MATERIAL TESTING AND STANDARDS

Reference Books:

G. E. Dieter, Mechanical Metallurgy, McGraw Hill Book Company, 1987.

Testing of metallic materials by A.V.K Suryanarayana, PHI

ASTM standards

UNIT III

- Torsion test: Introduction, Mechanical properties in torsion, Torsional stresses for large plastic strains, Types of torsion failures, Torsion test vs tension test, Hot torsion test.
- Fatigue and Creep Testing – Elementary treatment of fatigue phenomenon, S – N curve and corrosion fatigue, fatigue testing principle, Signification of Creep testing procedure , creep curve and its interpretation, stress-rupture test.
- Metallurgical and mechanical factors affecting, creep and fatigue failures.

TORSION TEST

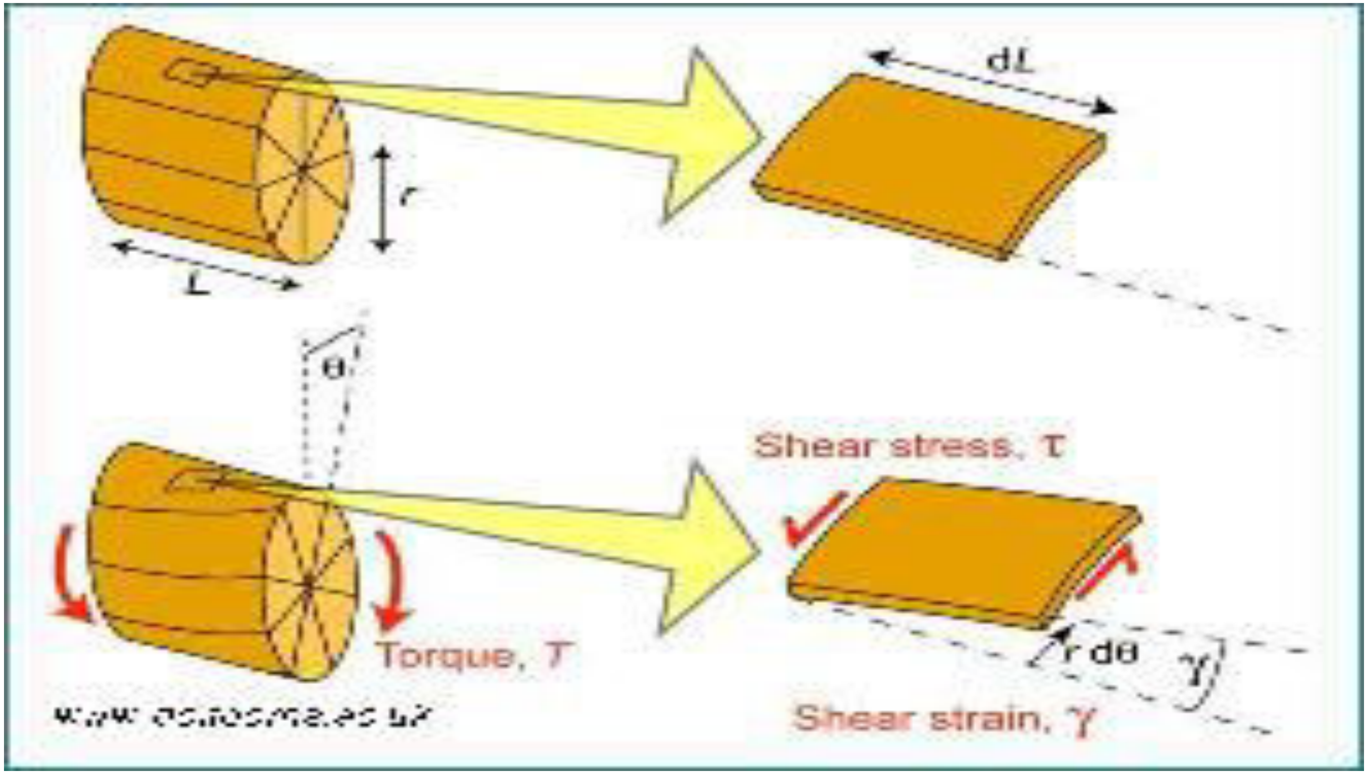
- A torsion test can be conducted on most materials to determine the torsional properties of the material. These properties include but are not limited to:

  - Modulus of elasticity in shear
  - Yield shear strength
  - Ultimate shear strength
  - Modulus of rupture in shear
  - Ductility

TORSION TEST

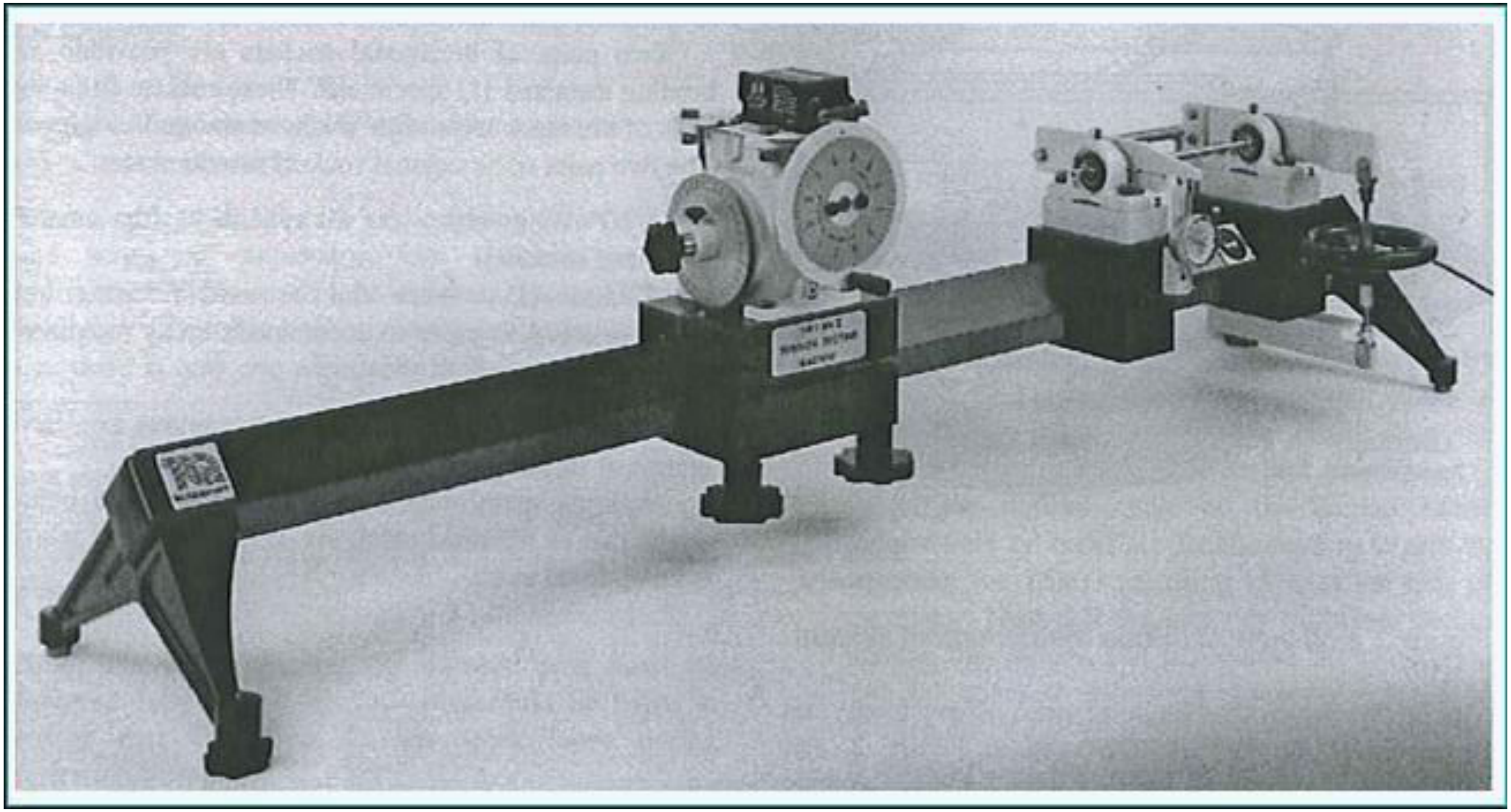
- In many areas of engineering applications, materials are sometimes subjected to torsion in services, for example, drive shafts, axles and twisted drills. Moreover, structural applications such as bridges, springs, car bodies, airplane fuselages and boat hulls are randomly subjected to torsion.
- The materials used in this case should require not only adequate strength but also be able to withstand torque in operation.

