# Creep Behaviour

- Creep is defined as the **time-dependent** and **permanent** deformation of materials when subjected to a **constant** load or stress under a **constant** elevated temperature.

- The technological developments required materials that resist high temperatures are:

  – **Gas turbines**, whose blades operate at temperatures of 800-950K. The burner and afterburner sections operate at even higher temperatures, viz. 1300-1400K.

  – **Nuclear reactors**, where pressure vessels and piping operate at 650-750 K. Reactor skirts operate at 850-950 K.

  – Chemical and petrochemical industries.

- The creep becomes important only for temperatures greater than about $0.4T_m$ (T_m= absolute melting temperature) for metals and ceramics.

- In glasses and polymers, creep becomes important at temperatures **above T_g**, the glass transition temperature. At **$T>T_g$**, these materials turn rubbery or leathery, and viscoelastic and viscoplastic effects become important.

- Upon application of the load there is an **instantaneous deformation**, as indicated in the figure, which is mostly elastic.

- **Primary or transient creep** indicates **decreasing** creep rate due to an increase in creep resistance or strain hardening-deformation.

- Secondary or **steady-state creep**, the rate is constant due to a **balance** between the competing processes of strain hardening and recovery.
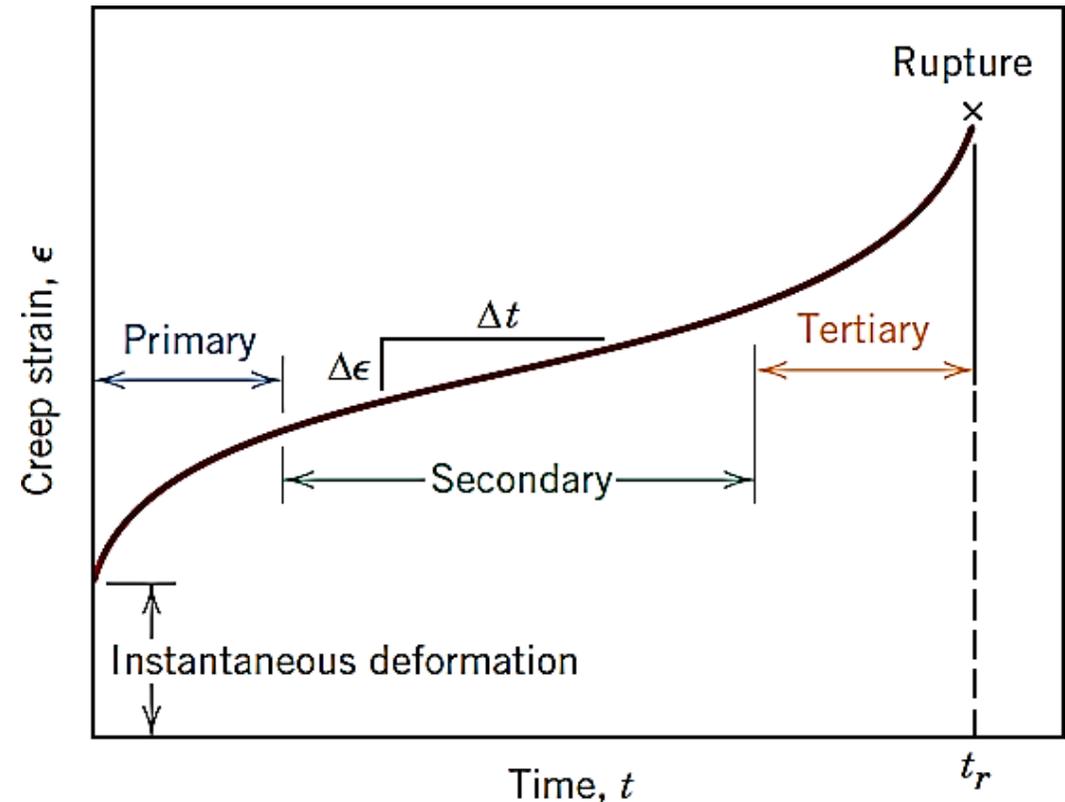
- **Tertiary** creep: there is an acceleration of the strain rate and the failure termed rupture results from microstructure and /or metallurgical changes

- These changes lead to a decrease in the effective cross-sectional area and an increase in strain rate.

