Module-08

Failure

Contents

Failure – Classification

- Failure of a material component is the loss of ability to function normally *or* to perform the intended job!

- Three general ways failure:

  Excessive elastic deformation, E.g.: buckling. Controlled by design and elastic modulus of the material.

  Excessive plastic deformation, Controlled by yield strength of the material. E.g.: loss of shape, creep and/ or stress-rupture at elevated temperatures.

  Fracture, involves complete disruption of continuity of a component – under static load: brittle *or* ductile, under fluctuating/cyclic load: fatigue, mode in which most machine parts fail in service.

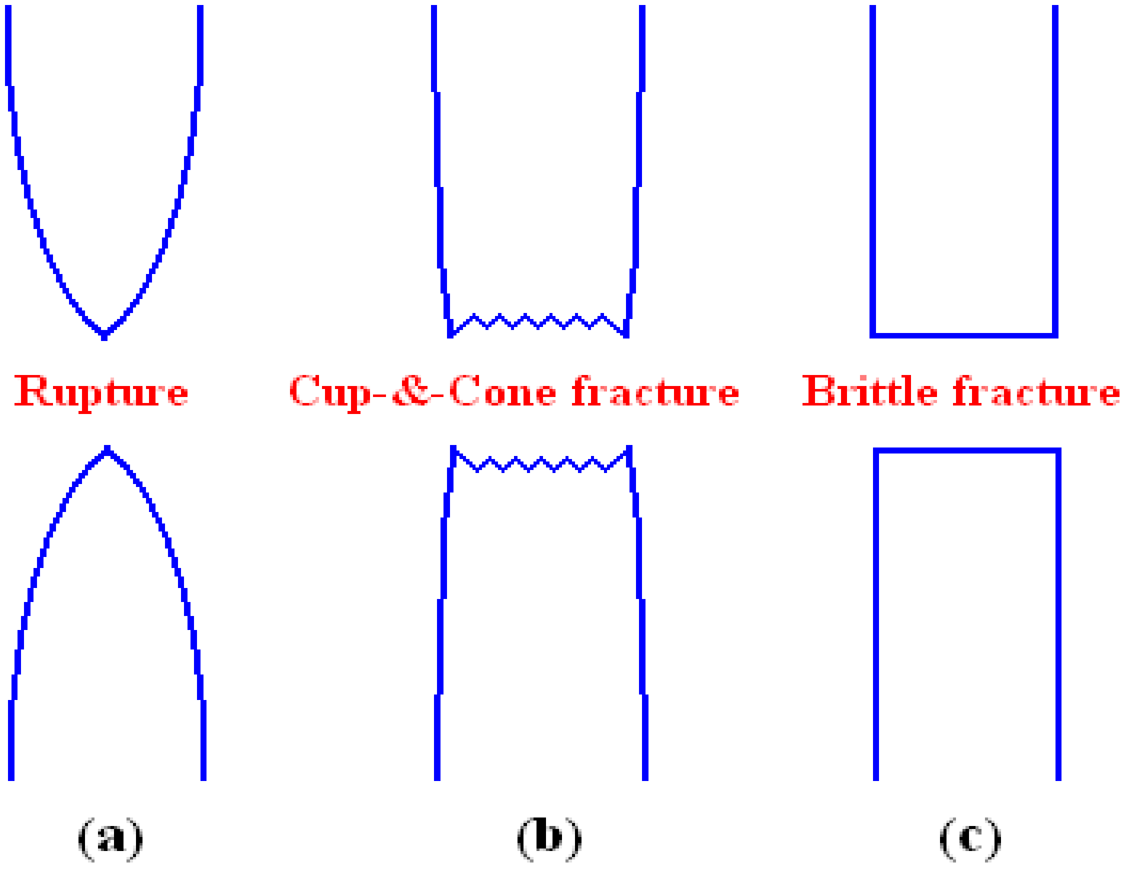
Fracture

- Fracture *defined* as the separation or fragmentation of a solid body into two *or* more parts under the action of stress.
- Fracture is classified based on several characteristic features:

characteristic	*terms used*	
Strain to fracture	***Ductile***	***Brittle***
Crystallographic mode	Shear	Cleavage
Appearance	Fibrous and gray	Granular and bright
Crack propagation	Along grain boundaries	Through grains

Fracture modes

- Ductile and Brittle are relative terms.
- Most of the fractures belong to one of the following modes: (a) rupture, (b) cup-&-cone and (c) brittle.



Ductile fracture Vs Brittle fracture

Parameter	***Ductile fracture***	***Brittle fracture***
Strain energy required	Higher	Lower
Stress, during cracking	Increasing	Constant
Crack propagation	Slow	Fast
Warning sign	Plastic deformation	None
Deformation	Extensive	Little
Necking	Yes	No
Fractured surface	Rough and dull	Smooth and bright
Type of materials	Most metals (not too cold)	Ceramics, Glasses, Ice