- Even though torsion test is not as universal as tension test and do not have any standardized testing procedure, the significance lies on particular engineering applications and for the study of plastic flow in materials.
- Torsion test is applicable for testing brittle materials such as tool steels and the test has also been used to determine the forgeability of the materials by means of torsion testing at elevated temperatures.



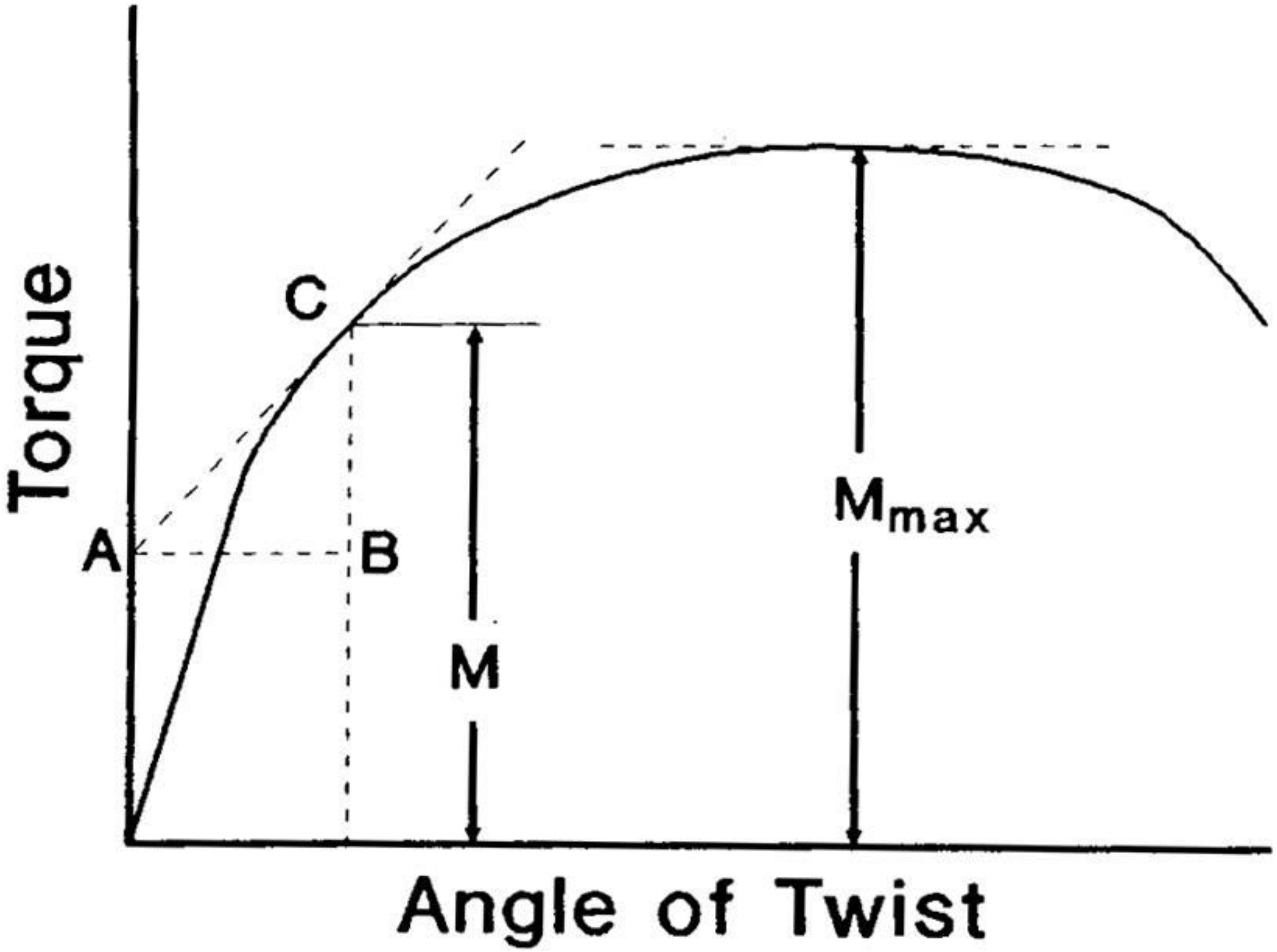
- Generally, torsion occurs when the twisting moment or torque is applied to a member according to figure

- The torque is the product of tangential force multiplied by the radial distance from the twisting axis and the tangent, measured in a unit of N.m.
- In torsion testing, the relationship between torque and degree of rotation is graphically presented and parameters such as
  - Ultimate torsional shearing strength (modulus of rupture),
  - shear strength at proportional limit and
  - shear modulus (modulus of rigidity) are generally investigated.
- Moreover, fracture surfaces of specimens tested under torsion can be used to determine the characteristics of the materials whether it would fail in a brittle or a ductile manner.