- For long-life applications, the most important parameter from a creep test is the slope of the steady-state creep rate, $\dot{\epsilon}_s$.

- The primary part and the secondary part of the creep curve are frequently described using empirical laws e.g., the *Garofalo* equation:

$$\varepsilon = \varepsilon_0 + \varepsilon_t[1 - exp(-mt)] + \dot{\varepsilon}_{II}t$$

Where ε_t describes the additional strain during transient creep, $1/m$ quantifies the transition time between regions I and II, and $\dot{\varepsilon}_{II}$ is the constant creep rate during secondary creep.

- For many relatively **short-life creep** situations, time to rupture, or the rupture lifetime t_r, is the dominant design consideration.

High-temperature behaviour of materials

- **Designing** materials for high temperature applications is one of the most challenging tasks for a material scientist.

- Various thermodynamic and kinetic factors tend to deteriorate the **desirable microstructure** (kinetics of processes are an exponential function of temperature).

- Strength decreases and material damage (void formation, creep oxidation) **tends to accumulate**.

- Cycling between high and low temperature will cause **thermal fatigue**.

High Temperature Effects

- **Increased vacancy concentration:** at high temperatures more vacancies are thermodynamically stabilized.

- **Thermal expansion:** material will expand and in multiphase materials/hybrids thermal stresses will develop due to differential thermal expansion of the components.

- **High diffusion rate:** diffusion controlled processes become important.

- **Phase transformations** can occur: this not only can give rise to undesirable microstructure, but lead to generation of internal stresses.

- Precipitates may dissolve. Grain related. **Grain boundary weakening** may lead to grain boundary sliding and wedge cracking. Grain boundary migration. Recrystallization / grain growth. **Decrease in strength.**

- **Dislocation related:** these factors will lead to decrease in strength. New slip systems can become active. Change of slip system. Decrease in dislocation density

- Overaging of precipitate particles and **particle coarsening. Decrease in strength**

- The material may creep (time dependent elongation at constant load/stress).

Different tests may be required to evaluate high temperature properties.

1. **High Temperature Tensile Test**: this test provides useful data for **short term** applications such as rocket parts.

2. **Creep Test**: Measures **dimensional changes** accurately at constant high temperature and constant load or stress. It is Useful for **long term** applications such as turbine blades.

3. **Stress Rupture Test** (**Creep rupture test**): Measures **time to failure** at specified stress and temperature. Useful where some strain can be tolerated but failure must be avoided, such as large furnace housings.

- With either increasing stress or temperature, the following will be noted:
   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.

