREEP?

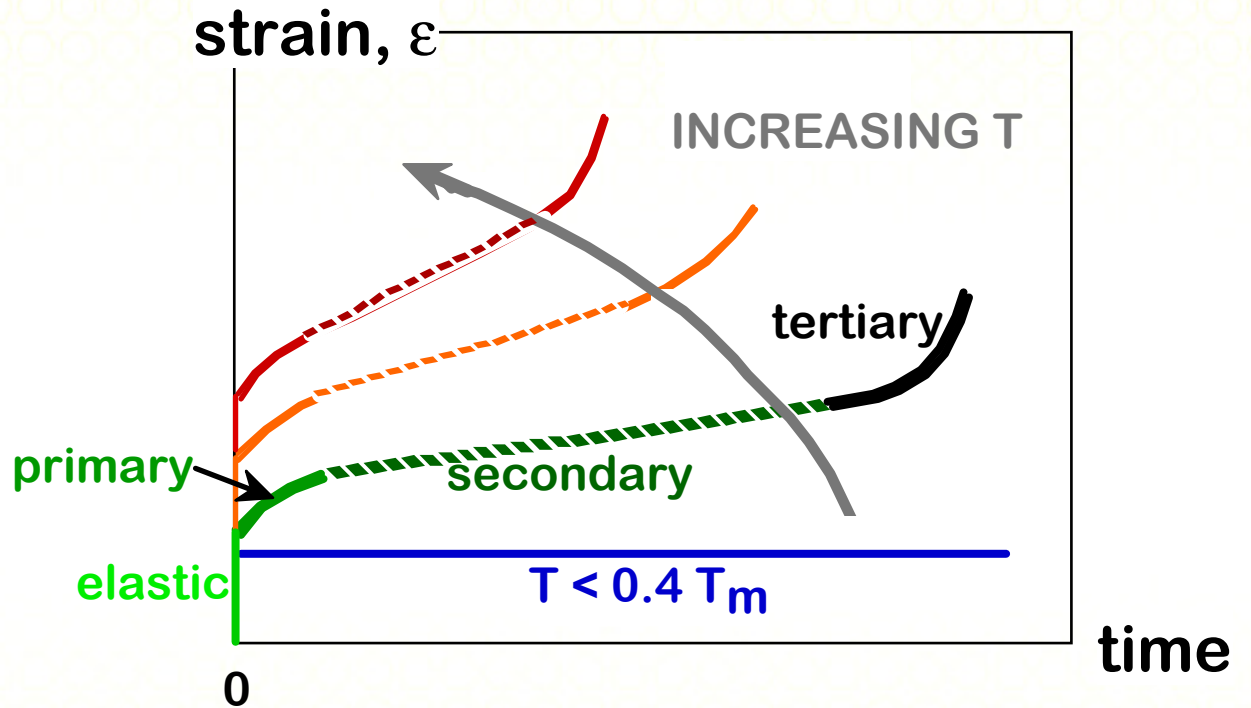
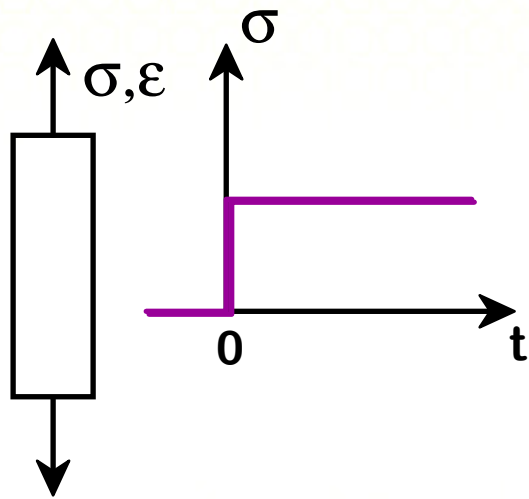
- Time – dependent permanent plastic deformation, which generally occurs at high temperatures ( $T > 0.4T_m$ ), under a constant load or stress.
  - It can also happened at room temperature for soft metals such as Lead.
  - It is a slow process, where deformation changes with time.

Creep is important in applications such as: turbine blades (jet engines), gas turbines, power plants (boilers and steam lines) which must operate at high stresses and high temperatures without any changes in dimensions.