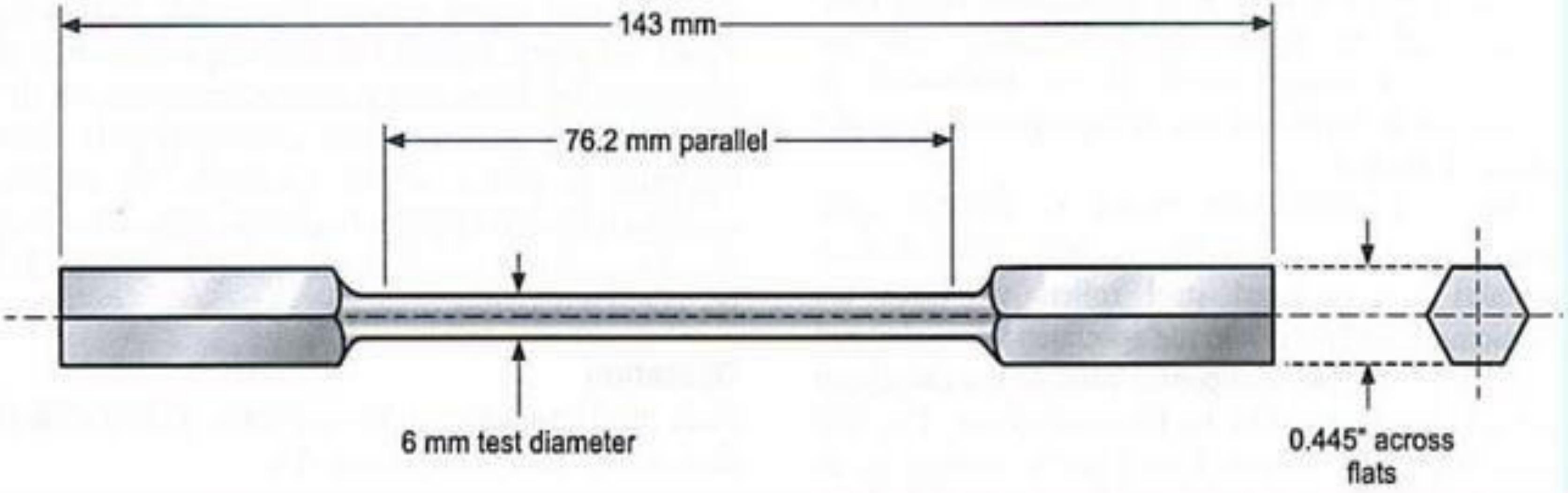
Torsion Testing Machine

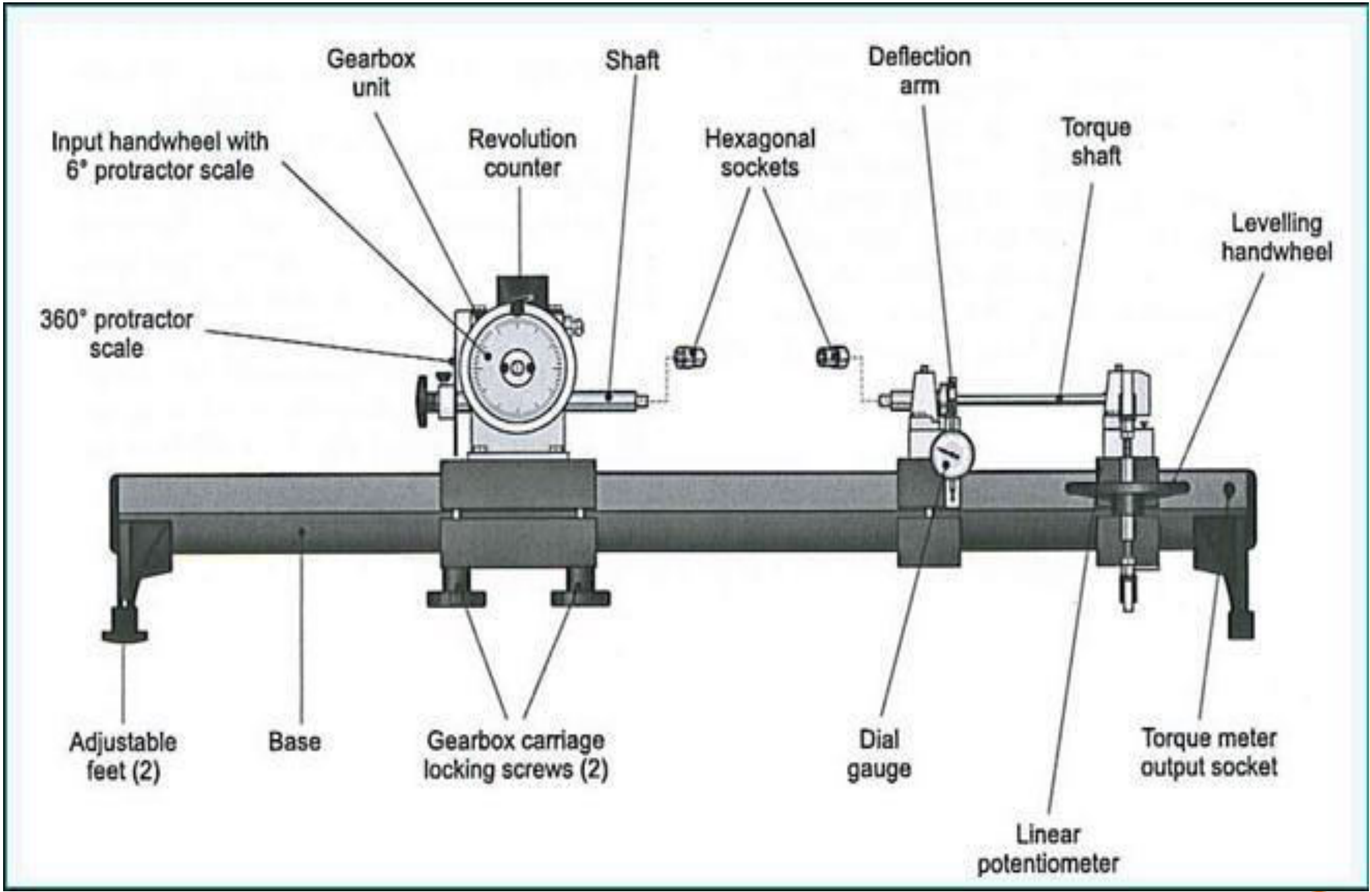
- In order to study the response of materials under a torsional force, the torsion test is performed by mounting the specimen onto a torsion testing machine and then applying the twisting moment till failure.
- The torque and degree of rotation are measured and plotted as shown in figure


Torque
C
A
B
M
Mmax
Angle of Twist

- Normally, the test specimens used are of a cylindrical rod type since the stress distribution across the section of the rod is the simplest geometry, which is easy for the calculation of the stresses.
- Both ends of the cylindrical specimen are tightened to hexagonal sockets in which one is fitted to a torque shaft and another is fitted to an input shaft.
- The twisting moment is applied by turning the input handwheel as illustrated in figure to produce torque until the specimen fails

Code Ref.	Specification
MT 15	0.15% Carbon steel as drawn
MT 15 N	0.15% Carbon steel normalised at 900°C
MT 40	0.40% Carbon steel as drawn
MT 40 N	0.40% Carbon steel normalised at 860°C
MT R	Aluminium alloy B.S. 1476-HE 14. Annealed
MT X	Brass B.S. 249
MT CI	Cast iron

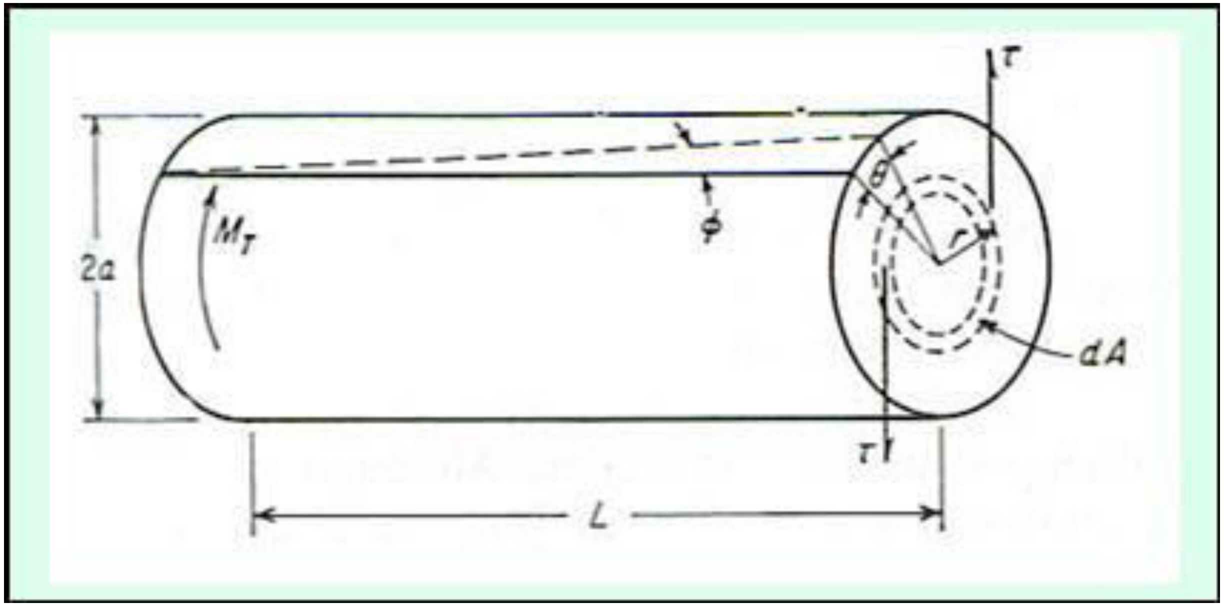



Gearbox unit
Shaft
Deflection arm
Input handwheel with 6° protractor scale
Revolution counter
Hexagonal sockets
Torque shaft
Levelling handwheel
360° protractor scale
Adjustable feet (2)
Base
Gearbox carriage locking screws (2)
Dial gauge
Torque meter output socket
Linear potentiometer

- When the twisting moment is applied, the torque is reacted by a torque shaft, which moves in relation to the deflection arm.
- The movement of the deflection arm is measured by a linear potentiometer, which is connected to a calibrated digital torque meter to give a readout of the torque in a unit of Nm or lb.in.
- The more we turn the input handwheel clockwise to increase the degree of rotation, the more torque is produced

- At the initial stage, the graphical relationship of the torque and degree of rotation measured is linear
- The specimen is elastically deformed and the recovery of the specimen to its original shape is possible if the specimen is unloaded.
- However, if a high degree of rotation is applied passing a proportional limit, the specimen starts to deform plastically and will not return to its original shape when the input handwheel is turned anti-clockwise.

- The degree of rotation can be read out from two protractors, elastic and plastic range protractors.
- First, an elastic range protractor scale is fitted on the input handwheel connected to the input shaft of the gear box.
- This protractor scale provides an accurate reading of 0.1^{o} and thus one revolution represents 6^{o} .
- A resettable revolution counter is fitted to the gearbox to record the overall input revolutions.
- When the twisting moment is large, the second protractor scale is required for the readouts in the plastic range of deformation.
- The second protractor is fitted onto the output shaft and provides a reading of 1^{o} with one revolution representing 360^{o} .



- Considering a cylindrical bar with one end being twisted as shown in above figure, the twisting moment M_T is resisted by the shear stress τ existing across the specimen section.