$T_3 > T_2 > T_1$

$\sigma_3 > \sigma_2 > \sigma_1$

T_3 or σ_3

T_2 or σ_2

T_1 or σ_1

Creep strain

$T < 0.4T_m$

Time
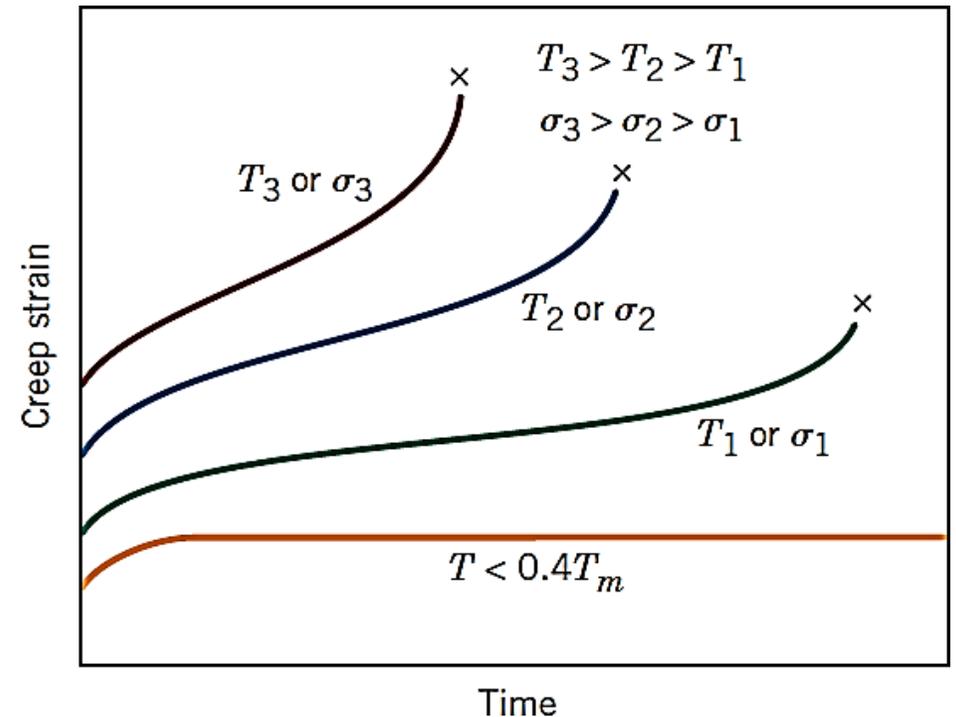
- With increase in temperature, the creep rate increase because the softening processes. Therefore, the creep rate is closely related to the Arrhenius equation;

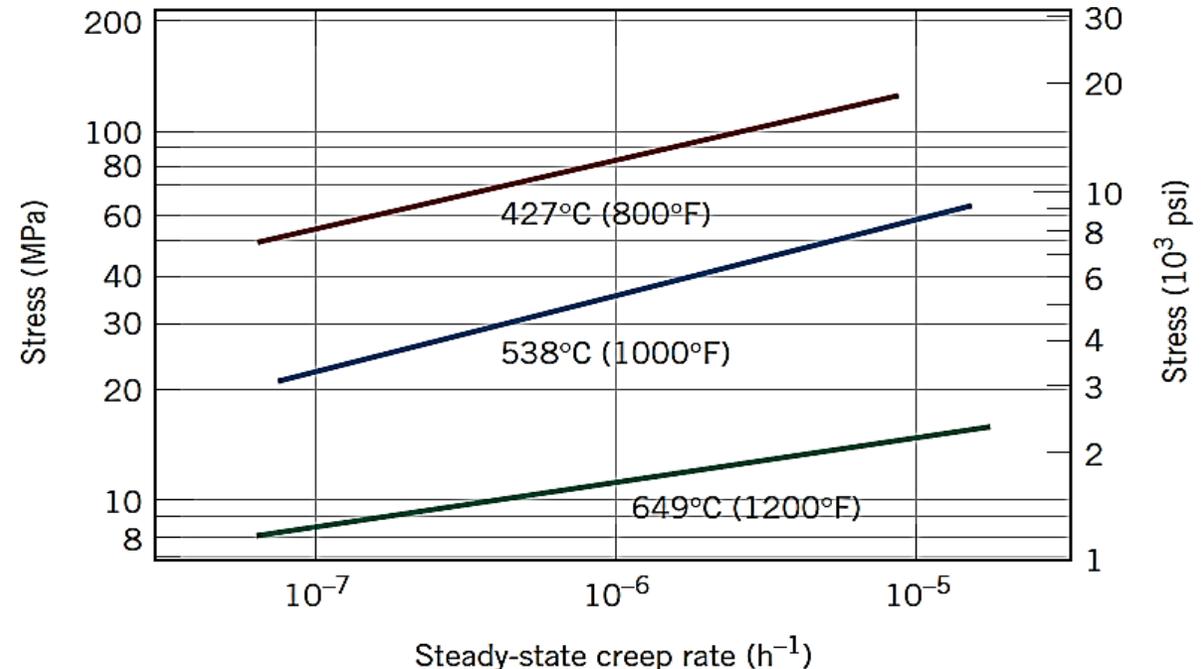$$\dot{\epsilon}_s = A \exp\left(-\frac{Q_c}{RT}\right)$$

where $\dot{\epsilon}_s$ is the secondary creep rate, Q_c is the activation energy for creep for the material under test (joules per atom), R is the universal gas constant ($R = 8.314$ J/mol.K), T is the absolute temperature and A is a constant.