## THEORY OF CREEP

Creep behaviour of a metal is determined by measuring the strain ( $\epsilon$ ) deformation as function of time under constant stress







# CREEP

- Creep occurs even with high strength materials with high heat resistant.
- At high temperature atomic bonding starts to fail, causing movement of atoms and atomic planes.
- Restructuring of atoms also occur at high temperature.
- Movements of dislocations also more likely at high temperature through diffusion.

Typical creep rate:

Jet engine: 1% in 10,000 hours.

Steam generator: 1% at 100,000 hours.

Special test required!!!!!!!!!!!!

To evaluate performance of materials at high temperature

**Creep is dangerous as an unanticipated failure could prove fatal.**



## CREEP CURVE

### 1. Stage I: Primary Creep

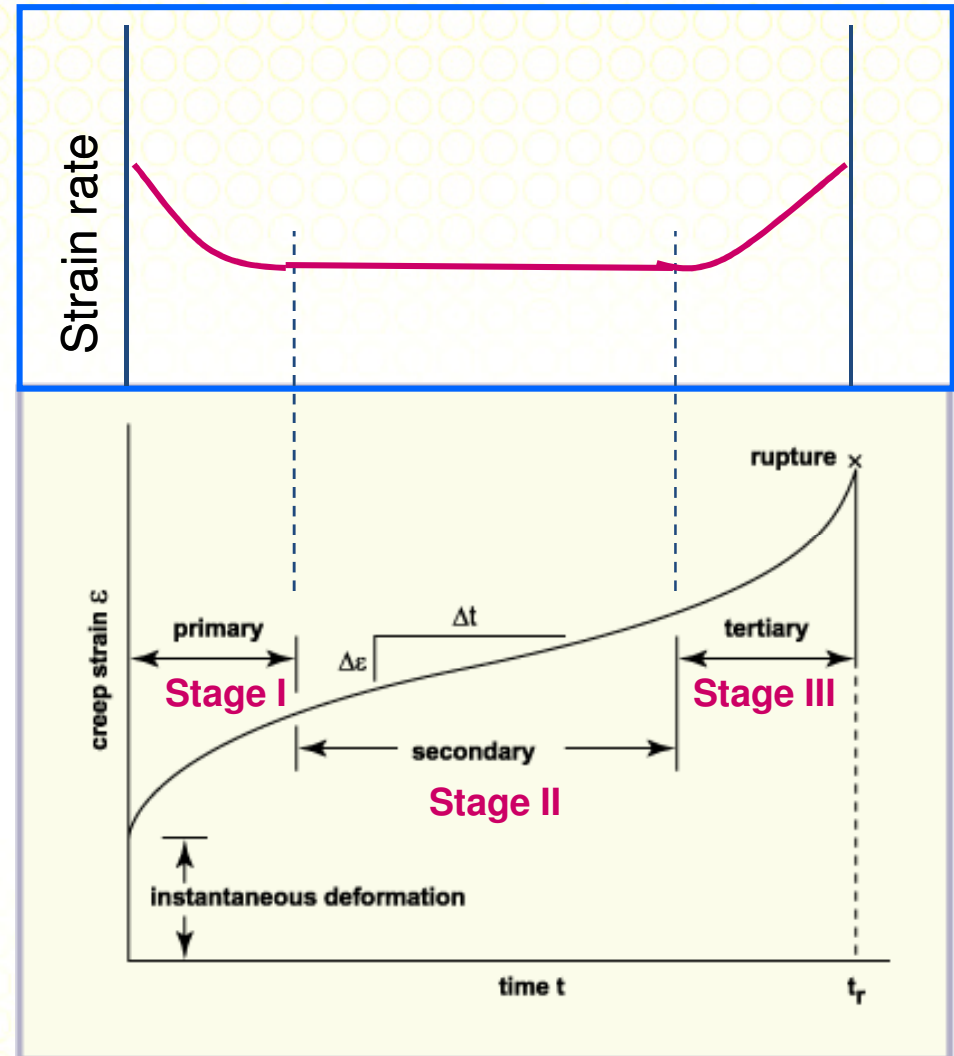
- Strain rate decreases as strain increases. Resistance to plastic deformation: strain hardening

### 2. Stage II: Secondary (steady-state) Creep (used as design tool)

- Strain rate minimum and constant
- Balance between recovery = strain hardening. Fracture will not occur.