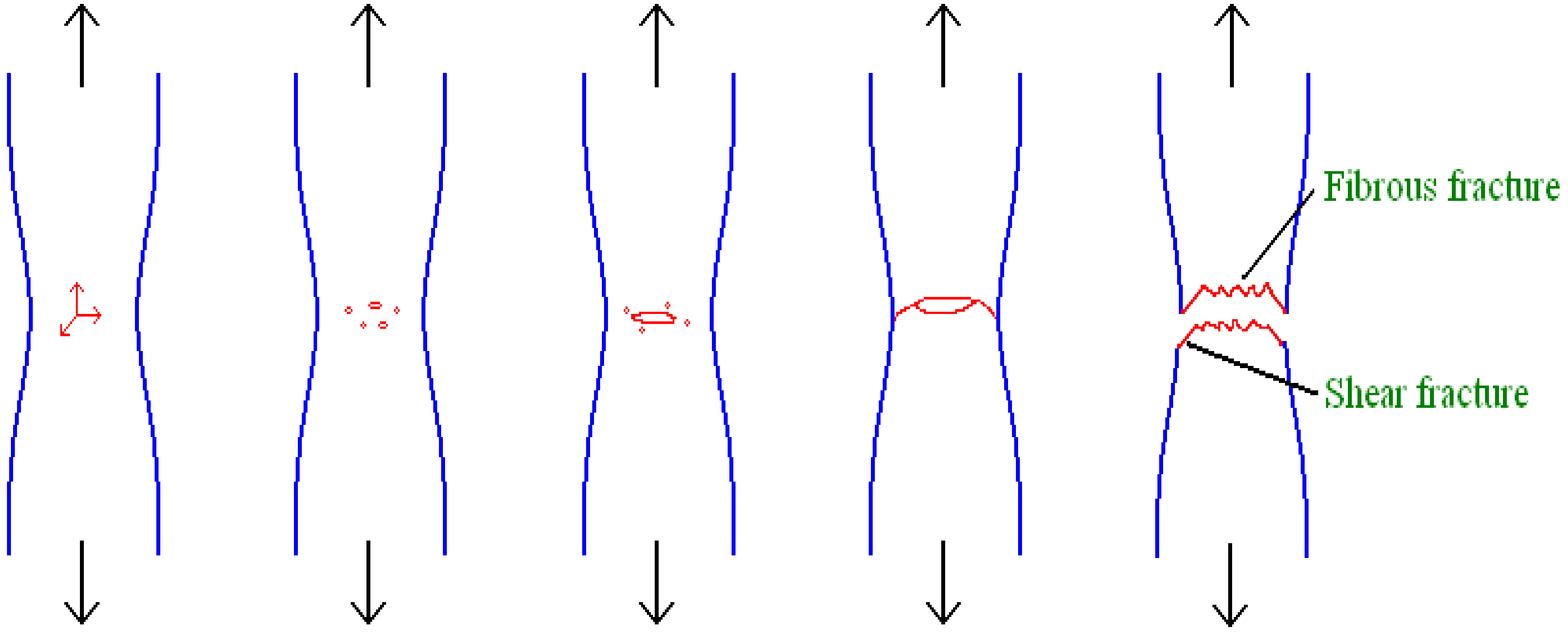
Ductile fracture

- Ductile fracture in tension occurs after appreciable plastic deformation.
- It is usually preceded by necking.
- It exhibits three stages - (1) formation of cavities (2) growth of cavities (3) final failure involving rapid crack propagation at about 45 to the tensile axis.
- Fractography of ductile fracture reveals numerous spherical dimples separated by thin walls on the fractured surface.
- McClintock's strain to ductile fracture, ε_f,

$$\varepsilon_f = \frac{(1-n)\ln(l_0/2b_0)}{\sinh\left[(1-n)(\sigma_a+\sigma_b)/(2\bar{\sigma}/\sqrt{3})\right]}$$

Ductile fracture (contd….)

- Stages of void nucleation, void growth, crack initiation and eventual fracture under ductile fracture mode:



Brittle fracture

- Brittle fracture intakes place with little *or* no preceding plastic deformation.
- It occurs, often at unpredictable levels of stress, by rapid crack propagation.
- Crack propagates nearly perpendicular to the direction of applied tensile stress, and hence called cleavage fracture.
- Most often brittle fracture occurs through grains i.e. transgranular.
- Three stages of brittle fracture - (1) plastic deformation that causes dislocation pile-ups at obstacles, (2) micro-crack nucleation as a result of build-up of shear stresses, (3) eventual crack propagation under applied stress aided by stored elastic energy.

Brittle fracture – Griffith Theory

- Nominal fracture stress that causes brittle fracture in presence of cracks (length of interior crack=2*c*), the stress raisers,

$$\sigma_f \approx \left(\frac{E\gamma}{4c}\right)^{1/2}$$

- *Griffith's criteria:* a crack will propagate when the decrease in elastic energy is at least equal to the energy required to create the new crack surface. Thus for thin plates:

$$\sigma = \left(\frac{2E\gamma}{c\pi}\right)^{1/2}$$

- For thick plates: $\sigma = \left(\frac{2E\gamma}{(1-\nu^2)c\pi}\right)^{1/2}$

- When plastic energy is also taken into account (Orowan's modification):

$$\sigma = \left(\frac{2E(\gamma + p)}{c\pi}\right)^{1/2} \approx \left(\frac{Ep}{c}\right)^{1/2}$$

Fracture mechanics

- Relatively new field of mechanics, that deals with possibility whether a crack of given length in a material with known toughness is dangerous at a given stress level or not!
- Fracture resistance of a material in the presence of cracks, known as fracture toughness, is expressed in two forms.