- This shear stress is zero at the center of the bar, increases linearly with its radius and finally reaches its maximum value at the peripheral of the bar.
- If the cylindrical bar with a length of *L, the twisting moment can be related* to the shear stress as follow:
  - ***<u>Formulae and numericals</u>***

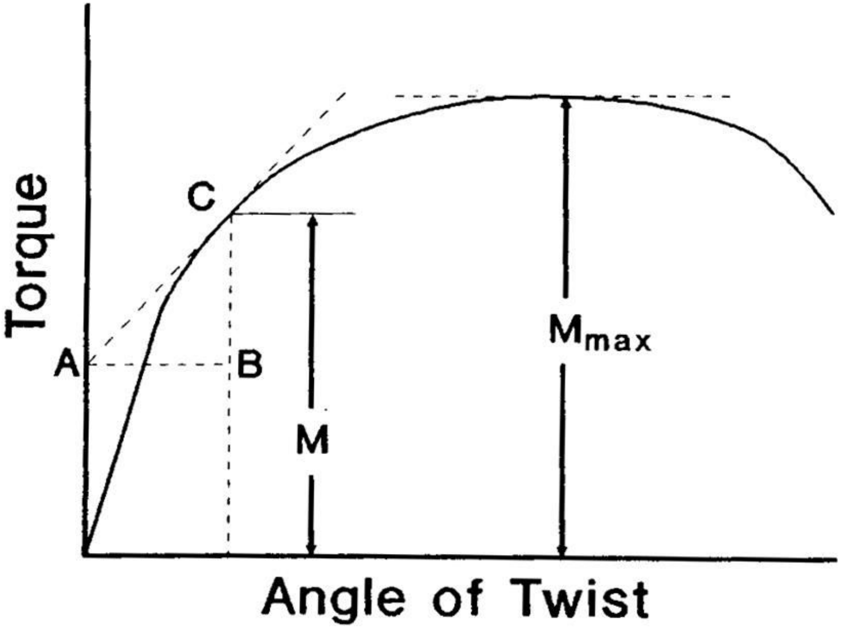
$$\frac{M_T}{J} = \frac{G\theta}{L} = \frac{\tau}{r} \qquad \ldots(1)$$

The shear strain, γ, can be calculated from equation 2

$$\gamma = \tan\theta = \frac{r\theta}{L} \qquad \ldots(2)$$

where	J	is the polar moment of inertia, mm^2 or in^2
	G	is the shear modulus, N/mm^2 or lbf/in^2
	θ	is degree of rotation, radian
	r	is the radius of the cylindrical bar, mm or in
	L	is the length of the cylindrical bar, mm or in
	τ	is the shear stress, N/mm^2 or lbf/in^2

- According to the graphical relationship of torque and degree of rotation, we can notice that the torsion specimen deformed elastically and then plastically similar to the case of the tension tested specimen.



- The initial stage of elastic behavior shows a linear relationship of torque and degree of rotation with its slope representing the shear modulus of the modulus of rigidity, G.
- The stress at the proportional limit is frequently determined at 0.04 rad.m^{-1} of the gauge length.
- Beyond the proportional limit, specimen deformed in a plastic manner and the relationship between the torque and the degree of rotation is no longer linear.

- However the determination of the proportional limit carried out using a torsional specimen of a thin-wall tube type will provides a more accurate value in comparison to that obtained from a cylindrical rod type specimen.
- Since the stresses vary across the section of the specimen from the center toward the peripheral of the specimen as mentioned previously, the reduced effect of stress distribution in the thin-walled specimen is therefore beneficial for the calculation of the stress.

- Within the elastic range of deformation, the shear stress can be calculated according to equation 1

$$\tau = \frac{M_T r}{J} \qquad \ldots(3)$$

- For a solid cylindrical specimen, the polar moment $J = \pi D^4 / 32$, *we can therefore determine* the shear stress as shown in equation 4

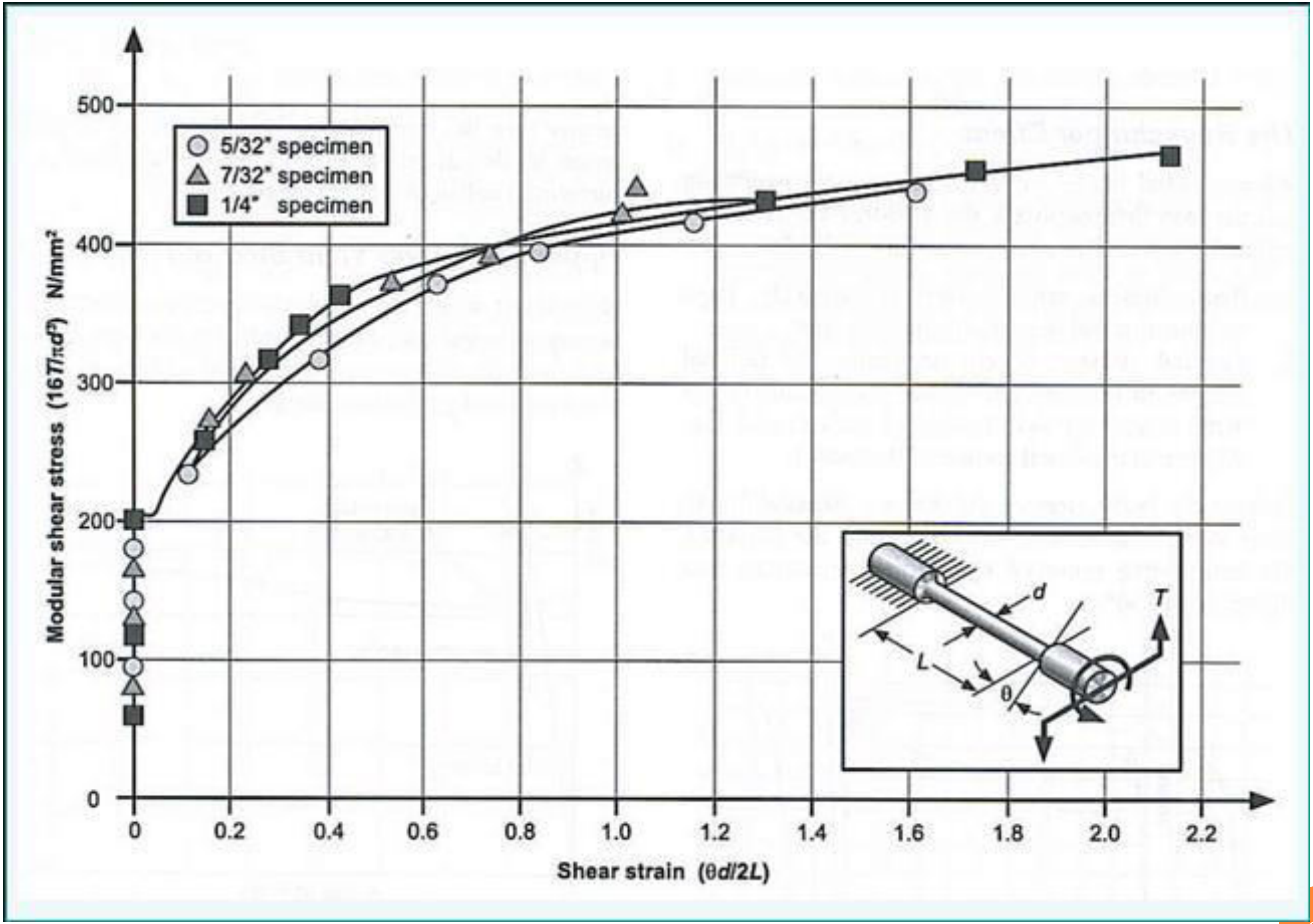
$$\tau = \frac{M_T D / 2}{\pi D^4 / 32} = \frac{16 M_T}{\pi D^3}$$

- For a tube specimen, the maximum shear stress at the peripheral of the tube can be calculated from equation 5

$$\tau = \frac{16M_T D_1}{\pi(D_1^4 - D_2^4)}$$

- where
  - *D_1 is the outer diameter of the tube*
  - *D_2 is the inner diameter of the tube*

- Therefore, if the torque and the degree of rotation are known according to the experimental result, the shear stress and the shear strain can be determined from equations 2 and 4.
- The obtained information is then used for the construction of the graphical relationship between the modular shear stress ($16M_T/aD^3$) *and the shear strain* ($\theta r/L$) *as illustrated in figure*