### 3. Stage III: Tertiary Creep (failure-rupture)

- Strain rate increases. reduction in cross-sectional area due to voids, necking reduce



Typical Creep Curve



## Creep Curve

- The slope of creep curve is referred to 'creep rate' ( $d\varepsilon/dt$ )
- instantaneous deformation : elastic deformation due to applied load and occurs at  $T < 0.4 T_m$ .
- During the creep test, applied load is constant, thus the specimen will elongate and its cross sectional area will decrease.

### 1. Stage I: **Primary Creep**

- Strain rate decreases as strain increases. Resistance to plastic deformation: strain hardening
- deformation becomes more difficult as the material is strained.

### 2. Stage II: **Secondary (steady-state) Creep** (*used as design tool*)

- Strain rate minimum and constant
- Balance between recovery = strain hardening. Fracture will not occur. **The materials become softer and retains its ability to experience deformation**

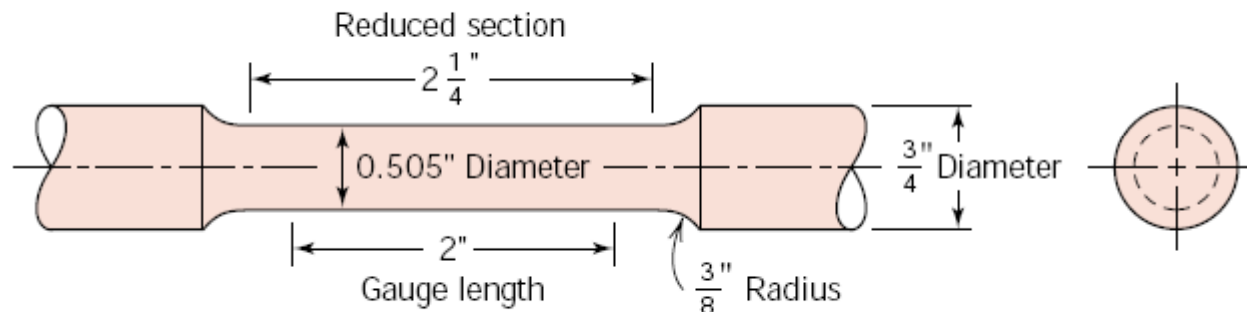
### 3. Stage III: **Tertiary Creep** (*failure-rupture*)

- Strain rate increases. reduction in cross-sectional.
- Failure, due to microstructure and/or metallurgical changes e.g. grain boundary separation and the formation of internal cracks, cavities and voids.



- **Specimen geometry:**

Creep test is conducted in uniaxial tension using specimen having the same geometry as for



For brittle materials : uniaxial compression test more appropriate.

**For long-life application** e.g. nuclear power plant components, is scheduled to be use for several decades and when failure or too much strain are not the options.