  (1) Strain-energy release rate, *G*: $$G = \frac{\pi\sigma^2 c}{E}$$

  (2) Stress concentration factor, *K*: $$K = \alpha\sigma\sqrt{c\pi}$$

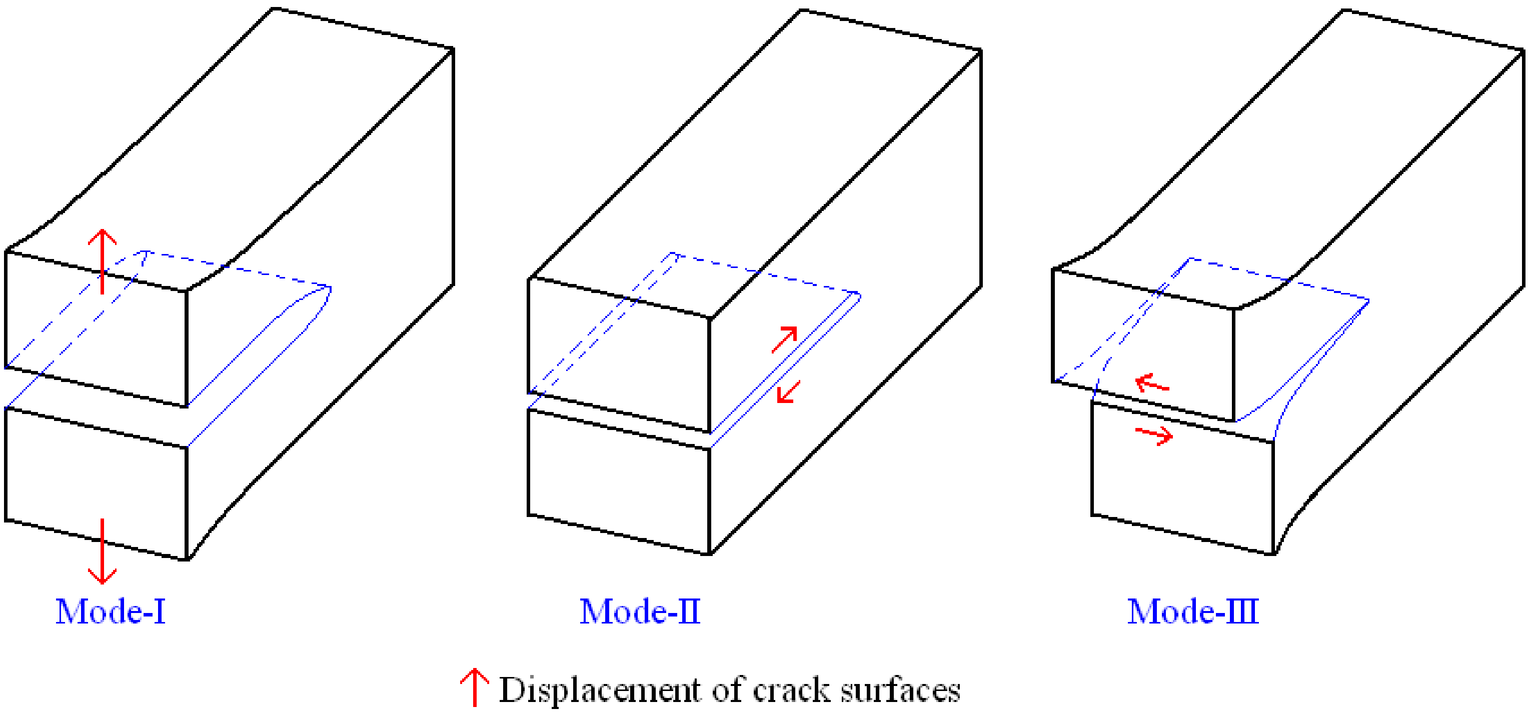
- Both parameters are related as:

  For plane stress conditions i.e. thin plates: $K^2 = GE$

  For plane strain conditions i.e. thick plates: $K^2 = GE/(1-\nu^2)$

Fracture mechanics (contd….)

- *K* depends on many factors, the most influential of which are temperature, strain rate, microstructure and orientation of fracture. The value of *K* decreases with increasing strain rate, grain size and/or decreasing temperature.
- Depending on the orientation of fracture, three modes of fracture are identified as shown in the figure:

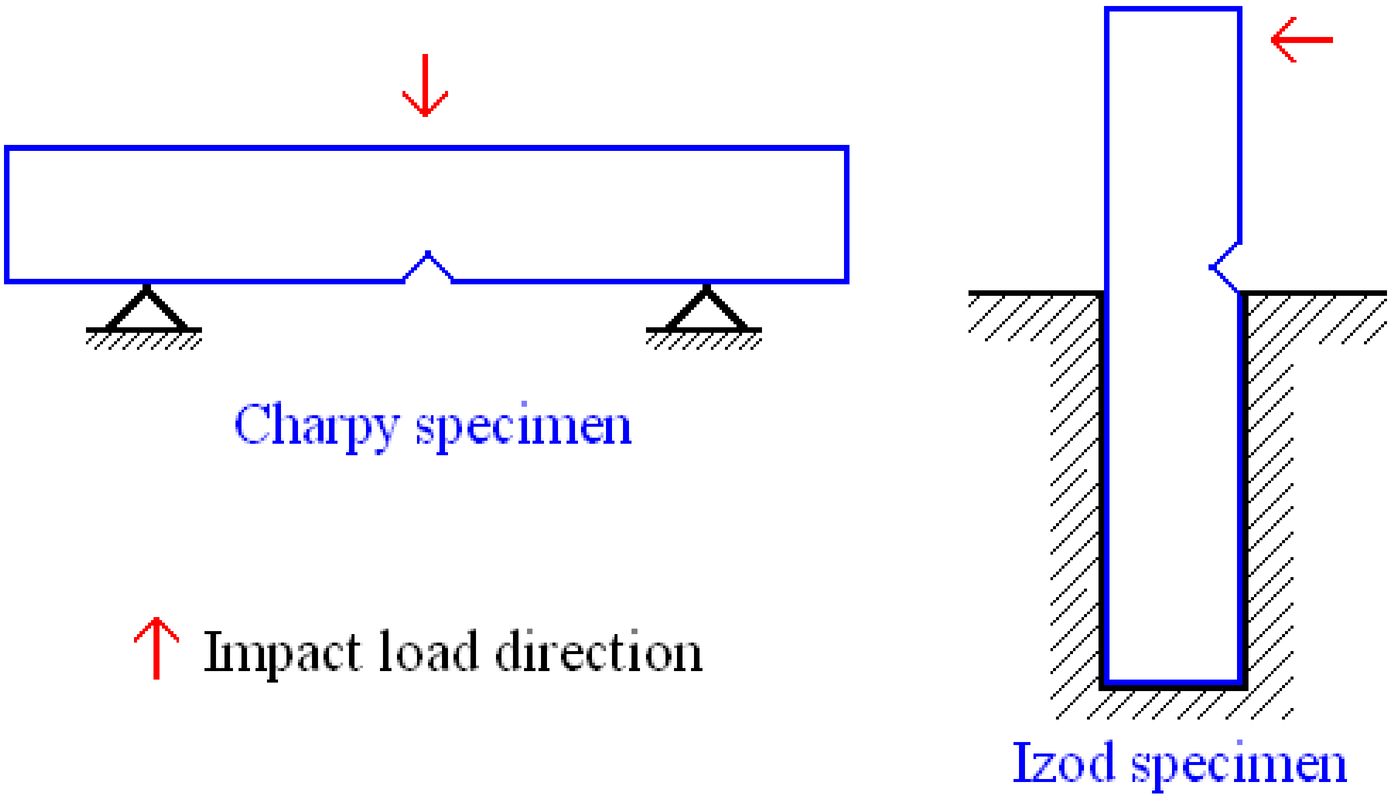


Notch-impact testing

- Ductile and Brittle are terms used to distinguish two extremes of fractures modes based on plastic deformation involved before fracture occurs.
- Three factors that aid transition from ductile to brittle-cleavage type of fracture are: (1) tri-axial state of stress (2) low temperature, and (3) rapid rate of loading.
- Since brittle fracture is most unpredictable, its been extend at a greater extent. Usually a notch will be introduced to simulate the conditions.
- A notch increases the tendency for brittle fracture by four means: (a) by producing high local stresses, (b) by introducing a tri-axial state of stress, (c) by producing high local strain hardening and cracking, and (d) by producing a local magnification to the strain rate.