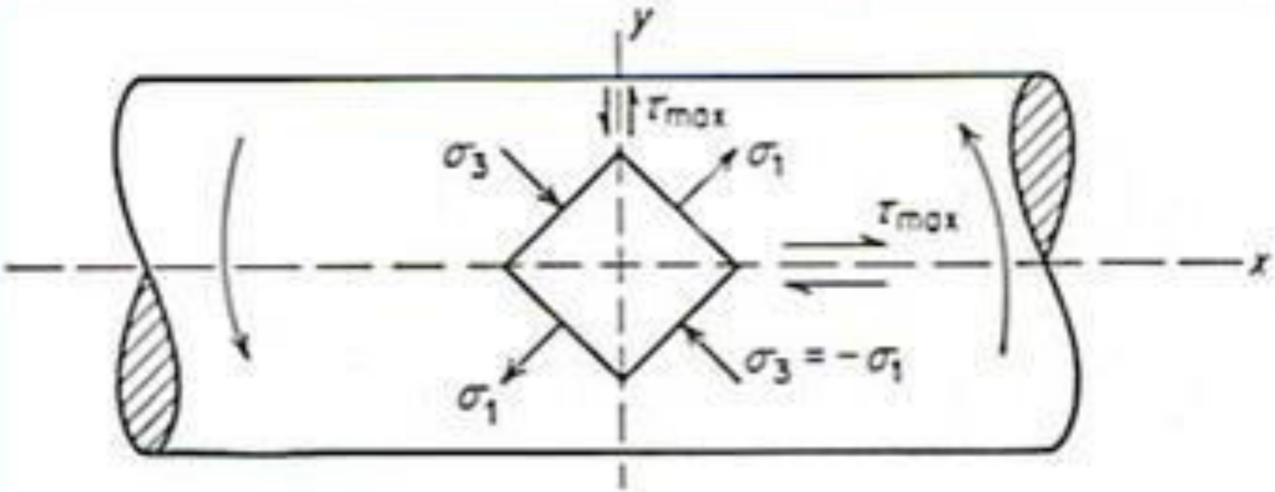

500
400
300
200
100
0
Modular shear stress (16$T/\pi d^3$) N/mm^2
○ 5/32" specimen
△ 7/32" specimen
■ 1/4" specimen
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Shear strain ($\theta d/2L$)
d
T
L
θ

- The curve is somewhat similar to those typical stress-strain curves tested under tension, giving elastic and plastic ranges with respect to the torsional stress applied.
- Nevertheless, the calculated shear stress according to equation 4 is only suitable for the evaluation of the stresses in the elastic range
- The plastic stress obtained from the shear stress-shear strain curve is therefore larger than the real stress..

- Furthermore, in the case that there is a large amount of plastic deformation involved, the length of the specimen is considerably changed, which can result in the superposition of the longitudinal stresses on the torsional shear stresses.
- Even though, the former is considered to be small and can be neglected, they might also affect the torsional failure strain of the specimen.

TYPES OF TORSION FAILURE

- Torsion failures are different from tension failures and normally provide little deformation or elongation.
- The characteristic of the fracture surface is related to the state of stress at the point on the bar surface, which can be described as shown in figure.
- It can be seen that the maximum shear stresses exist along two planes, which are perpendicular to each other.
- One is perpendicular to the longitudinal axis (yy) and another is aligned parallel to the longitudinal axis (xx).



State of stresses in torsion

(a) Shear (ductile) failure

(b) Tensile (brittle) failure

- The principal stresses σ_1 and σ_3 are inclined at 45^o to the longitudinal axis and have their magnitudes equal to those of the shear stresses. The principle stress σ_1 is tensile while the principle stress σ_3 is compressive.
- The intermediate stress σ_2 is zero under torsion.
- As mentioned previously, the characteristics of torsion fractures are influenced by torsional and tensile forces. These result in two types of torsion failures;
  - 1) ductile failure due to the shear stresses
  - 2) brittle failure due to the tensile stresses

- The former produces the fracture surface along the plane of the maximum shear stress and more frequently normal to the longitudinal axis as shown in figures a) and b).
- The latter exhibits the fracture planes normal to the directions of the tensile stresses, which are 45^o to the longitudinal axis.

REFER FATIGUE FROM CLASS NOTES

Feel free to contact me for any difficulties

CREEP

CREEP AND STRESS RUPTURE

- This provides the understanding of deformation and fracture behavior of material at high temperature.
- Creep and stress rupture tests will be compared such that the interpretation of test data will be discussed for engineering applications. This will lead to the selection of metal and alloys for desired uses at high temperature

- High temperature applications
  1. Steam power plant.
  2. Oil refinery
  3. Steam turbine used in power plant.
  4. Process plant

HIGH TEMPERATURE MATERIALS PROBLEM

- As temperature increases
  1. Atoms move faster diffusion-controlled process.
  2. This affects mechanical properties of materials.
  3. Greater mobility of dislocations (climb).
  4. Increased amount of vacancies.
  5. Deformation at grain boundaries.
  6. Metallurgical changes, i.e., phase transformation, precipitation, oxidation, recrystallisation.
- The properties needed are:
  1. Improved high temperature strength.
  2. Good oxidation resistance.

WHAT IS CREEP?

- Creep occurs when a metal is subjected to a constant tensile load at an elevated temperature. Undergo a time-dependent increase in length.

AT WHICH TEMPERATURE THAT MATERIAL WILL CREEP?

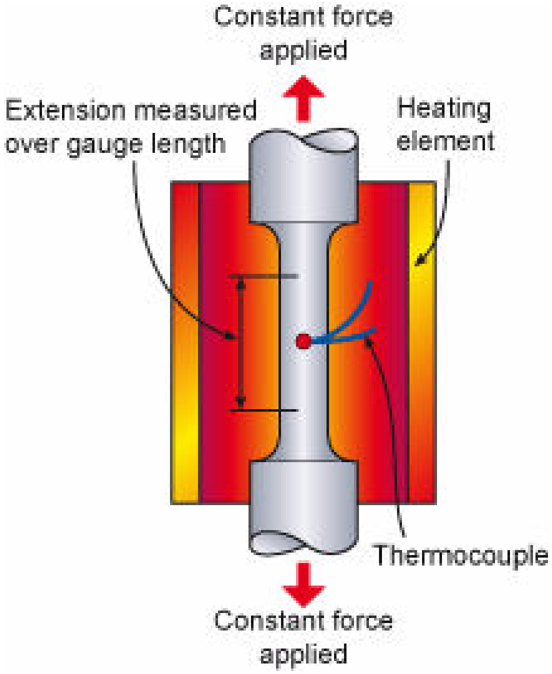
- Since materials have its own different melting point, each will creep when the homologous temperature > 0.5.

$$\text{Homologous temp} = \frac{\text{Testing temperature}}{\text{Melting temperature}} > 0.5$$