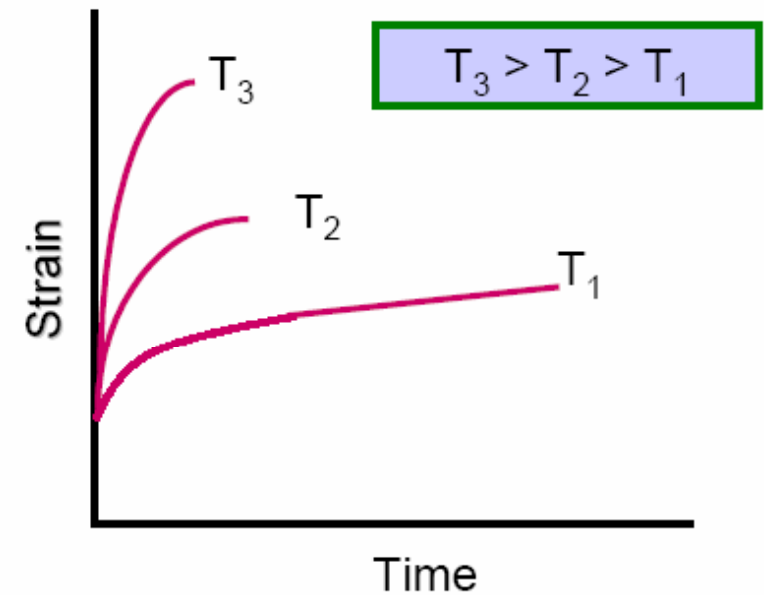
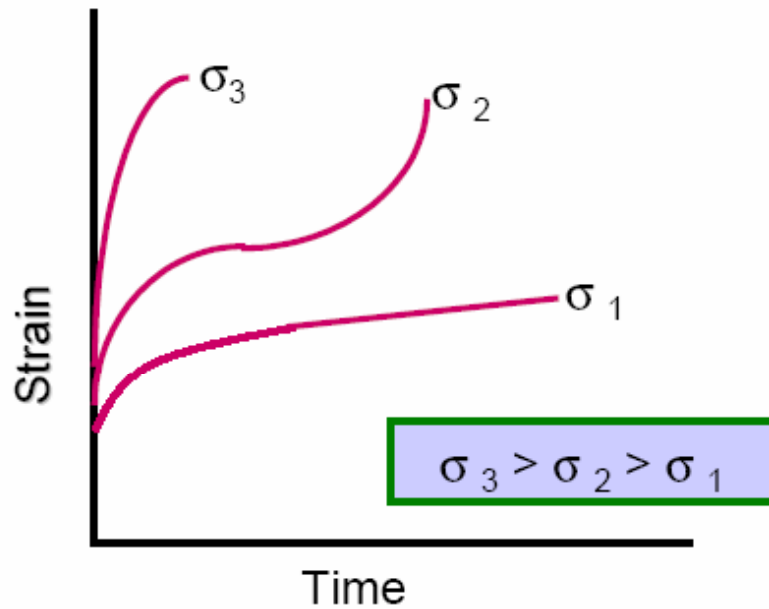
**For short life application:** e.g. turbine blade in military aircraft and rocket motor nozzles

- time to rupture or the rupture lifetime,  $t_r$  is the dominant design consideration
- Thus, creep characteristics of a material allow the design engineer to choose right materials to suit a specific application.

# Stress and temperature effects

- At temperature below  $0.4 T_m$  and after the initial deformation, the strain is virtually independent of time.
- With increasing stress or temperature:
  1. The instantaneous strain at the time of stress application increases
  2. The steady state creep rate is increased
  3. The rupture lifetime is diminished

## EFFECT OF STRESS AND TEMPERATURE



- Steady-state creep increases with increasing temperature and stress



## Effect of STRESS and TEMPERATURE on Steady-State Creep

### 1. Temperature constant

- Steady-state creep data follows:

*C and n are material constants*

*(some reference, replace C with K)*

$$\frac{d\varepsilon}{dt} = C\sigma^n$$

### 2. Stress Constant

- Steady-state creep follows:

$$\frac{d\varepsilon}{dt} = Ae^{\left(\frac{-Q}{RT}\right)}$$

*A: constant, Q: activation energy, R: gas constant, T: absolute temperature*

- Steady-state creep (with both T and  $\sigma$ ) is therefore:

$$\frac{d\varepsilon}{dt} = K\sigma^n e^{\left(\frac{-Q}{RT}\right)}$$



# Structural changes during creep

- Principal deformation process at elevated temperature:

1. Slip

2. Sub-grain formation

3. Grain boundary sliding



- In large grains specimens, local region may undergo lattice rotations -----→ produce misorientation
- In metal at elevated temperature, secondary deformation which occurs such as:
  - ❖ Formation of coarse slip band
  - ❖ Grain boundary migration

## 1. Deformation by slip

- At elevated temperature : new slip system may become operative

- E.g. Al –FCC system

At above 500°F , slip planes – { 111}, {100} or {211}

Zn, Mg – HCP

may undergoes non basal plane slip

- Slip bands produced at high temperature are coarser and more widely spaced than for room temperature deformation



## 2. Subgrain formation

- Creep deformation is quite inhomogeneous – more lattice bending e.g. near grain boundaries
  - Bending results in the formation of excess dislocation such as [dislocation climb](#) phenomenon
  - The dislocations arrange themselves into a low-angle grain boundary

The formation of sub-grain has been studied by x-rays, metallography, and thin film electron microscopy

Size of subgrain depends on: stress, temperature  
large subgrain produced by high temperature, low stress  
or low creep rate