- the steady-state creep rate as a function of stress can be written as;

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

Now, when the influence of temperature is included,

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

Creep Mechanisms

## 1. Dislocation creep:

- Creep deformation can occur by **dislocation movement** in metals.

- If an edge dislocation **encounters** an obstacle e.g., a precipitate, it needs a certain minimal stress to overcome the obstacle **at low temperatures**; otherwise it will be stopped.

- At elevated temperatures, the dislocation can **evade** the obstacle by adding or emitting vacancies. Using this mechanism, called climb, the dislocation can leave its original slip plane (see the figure here).

- Vacancies can be **transported** from one dislocation to the other, with one dislocation acting as vacancy **source**, the other as vacancy **sink**.
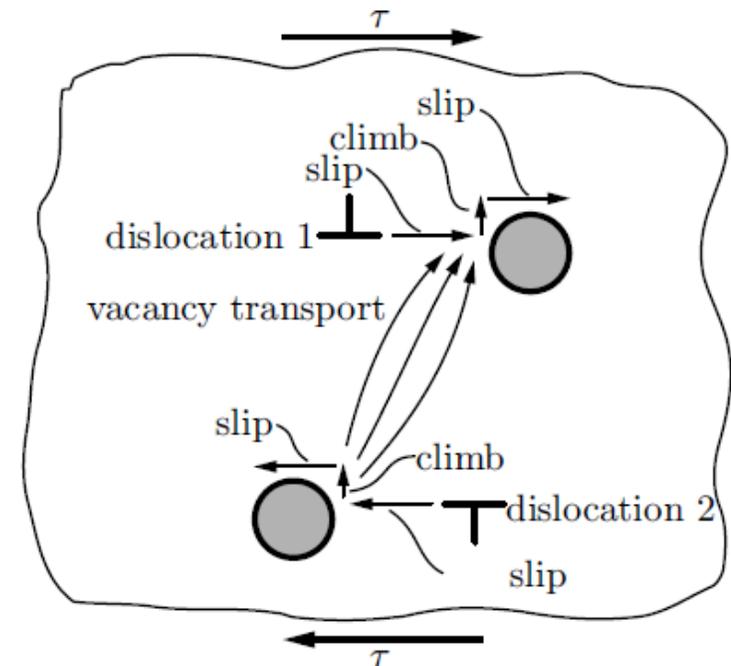
2. Grain boundary sliding:

- At high temperatures, **grains** in metals and ceramics can **move** against each other. This process is called grain boundary sliding.

- In metals, grain boundary sliding usually **contributes** only slightly to the overall deformation, but it is nevertheless important for two reasons:

    – In **diffusion creep**, grain boundary sliding ensures the **compatibility** of the grains during the deformation as sketched in the figure shown.