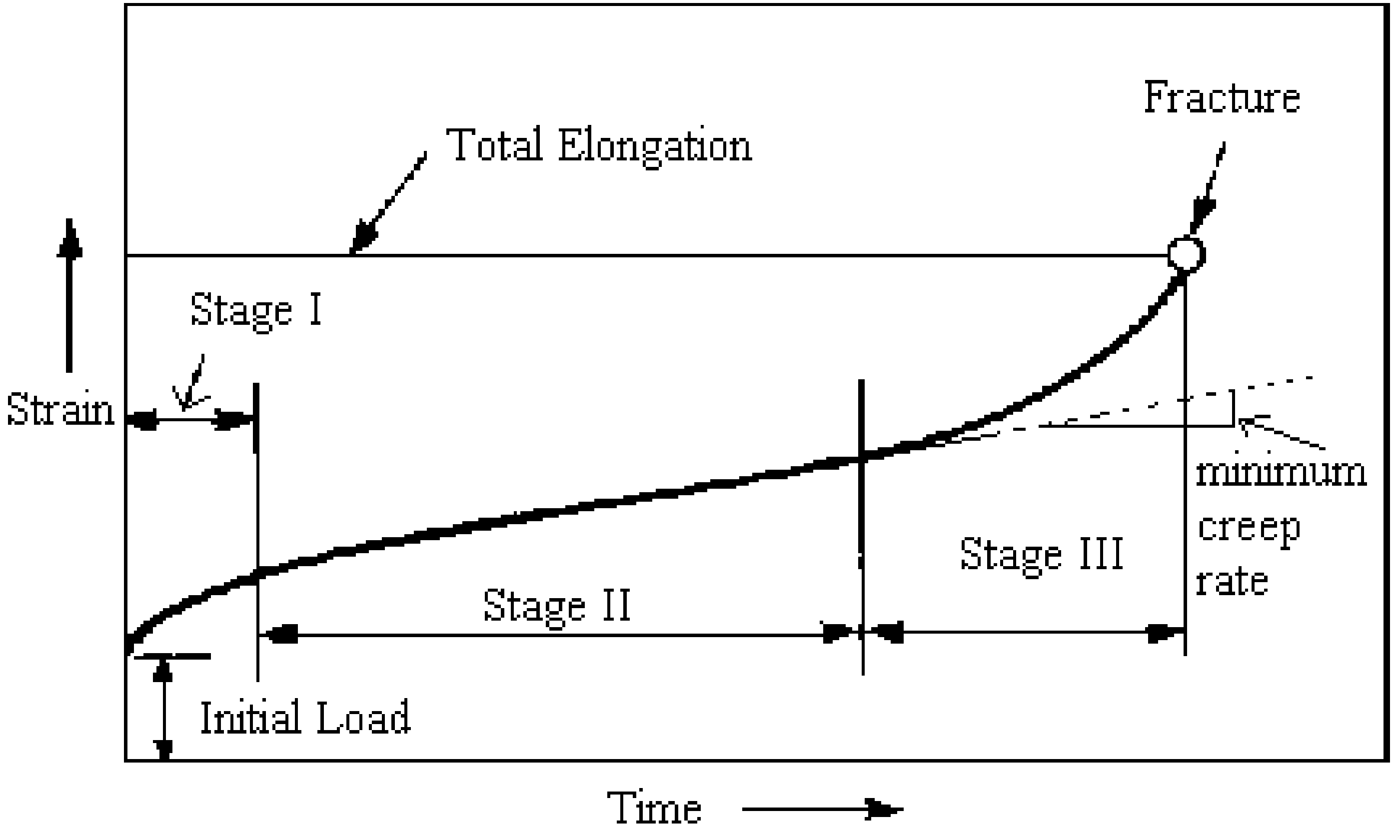
- The creep test measure the dimensional changes which occur when subjected to high temperature.
- The rupture test measures the effect of temperature on the longtime load bearing characteristics.

CREEP TEST

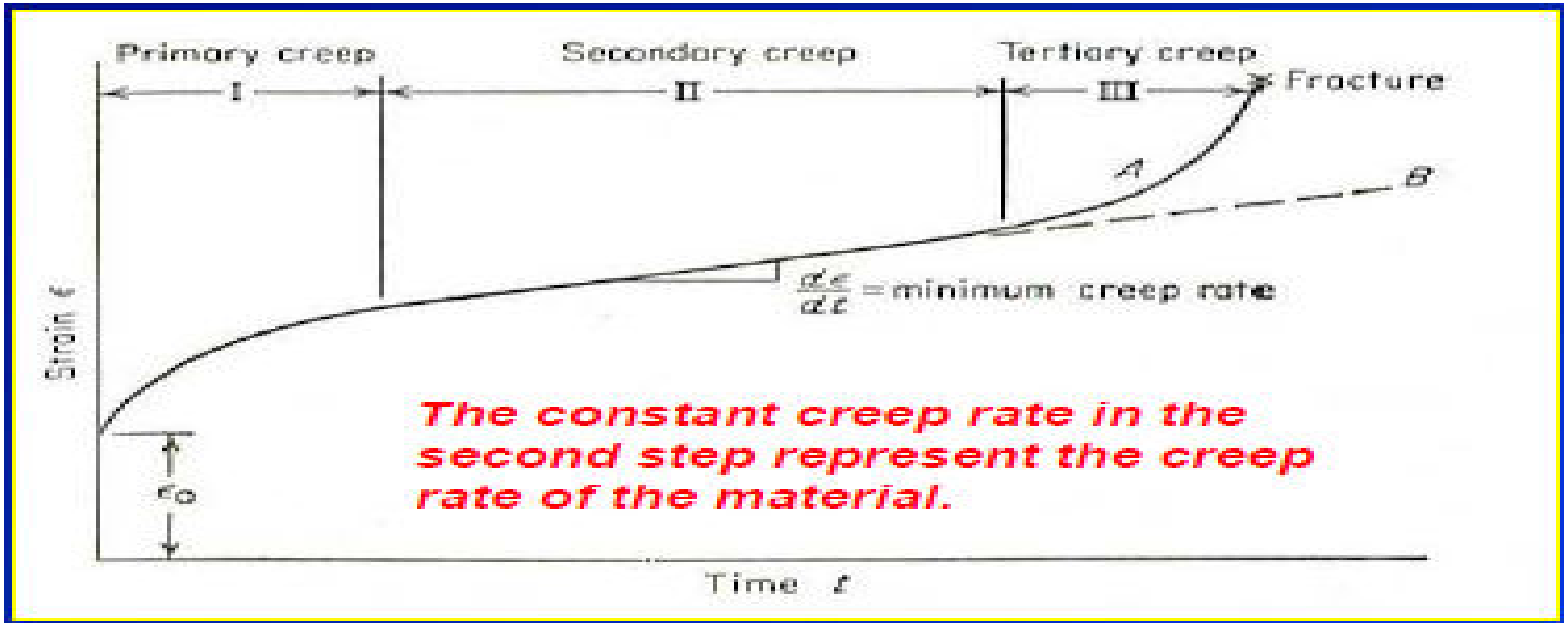
- The creep test is carried out by applying a constant load to a tensile specimen maintained at a constant temperature, (according to ASTM E139-70).



CREEP CURVE.


Fracture
Total Elongation
Stage I
Strain
minimum
creep
rate
Stage III
Stage II
Initial Load
Time

THE CREEP CURVE



The constant creep rate in the second step represent the creep rate of the material.

- A typical creep curve shows three distinct stages with different creep rates. After an initial rapid elongation ε_o, the creep rate decrease with time until reaching the steady state.

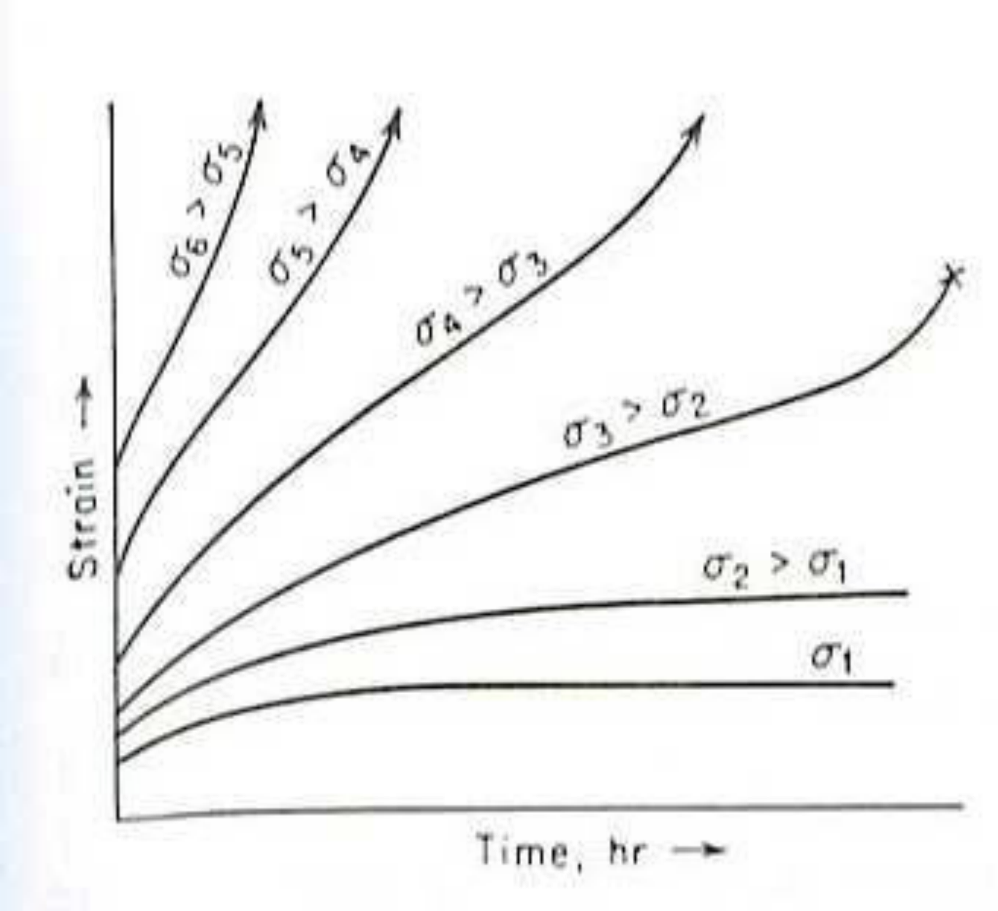
1. Primary creep provides decreasing creep rate.
2. Secondary creep gives the representing constant creep rate.
3. Tertiary creep yields a rapid creep rate till failure.