### 3. Grain boundary sliding

- At elevated temperature: the grains in polycrystalline metals are able to move relative to each other
- Boundary sliding is a shear process which occurs in the direction of the grain boundary.
- Promoted by : increasing the temperature or decreasing the strain rate



## MECHANISMS OF CREEP

- Mechanisms for creep in metals include:
  1. Dislocation Slip and Dislocation Climb
  2. Grain Boundary Sliding
  3. Diffusion Creep and dislocation creep

More than one creep mechanism will operate at the same time (In parallel), but they operate independently each other.

$$\frac{d\varepsilon}{dt} = \sum_i (d\varepsilon / dt)_i$$

The fastest mechanism will control the creep behavior, the slowest mechanism will control the creep deformation



## Mechanisms for creep in metals (1)

### 1. Dislocation Slip and Dislocation Climb

- Creep deformation is a thermally activated process: as temperature increases the stress required to produce plastic deformation decreases.
- At low temperatures, dislocation slip dominates. (high temp. diffusion is dominates)
- Slip is a conservative motion:
  - Dislocation moves in the surface that contains both its line and burgers vector (slip plane)





- At intermediate and higher temperatures (at high stresses), dislocation climb dominates
- Climb is a **non-conservative** motion. Dislocation moves out of the slip plane
- Dislocation climb involves migration (diffusion) of atoms within the lattice, described by Ficks Law:

$$D = D_0 \exp\left(-\frac{Q}{RT}\right)$$

- Diffusion controlled mechanisms have significant effects on high temperature mechanical properties and performances.
- Dislocation climb is the mechanism responsible to achieve the desired balance between recovery and strain hardening during secondary creep.

- During strain hardening dislocation density increases resulting in dislocation interaction, which may lead to **immobile (sessile)** dislocations .

\*\*sessile dislocation is refer to low mobility dislocation, produced by dislocation reaction . Do not lie on the slip plane and act as barrier to dislocation motion until the stress is increased to high level to break down the barrier.

\*\*\*e.g. of dislocation reaction: formation of [Lomer-Cottrell barriers](#) in FCC metals by slip on intersecting {111} planes

- ❖ This in turn will lead to **dislocation pile-up** on slip plane at barriers such as grain boundaries, second phases

- When the metal is strain hardened, the strain energy stored is also high.



- During steady-state, the high strain energy stored combined with the increased temperature provide the **driving force for Recovery**.
- Recovery involves reduction in dislocation density (and lowering energy). In order to achieve this, dislocations must escape from tangled regions by a process called **dislocation climb**.



- A steady state creep occurs when, the rate of recovery is fast enough and the rate of strain hardening is slow enough, then a balance is reached between these competing factors

$$\frac{d\varepsilon_s}{dt} = \frac{r}{h} - \frac{\partial\sigma / \partial t}{\partial\sigma / \partial\varepsilon}$$

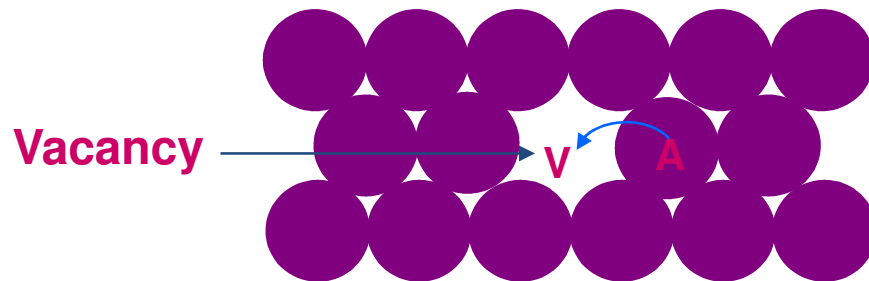
*h = rate of strain hardening*

*r = rate of thermal recovery by rearrangement and annihilation of dislocations*



- Before an atom can diffuse, it must have the *energy required to jump* into a neighbouring site, and that this *site must be vacant*.