    – At points where three grain boundaries meet (triple points), **movement** of the grain boundaries by sliding can cause a large **concentration** in local stresses and thus induce damage by rupture of the grain boundaries.
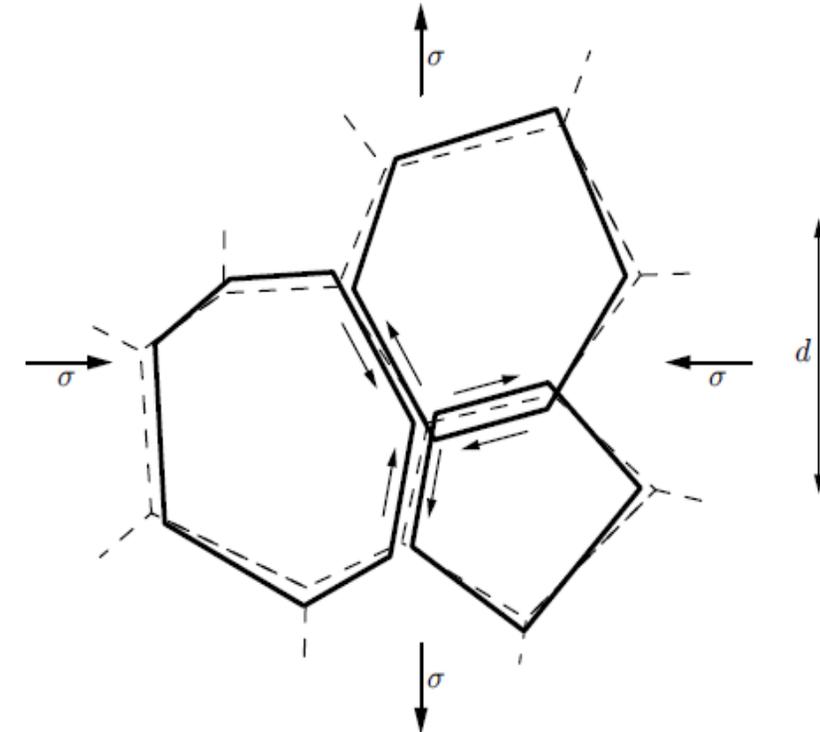
3. Diffusion creep (stress range $\sigma/G>10^{-4}$)

- It occurs in polycrystalline materials and it refers to the process in which atoms diffuse from grain boundaries more nearly parallel to the tensile axis to grain boundaries more nearly perpendicular to the tensile axis. As illustrated in the figure, vacancies are formed at grain boundaries with a normal vector oriented in the direction of the tensile stress.

- The vacancies move in such a way as to produce an **increase** in length of the grain along the direction of applied (tensile) stress. Hence, the vacancies move from the top and bottom region in the figure to the lateral regions of the grain.

- The boundaries **perpendicular** (or close to perpendicular) to the loading direction are distended and are **sources** of vacancies. The boundaries close to **parallel** to the loading direction act as **sinks**.
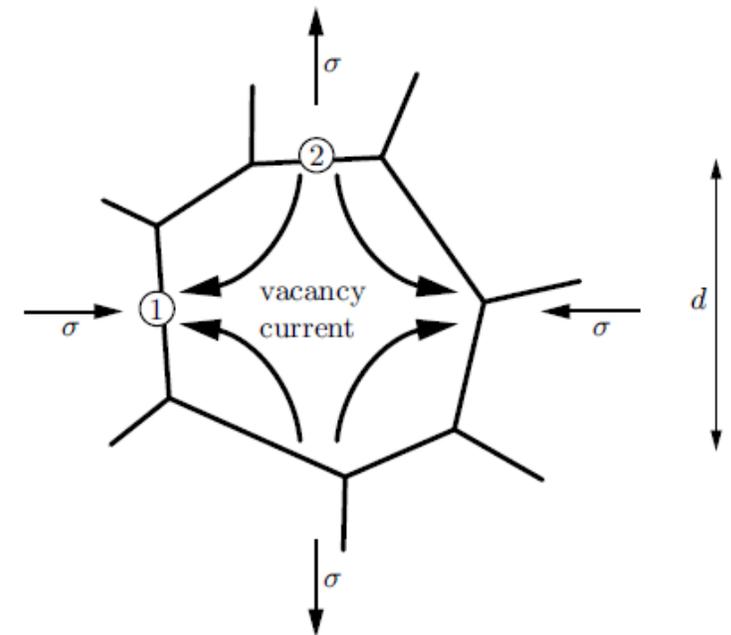
The Stress Rupture Test

- Where **life** is the important design parameter, then the test is carried out **to destruction** and this is known as a stress rupture test.