- ε_o is instantaneous strain on loading which is partly recoverable with time (anelastic) and partly nonrecoverable with time (plastic).

THREE STAGES OF CREEP

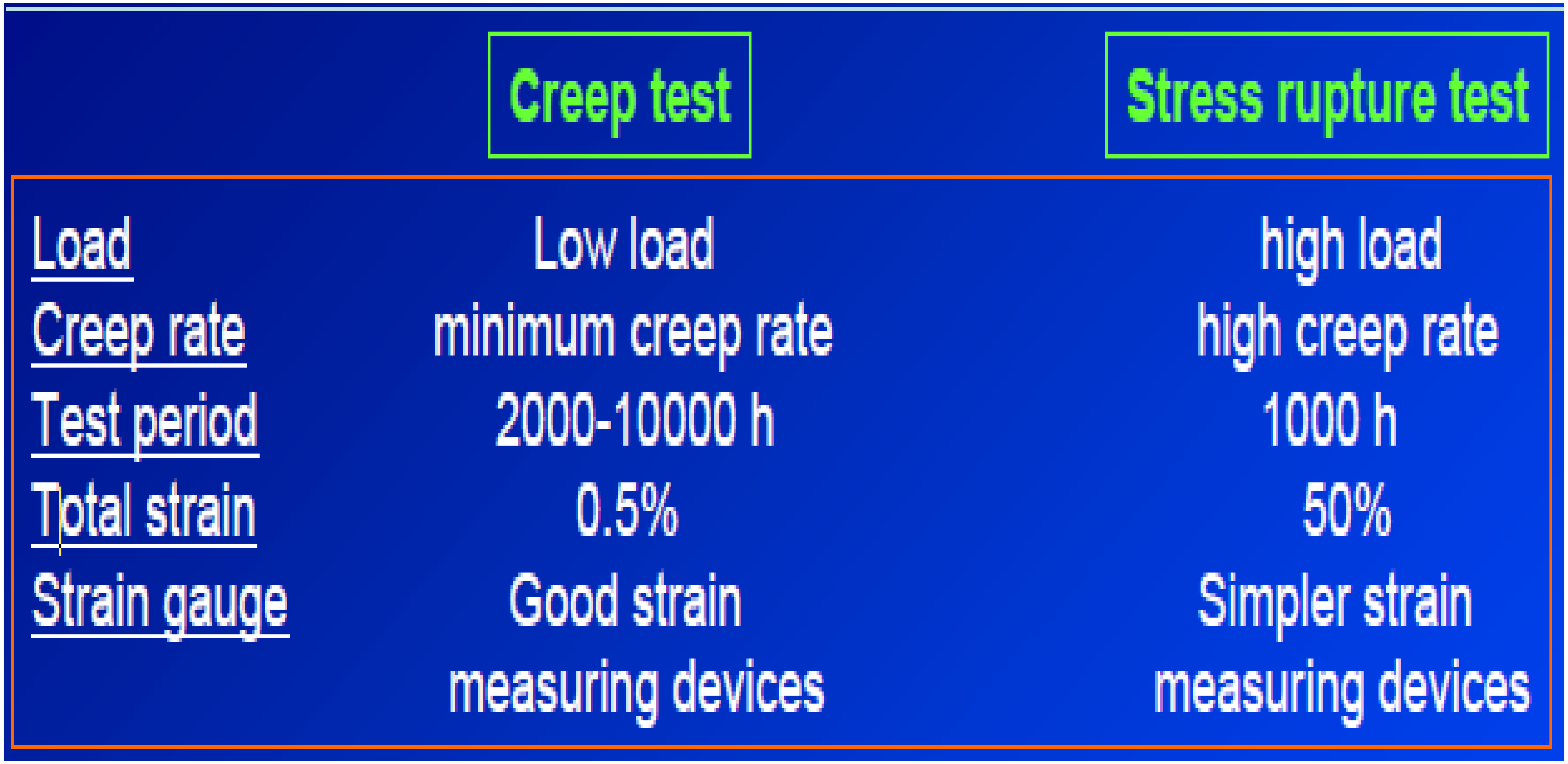
1. Primary creep is a period of transient creep. The creep resistance of the material increases due to material deformation. Predominate at low temperature test such as in the creep of lead at RT.
2. Secondary creep provides a nearly constant creep rate. The average value of the creep rate during this period is called the minimum creep rate.
3. Tertiary creep shows a rapid increase in the creep rate due to effectively reduced cross-sectional area of the specimen.

EFFECT OF STRESS ON CREEP CURVES AT CONSTANT TEMPERATURE



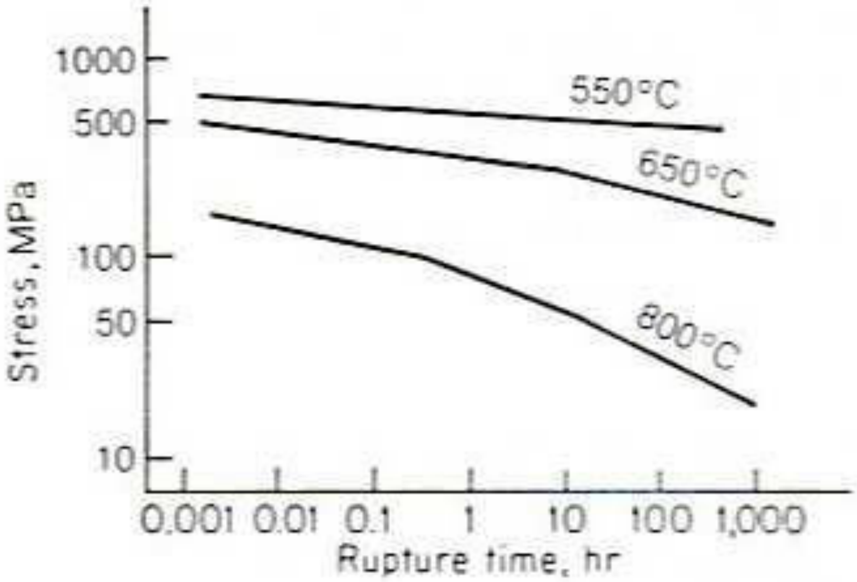
- The shape of creep curve will slightly change according to the applied stress at a constant temperature.
- As Applied stress increases Strain increases.
- As temperature stress increases creep rate increases.

THE STRESS RUPTURE TEST



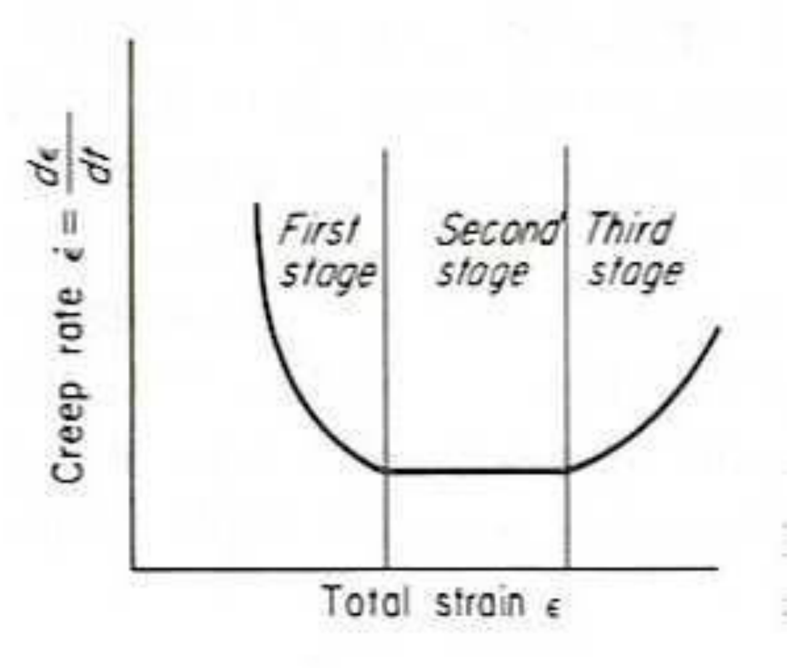
	Creep test	Stress rupture test
Load	Low load	high load
Creep rate	minimum creep rate	high creep rate
Test period	2000-10000 h	1000 h
Total strain	0.5%	50%
Strain gauge	Good strain measuring devices	Simpler strain measuring devices

- 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.