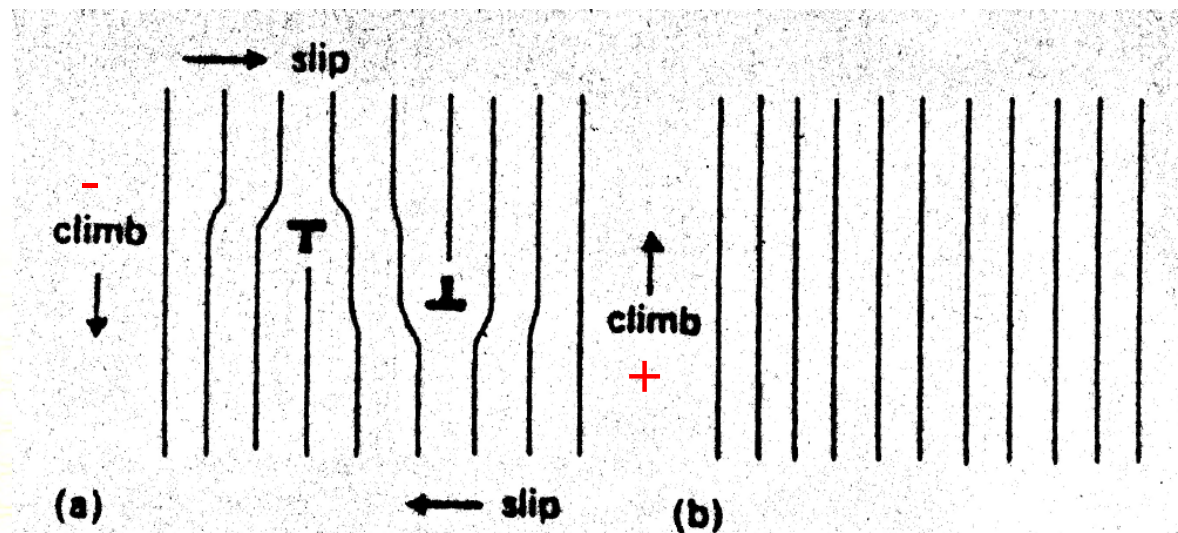
$$E_d = E_m + E_f = e^{(-E_m/RT)} = e^{(-E_f/RT)}$$



Mechanism of self-diffusion: Atom A jumps into the vacancy, V

- As the *temperature increases*, *diffusion rate increases* because the *energy required to move an atom to a neighbouring site decreases* and the *number of vacancies increases*.

- The rate controlling process in steady-state creep is **climb** whereby edge dislocations climb out of their slip planes by absorbing or emitting vacancies.
- The left-hand dislocation must climb “down” and the right-hand one must climb “up” until they both reach a common slip plane. They then move towards one another by slip and annihilate one another (because they are of opposite sign).
- This model of edge dislocations undergoing climb assumes that:
  1. *The extra half-plane of atoms has a straight edge*
  2. *Climb occurs by removal of a complete line of atoms*



**Mechanism of recovery due to movement of positive and negative edge dislocations**

- In positive climb (vacancy diffusion)
  - ❖ Atoms are removed from the extra half plane of atoms at a positive edge dislocation, so that this extra half plane moves up one atom spacing.
- In negative climb
  - ❖ A row of atoms is added below the extra half plane so that the dislocation lines moves down one spacing.



## Dislocation climb requires:

- diffusion vacancies or interstitials  
So the rate is control by atomic diffusion



- However, this does not occur as atoms are removed by diffusion.
- It is unlikely that complete rows of atoms are removed or added at the extra half plane in the climb process.

- Climb takes place in the following manner:
  - ❖ When an atom diffuses away leaving a vacancy, the dislocation now has two steps that are called **jogs**. Atoms A and B are most likely to diffuse away into the crystal because they have fewer neighbour atoms to which they are bonded. **Jogs form as a result of dislocation climb**
  - ❖ Jogs are steps on a dislocation that move (dislocation) from one slip plane to another
  - ❖ When this occurs the jogs move along the edge dislocation. As the diffusion of the atoms from the jogs continues the climb of dislocations increases.

# Jogs

- The creation of jogged on dislocation lines has many important implications in the theory of the plastic deformation of metals.
- A stable jog represents an increase in the length of the dislocation line, thus produce an increase in the energy of the crystal.
- The energy of a jog is less than the energy of a dislocation per atom plane because the entire length is lies in the distorted material of the core of the parent dislocation (in metal, energy of a jog  $\sim 0.5-1.0$  eV)



If the stress is high enough, the jogs strung out (strong effect) along the dislocation line can be forced together to form a **superjog** where the step height is 5-30 ' $b$ '.