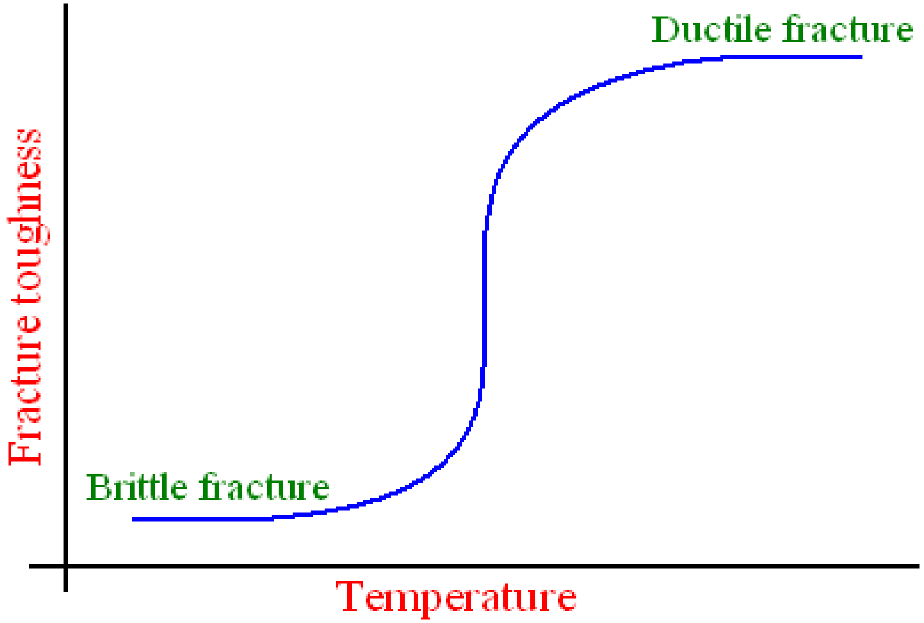
Notch-impact testing (contd….)

- A material's susceptibility to different kinds of fracture is measured using notched specimen subjected to impact load. Further study involves examining the fracture surfaces, and calculation of ductility.
- Two kind of specimen configurations & loading directions:



Ductile-to-Brittle transition

- Energy absorbed during the notch-impact is plotted as a function of temperature to know at what temperature range (DBTT) material fracture in a particular mode.



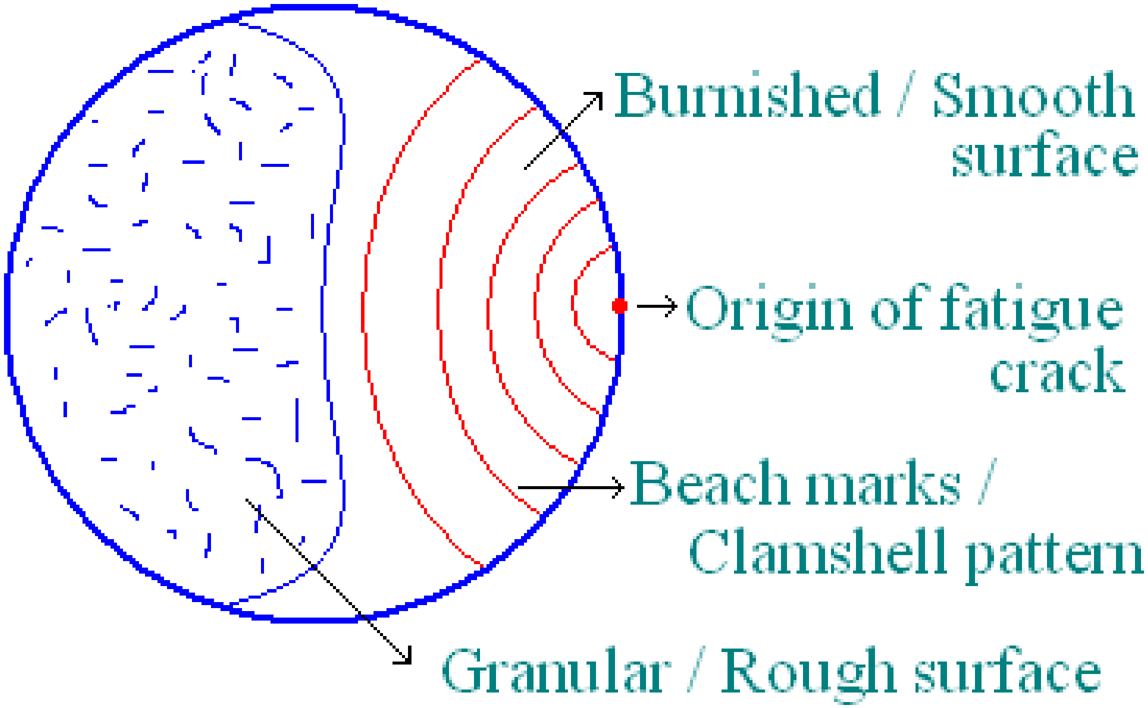
- In metals DBTT is around 0.1-0.2 T_m while in ceramics it is about 0.5-0.7 T_m, where T_m represents absolute melting temperature.

Fatigue failure

- Failure that occurs under fluctuating/cyclic loads – Fatigue.
- Fatigue occurs at stresses that considerable smaller than yield/tensile stress of the material.
- These failures are dangerous because they occur without any warning. Typical machine components subjected to fatigue are automobile crank-shaft, bridges, aircraft landing gear, etc.
- Fatigue failures occur in both metallic and non-metallic materials, and are responsible for a large number fraction of identifiable service failures of metals.
- Fatigue fracture surface is perpendicular to the direction of an applied stress.