- 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.

STRUCTURAL CHANGES DURIING CREEP



- Different creep rates result from changes in internal structure of the materials with creep rate and time.

STRUCTURAL CHANGES DURING CREEP

- 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
   - Creep deformation produces inhomoginiety especially around grain boundaries, allowing dislocations to arrange themselves into a low-angle grain boundary. Easy for metals with high stacking energy.

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.

MECHANISM OF CREEP DEFORMATION

- The chief creep deformation mechanisms can be grouped into

1. Dislocation glide:
   - Involves dislocation moving along slip planes and overcoming barriers by thermal activation. Occurs at high stress.
2. Dislocation creep
   - Involves dislocation movement to overcome barriers by diffusion of vacancies or interstitials.
3. Diffusion creep
   - Involves the flow of vacancies and interstitials through a crystal under the influence of applied stress.

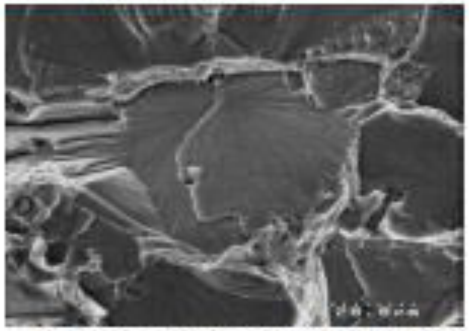
4. Grain boundary sliding
   - Involves the sliding of grains past each other

Fracture at elevated temperature

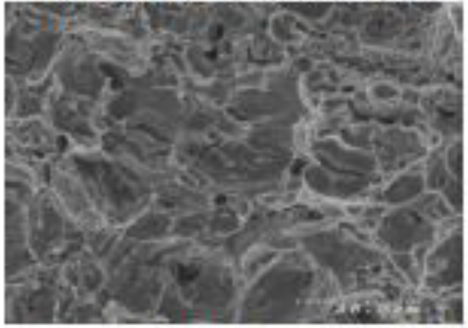
Transgranular fracture → Temp → **Intergranular fracture**

Slip planes are weaker than grain boundaries

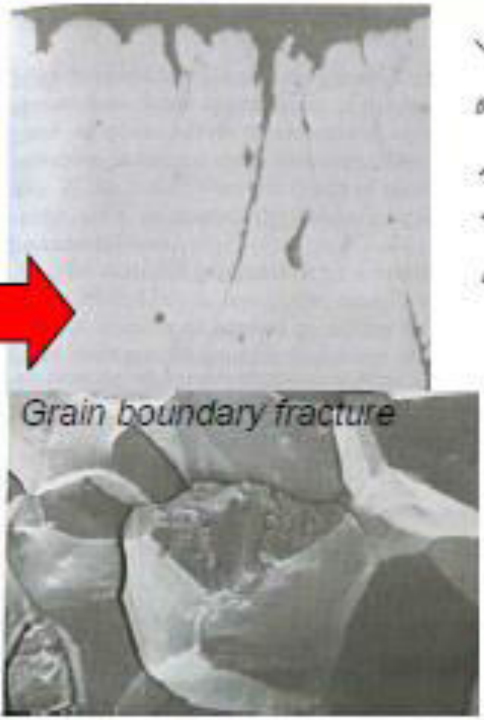
Grain boundaries are weaker than slip planes.



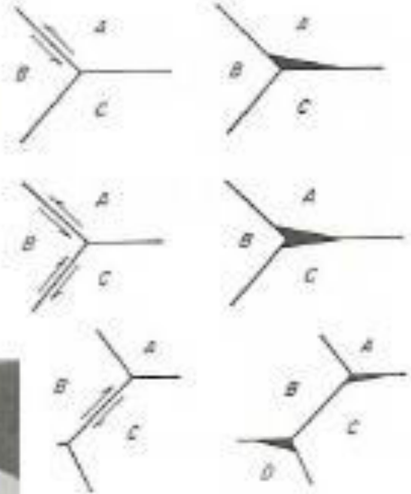
Transgranular cleavage fracture



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.

Equicohesive temperature

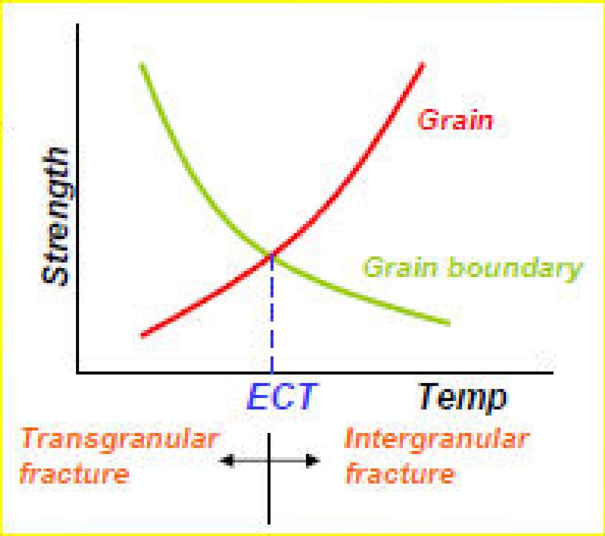
- *Strength of **GB** = **grain** at the equicohesive temperature (**ECT**).*

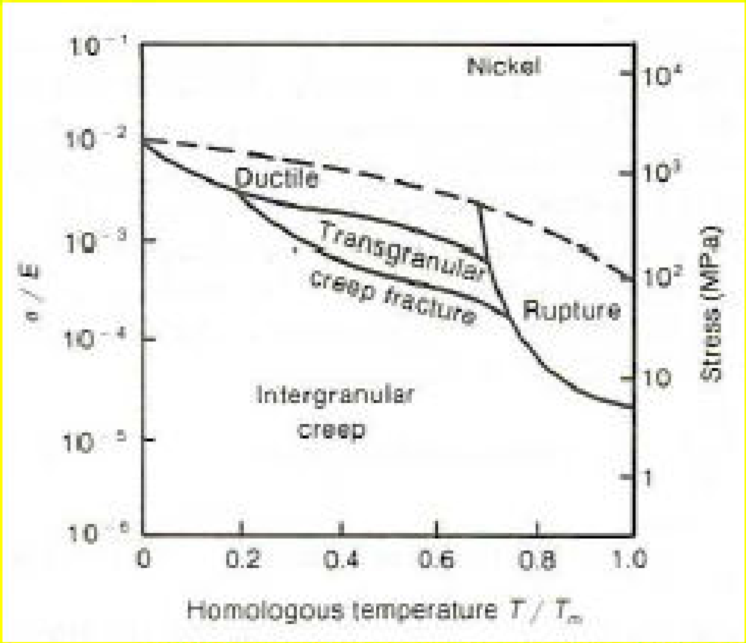
Strength rate ↓ **ECT** ↓

Increasing the tendency for intergranular failure

- 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.

Note: *Single crystal structure is therefore appreciable for high temperature applications, i.e., nickel base alloy single crystal turbine blade.*





Fracture mechanism map for nickel

HIGH TEMPERATURE ALLOYS

- High temperature alloys are complex in their microstructures to obtain the required properties at service temperatures.
- High melting point alloys normally has high creep resistance.
- Metals with high stacking false energy is easy for slip which leads to creep.

- Fine precipitates having high thermal stability are necessary for high creep resistance (prevent grain growth).
- Ex:
  - (1) Nickel base alloy containing fine precipitates of intermetallic compounds Ni_3Al, Ni_3Ti or $Ni_3(Al,Ti)$,
  - (2) Creep resistance steels containing fine carbides VC, TiC, NbC, Mo_2C or $Cr_{23}C_6$.

DRAWBACKS

- Difficult to fabricate by hot-working, cold working or welding.
- Highly alloyed metals are difficult to produced by precision casting.