- The total strain in a rupture test is **much higher** than in a creep test. Also, the loads used are generally higher, and thus the time of the test is shorter, than for creep.

- The principle information obtained is the time to failure at a fixed temperature under nominal stress conditions.

- Changing of the slope indicates **structural change** in the material, i.e., transgranular to intergranular fracture, oxidation, recrystallization, grain growth.

Stress vs Time to rupture curves at 500 °C, 700 °C, 900 °C
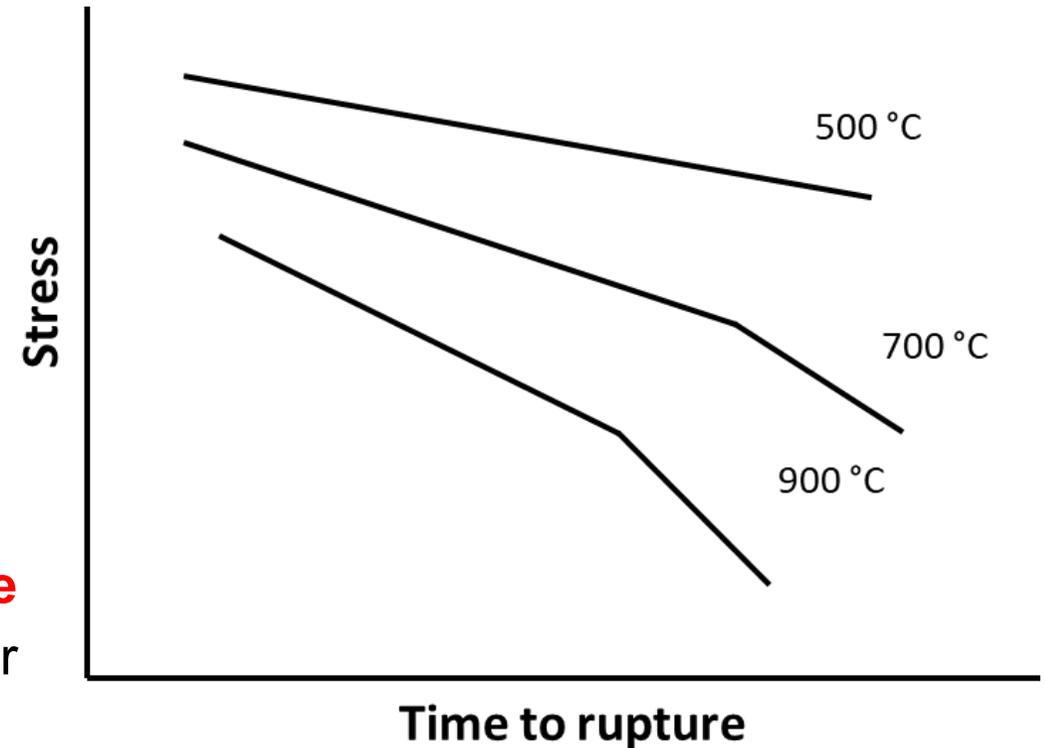
- There are **three principal** deformation processes at elevated temperature.

1. Deformation by slip

– More slip systems operate at high temperature

– Slip bands are coarser and widely spaced.

2. Subgrain formation

3. Grain boundary sliding

– Produced by shear process and promoted by increasing temperature/or decreasing strain rate.

– Results in grain boundary folding or grain boundary migration.

– Initiates grain boundary fracture

The table below reveals a comparison of creep with stress rupture tests.

Creep test	Stress Rupture Test
Measures strain versus time at constant temperature and load or stress	Measures stress versus time to rupture at constant temperature.
Relatively low loads and creep rates.	Higher loads and creep rates.
Long duration, 2,000 to 10,000 hours. Not always to fracture	Shorter duration, less than 1,000 hours typically. Always to fracture.
Strain measured accurately using sensitive equipment (inductance gauges) to determine creep rate. Strains typically less than 0.5%.	Simpler less sensitive strain measuring equipment (dial gauges). Time and strain to fracture measured. Strains typically up to 50%.