Fatigue failure (contd….)

- Fatigue failure can be recognized from the appearance of the fracture surface:



- Any point with stress concentration such as sharp corner *or* notch *or* metallurgical inclusion can act as point of initiation of fatigue crack.

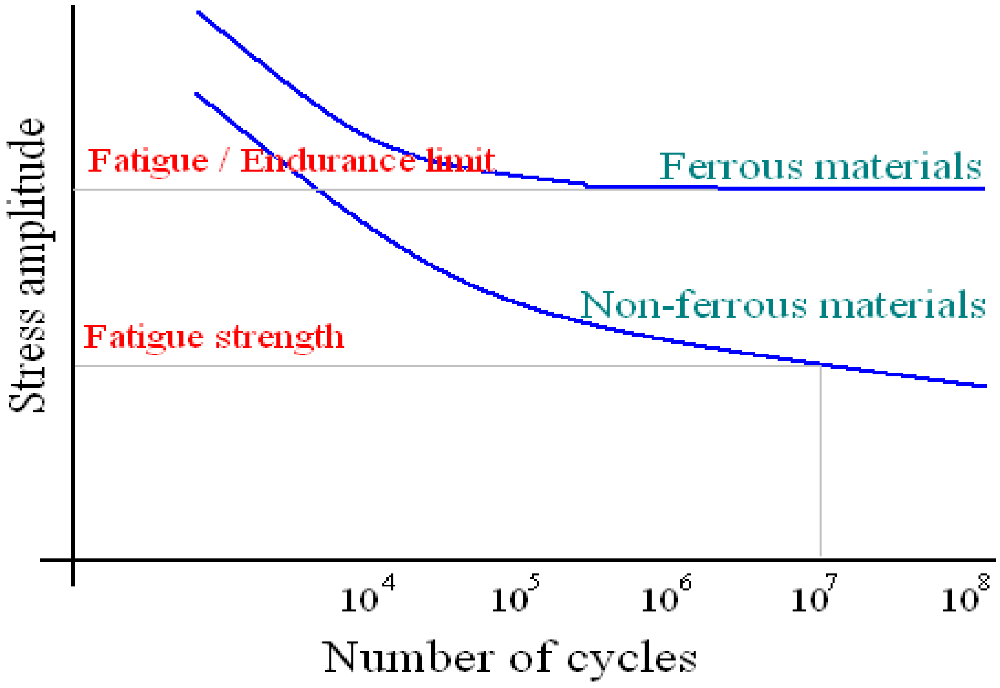
Fatigue failure (contd….)

- Three basic requisites for occurrence of fatigue fracture are: (a) a maximum tensile stress of sufficiently high value (b) a large enough variation or fluctuation in the applied stress and (c) a sufficiently large number of cycles of applied stress.
- Stress cycles that can cause fatigue failure are characterized using the following parameters:

Range of stress,	$\sigma_r = \sigma_{max} - \sigma_{min}$
Alternating stress,	$\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min})/2$
Mean stress,	$\sigma_m = (\sigma_{max} + \sigma_{min})/2$
Stress ratio,	$R = \sigma_{min} / \sigma_{max}$
Amplitude ratio,	$A = \sigma_a / \sigma_m = (1-R) / (1+R)$

Fatigue testing – Data presentation

- Fatigue test, usually, involves applying fluctuating load cyclically.
- A specimen of rotating beam type is often used because of its simplicity.
- Fatigue data is usually presented by plotting maximum stress (*S*) against number of cycles to fracture (*N*), using a logarithmic scale for the latter variable.



S-N curve can be represented by the <u>Basquin equation</u>:

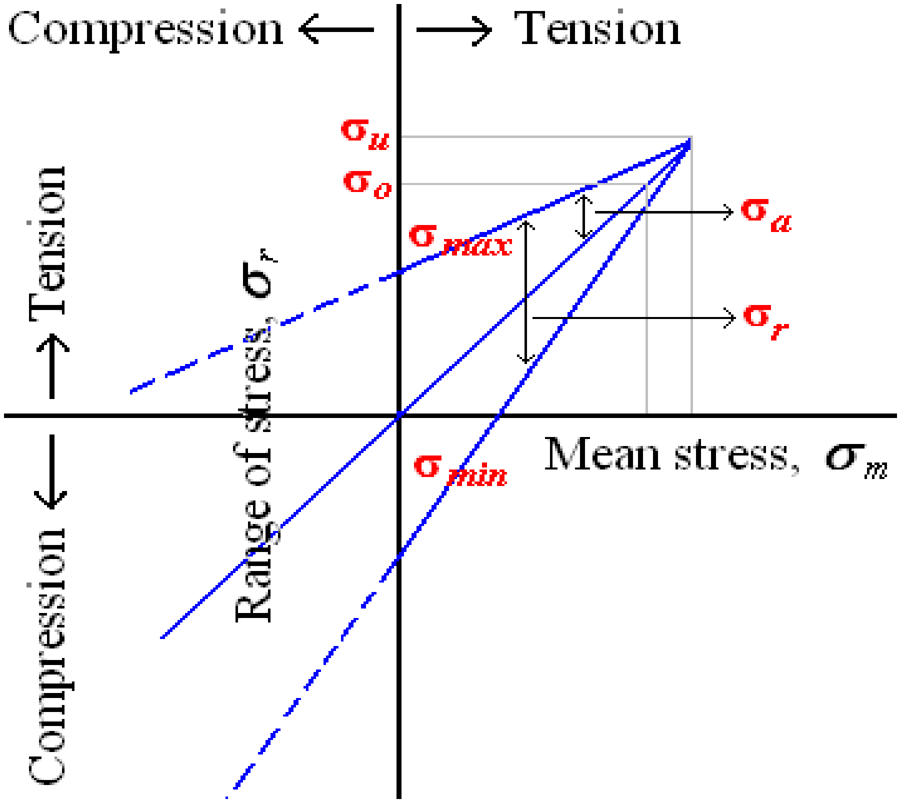
$$N\sigma_a^p = C$$

Fatigue parameters

- Material fails under fatigue mode at higher number of stress cycles if stress applied is lower.
- After a limiting stress, ferrous materials won't fail for any number of stress cycles. This limiting stress is called – *fatigue limit / endurance limit*.
- For non-ferrous materials, there is no particular limiting stress i.e. as stress reduces, number of cycles to failure keep increasing. Hence stress corresponding to 10^7 cycles is considered as characteristic of material, and known as *fatigue strength*. Number of cycles is called *fatigue life.*
- *Endurance ratio* – ratio of fatigue stress to tensile stress of a material. For most materials it is in the range of 0.4-0.5.