For very large superjog, step size  $\sim 200\text{\AA}$ , the distance between the two dislocation segments is large enough to prevent mutual interaction. The dislocations behave as separate single-ended sources.

- When the whole line of atoms have diffused away, the dislocation will have climbed normal to its slip plane by one atomic spacing
  1. The dislocation will then slip past the obstacle
  2. Dislocations of opposite sign will cancel (annihilate) each other
  3. Dislocations of the same sign will form a dislocation wall

- The climb process, therefore, has two requirements:
  1. It must be possible for self-diffusion to occur
  2. The dislocation must possess suitable sites for climb, that is jogs.
- Therefore, the total activation for climb  $E_c$  is:

$$E_c = E_d + E_j$$

- Sources of **Jogs** are from thermal activation ( $E_j$ ) and dislocation interaction
- *The steady-state creep is based on a balance between the strain hardening and the recovery which occurs during creep. The mechanism of recovery is the climb of edge dislocations which occurs by the movement of jogs along dislocations. Since dislocation intersections produce a large number of jogs, the rate-controlling step for climb is self-diffusion.*



## Why climb is not possible with screw dislocations ?

- Because there is no extra half plane of atoms for screw dislocations
- Burgers vector of screw dislocation is parallel to the dislocation line.
- No diffusion atoms is needed to allow the screw dislocation to move on to another slip plane.
- However, a higher stress or activation energy may be needed since the resolved shear stress may not be as high as on the original slip plane.

**Critical resolved shear stress is the component of shear stress, resolved in the direction of slip, necessary to initiate slip in a grain.**

**Shear stress: The instantaneous applied shear load divided by the cross sectional area across which it is applied.**



## Activation energy for steady-state creep

- Arrhenius-type rate equation:

$$\frac{d\varepsilon}{dt} = Ae^{-Q/RT}$$

*A: constant, Q: activation energy, R: gas constant, T: absolute temperature*



## Mechanisms for creep in metals (2)

### 2. Grain boundary sliding

- At elevated temperature:
  - the grains in polycrystalline metals are able to move relative to each other.
- Grain boundary sliding is a shear process which occurs in the direction of the grain boundary.
- Occurs due to increasing the temperature and/or decreasing the strain rate.
- Most of the sliding occurs along the grain boundary as a bulk movement of the two grains.
- Others: sliding also occurs in a softened area away from the boundary.
- Grain boundary sliding occurs discontinuously with time and the amount of shear displacement is not uniform along the grain boundary



## Sliding : two types of grain boundary failure:

2. Small holes formation on grain boundaries
  - especially for boundaries which perpendicular to the tensile axis
  - The growth of holes is due to the movement of lattice vacancies.

## How to observe grain boundary sliding phenomenon

- Scribing a line on a polished and etched surface and observe the shear offset where the line crosses the grain boundary

## Principal knowledge about grain boundary:

### At room temperature

- more grain boundaries or smaller grains size is gives good strength to materials.
- Boundary become barrier

### At high temperature

- Smaller grains size reduce the creep strength
- Because it can create more triple site which leads to formation of cracks
- Thus, creep resistance can be improved by increasing the grain size or developing a elongated grain structure through directional solidification



### 3. Dislocation creep and diffusion creep

**Diffusion creep**: involves the flow of vacancies and interstitial through a crystal under the influence of applied stress. Occurs for  $\sigma/G < 10^{-4}$

**Dislocation creep** : involves the movement of dislocations which overcome barriers by thermal assisted mechanism involving the diffusion of vacancies or interstitial. Occurs for  $10^{-4} < \sigma/G < 10^{-2}$  (G=shear modulus)

**Dislocation glide**: involves dislocations moving along slip planes and overcoming barriers by thermal activation. This mechanism occurs at high stress,  $\sigma/G > 10^{-2}$



- Diffusion creep is favored at high temperature and low stresses
- Dislocation creep is more dominant at low temperature and high stresses.