Fatigue data presentation – Goodman diagram

- The Goodman diagram presents the dependence of allowable stress ranges on mean stress for a material. Allowable stress range increases with increasing compressive mean stress i.e. compressive stress increases the fatigue limit.

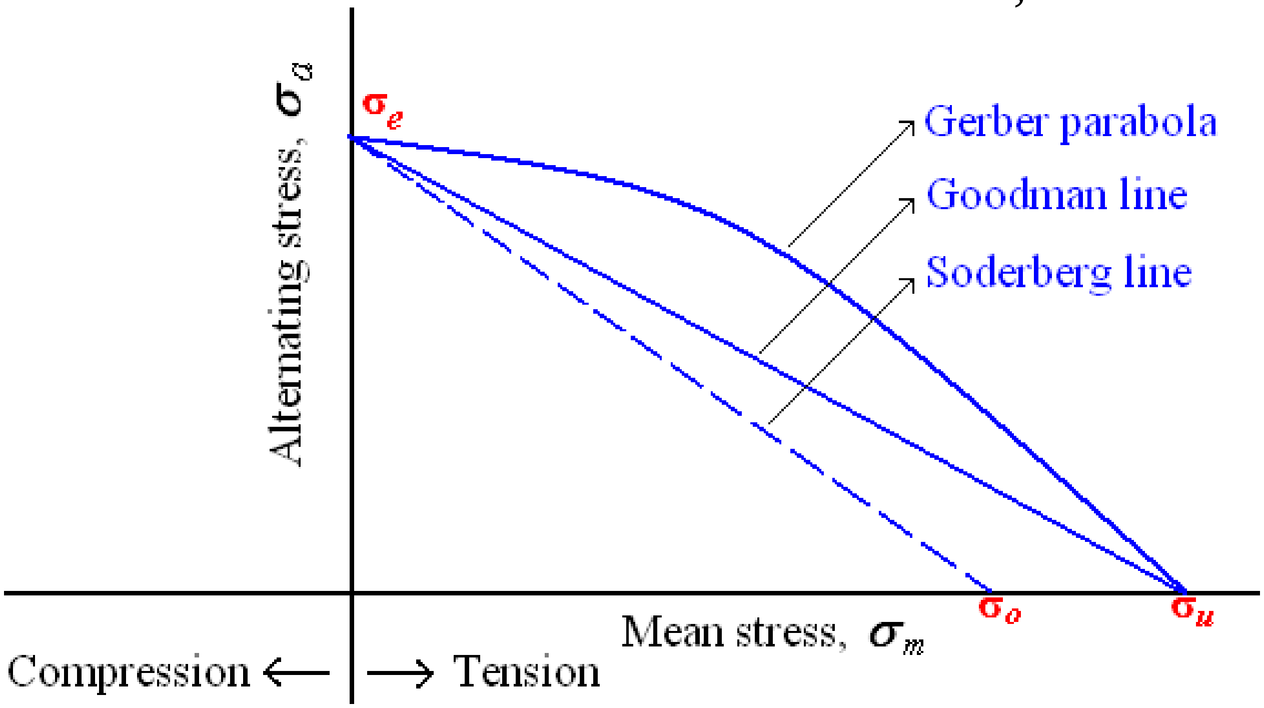


Fatigue data presentation (contd….)

- An alternative method of presenting mean stress data is by using Heig-Soderberg diagram. The following equation summarizes the diagram:

$$\sigma_a = \sigma_e \left[1 - \left(\frac{\sigma_m}{\sigma_u} \right)^x \right]$$

x=1 for Goodman line, x=2 for the Gerber parabola.



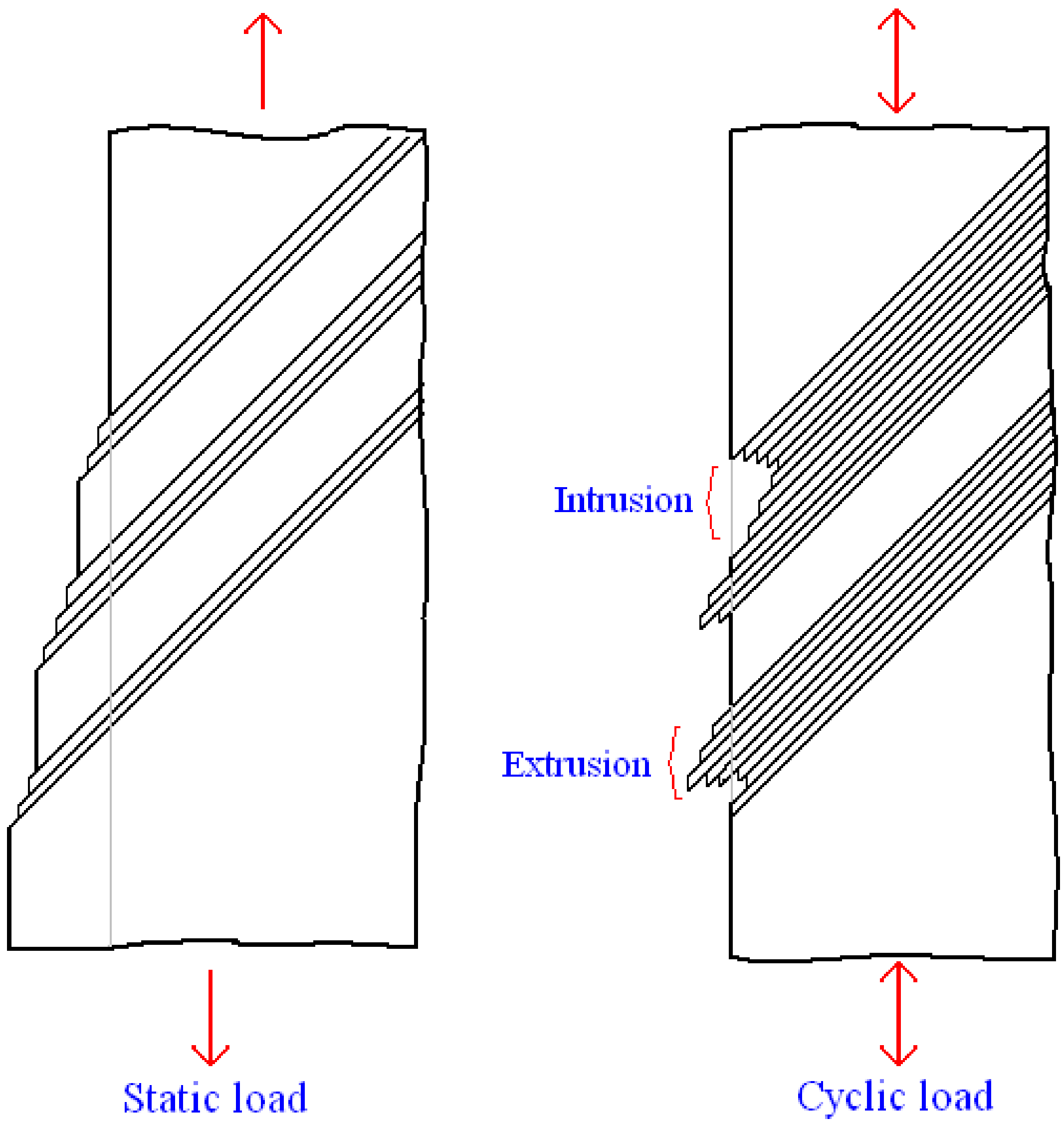
Fatigue – Crack initiation & propagation

- Fatigue failure consists of four stages: (a) crack initiation – includes the early development of fatigue damage that can be removed by suitable thermal anneal (b) slip-band crack growth – involves the deepening of initial crack on planes of high shear stress (stage-I crack growth) (c) crack growth on planes of high tensile stress – involves growth of crack in direction normal to maximum tensile stress (stage-II crack growth) (d) final ductile failure – occurs when the crack reaches a size so that the remaining cross-section cannot support the applied load.
- Stage-I is secondary to stage-II crack growth in importance because very low crack propagation rates involved during the stage.

Static load Vs Cyclic load

Feature	***Static load***	***Cyclic load***
Slip (*nm*)	1000	1-10
Deformation feature	Contour	Extrusions & Intrusions
Grains involved	All grains	Some grains
Vacancy concentration	Less	Very high
Necessity of diffusion	Required	Not necessary

Static load Vs Cyclic load (contd….)



Fatigue crack growth: Stage-I Vs Stage-II

Parameter	***Stage-I***	***Stage-II***
Stresses involved	Shear	Tensile
Crystallographic orientation	Yes	No
Crack propagation rate	Low (nm/cycle)	High (μm/cycle)
Slip on	Single slip plane	Multiple slip planes
Feature	Feature less	Striations

Fatigue crack propagation rate

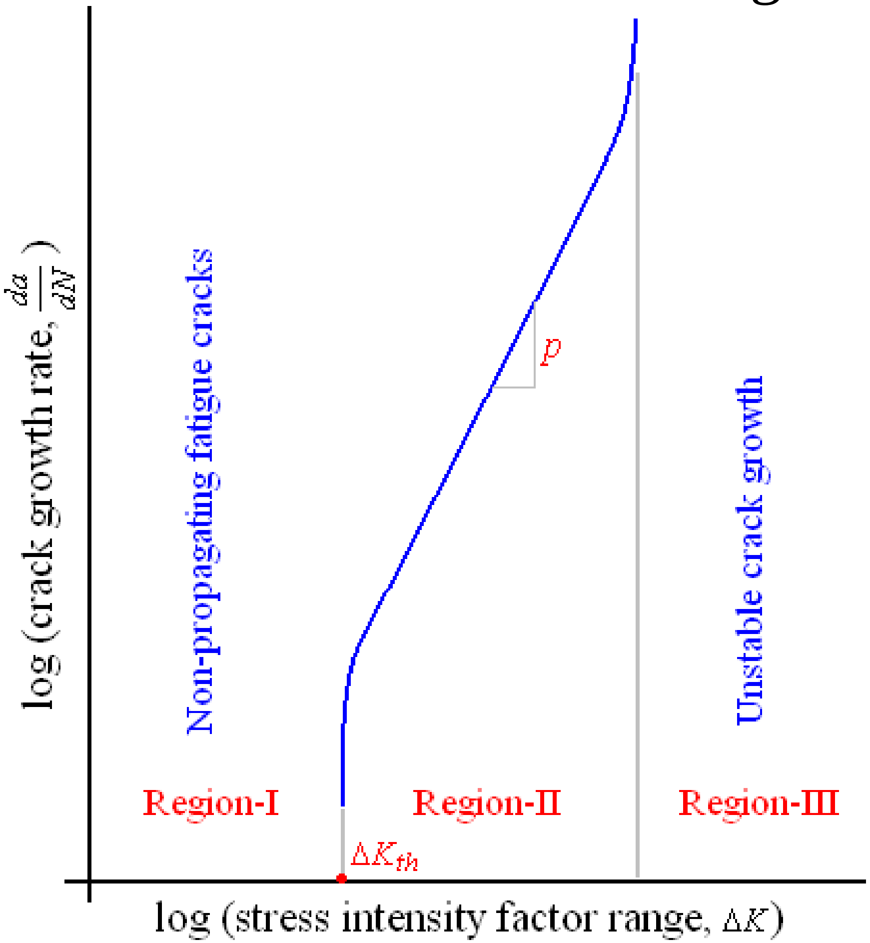
- Studies of fatigue crack propagation rate attained much importance because it can be used as fail-safe design consideration.