- At high temperature (above  $0.6T_m$ ), and low stresses

$$\tau = \eta \cdot d\gamma/dt$$

$\tau$  = shear stress,  $\gamma$  = shear strain,

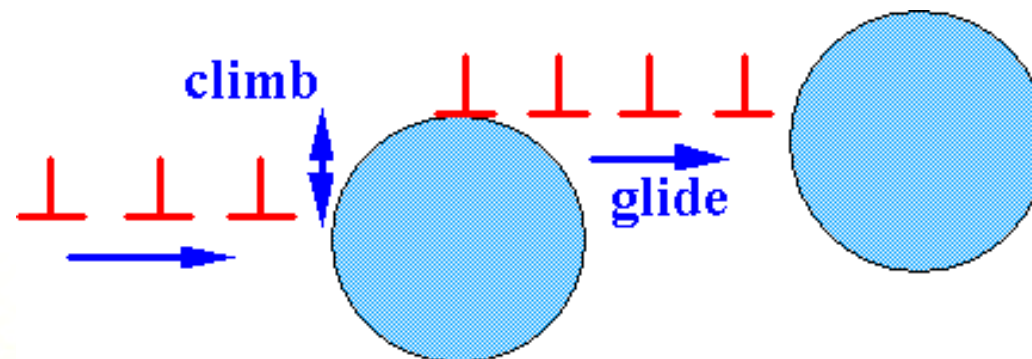
$\eta$  = coefficient of viscosity

- At higher stress and temperature  $< 0.4T_m$  deformation is primarily controlled by dislocation glide. Diffusion is considered negligible and does not contribute to deformation process.



# Dislocation glide

- Occurs at stress level are high relative to other creep deformation mechanism.
- The creep rate is established whereby the dislocations are impeded by obstacles e.g. precipitates, solute atoms and other dislocation.



**Mechanism of showing dislocations climb and then slip past an obstacle**

## Dislocation creep

- Occurs by dislocation glide aided by vacancy diffusion.
- Physical models of dislocation creep must predict the value of  $h$  and  $r$ .

$$\frac{d\varepsilon_s}{dt} = \frac{r}{h} - \frac{\partial \sigma / \partial t}{\partial \sigma / \partial \varepsilon}$$

where  $h = \text{rate of strain hardening}$

$r = \text{rate of thermal recovery by rearrangement and annihilation of dislocations}$





## Dislocation creep model by Weertman

- Weertman suggest: dislocation climb plays a major role in creep
- This model predicts an equation for creep rate in which stress is raised to the third power. But experimentally, for metal, the value of  $n$  is varies from 3-8, and 5 is most common.
- Then the steady state creep rate **power-law relation** can be written as ( for intermediate to high stress level and temperature above  $0.5T_m$ )



- Where:

*A and n are material constant*

*G = shear modulus*

*D<sub>v</sub> = bulk or lattice self-diffusion coefficient*

*b = burgers vector of dislocation*

*σ = applied stress*

*k = Boltzmann's constant*

*T = absolute temperature*

$$\dot{\epsilon}_s = \frac{AD_v Gb}{kT} \left( \frac{\sigma}{G} \right)^n$$

$$D_v = D_o \exp(-Q / kT)$$

Rearrange creep rate equation:

$$\dot{\epsilon}_s = B \sigma^n \exp(-Q / kT)$$

- At low stress, below  $\sigma/G = 5 \times 10^{-6}$ , a linear dependence on stress ( $n=1$ ) (Harper-Dorn creep).

due to climb-controlled creep, where the dislocation density does not change with the stress.

- $\sigma/G > 10^{-3}$ , power law breaks down and the measured creep rate are higher than predicted.



# Diffusion creep

- Diffusion creep refers to the deformation of crystalline solids by the diffusion of vacancies through their grains. Diffusion creep results in plastic deformation rather than brittle failure of the material.
- Diffusion creep becomes the controlling mechanism at high temperatures and relatively low stress,  $\sigma/G < 10^{-4}$
- Diffusion creep is caused by the migration of crystalline defects through the grains such that when a crystal is subjected to a greater degree of compression in one direction relative to another, defects migrate to the grains along the direction of compression, causing a net mass transfer that shortens the crystal in the direction of maximum compression.
- When vacancies move through the grains (surface of grains), this is called [Nabarro and Herring creep](#).



# References:

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- **Smith W.F., Foundation of Materials Science and Engineering, 4<sup>th</sup> edition, McGraw Hill, 2006.**
- **Fontana M.G., Corrosion Engineering, 3<sup>rd</sup> edition, McGraw Hill, 1991.**
- **Dieter G.E., Mechanical Metallurgy, 3<sup>rd</sup> edition, 1991.**