$$\frac{da}{dN} = fn(\sigma, a) = C\sigma_a^m a^n$$

- ***Paris law***:

$$\frac{da}{dN} = A(\Delta K)^p$$

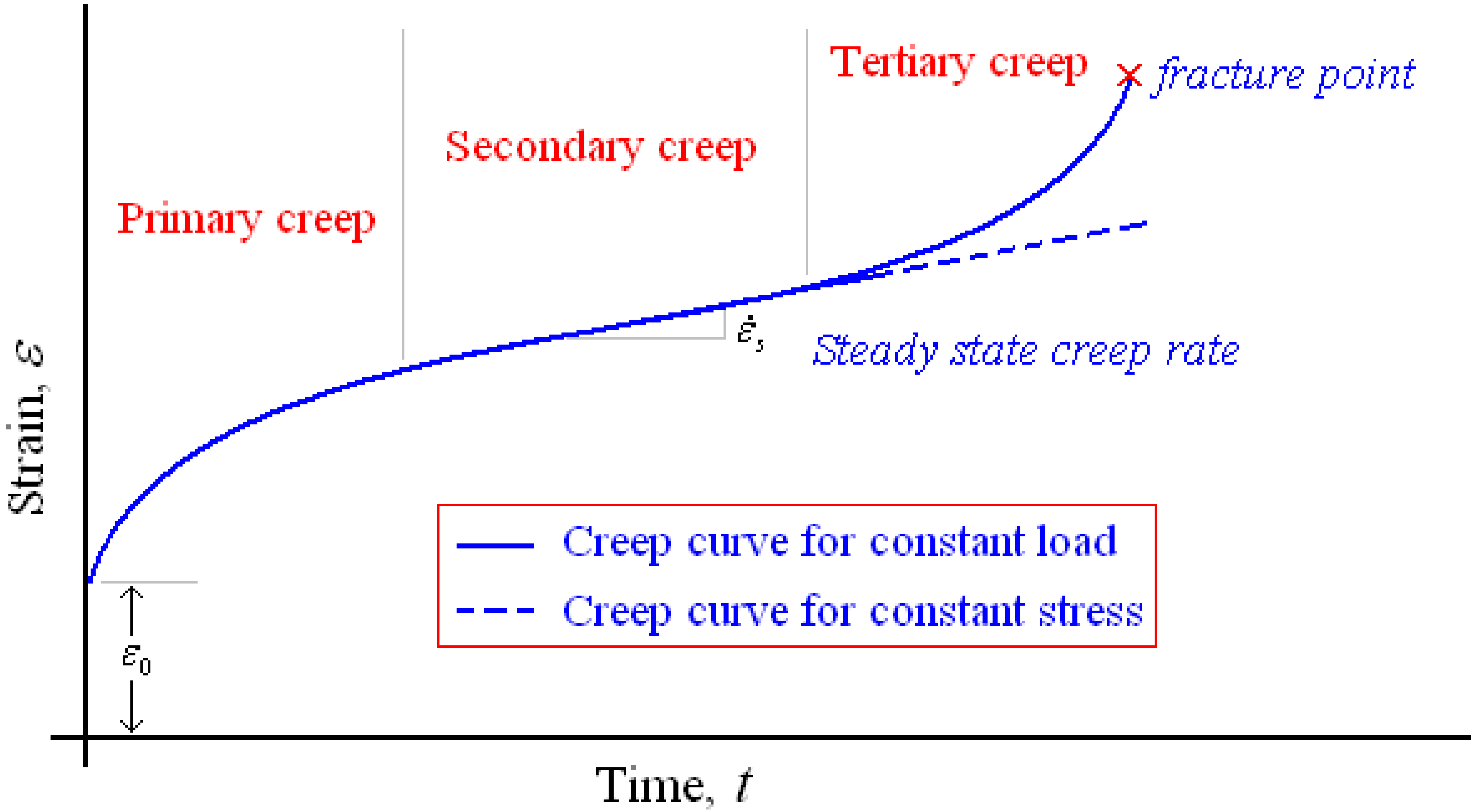
p= 3 for steels, 3-4 for Al alloys



Creep failure

- Deformation that occurs under constant load/stress and elevated temperatures which is time-dependent is known as *creep*.
- Creep deformation (constant stress) is possible at all temperatures above absolute zero. However, it is extremely sensitive to temperature.
- Hence, creep in usually considered important at elevated temperatures (temperatures greater than 0.4 *Tm*, *Tm* is absolute melting temperature).
- Creep test data is presented as a plot between time and strain known as creep curve.
- The slope of the creep curve is designated as creep rate.

Creep curve



Tertiary creep
fracture point
Secondary creep
Primary creep
Steady state creep rate
$\dot{\varepsilon}_s$
Strain, ε
ε_0
Time, t
Creep curve for constant load
Creep curve for constant stress

Creep curve (contd….)

- Creep curve is considered to be consists of three portions.
- After initial rapid elongation, *ε0*, the creep rate decreases continuously with time, and is known as *primary* or t*ransient creep*.
- Primary creep is followed by *secondary* or *steady-state* or *viscous creep*, which is characterized by constant creep rate. This stage of creep is often the longest duration of the three modes.
- Finally, a third stage of creep known as, *tertiary creep* occurs that is characterized by increase in creep rate.
- Andrade creep equation:

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

- Garofalo creep equation:

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

Creep in different stages

- First stage creep is associated with strain hardening of the sample.
- Constant creep rate during secondary creep is believed to be due to balance between the competing processes of strain hardening and recovery. Creep rate during the secondary creep is called the minimum creep rate.
- Third stage creep occurs in constant load tests at high stresses at high temperatures. This stage is greatly delayed in constant stress tests. Tertiary creep is believed to occur because of either reduction in cross-sectional area due to necking or internal void formation. Third stage is often associated with metallurgical changes such as coarsening of precipitate particles, recrystallization, or diffusional changes in the phases that are present.

Creep rate – Stress & Temperature effects

- Two most important parameter that influence creep rate are: stress and temperature.
- With increase in either stress or temperature (a) instantaneous elastic strain increases (b) steady state creep rate increases and (c) rupture lifetime decreases.

$$\dot{\varepsilon}_s = K_2 \sigma^n e^{-\frac{Q_c}{RT}}$$