failure (How to know whether a component has failed)

A part or assembly is considered to have failed under any of the 3 conditions.

Cannot start a) When it becomes completely inoperable

function b) When it is still operable but is no longer able to perform satishfactrily / doesn't give intended performance.

c) When serious deterioration has made it unreliable or unsafe for continued use, thus necessiating its complete removal ~~fr~~ from service, safety is compromised

fundamental sources of failure :-

- Aspect of design.
- Material selection.
- Material imperfections.
- Fabrication and processing
- Reworking
- Assembly - error in assembly.
- Inspection.
- testing
- quality control.
- Storage & shipment
- Service Conditions
- Maintenance
- Chemical damage.

A- Design.

- Mechanical notches -
  - ① - Presence of mechanical notches at points of high stress.
  - ② - The use of too sharp a fillet radius at a change in cross section of a shaft.
  - ③ - Sharp corners in bending or torsional loading.

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Tensile testing Specimen  → No sharp Corners.

Steps.

a) Material & fabrication
b) Macro examination of the fracture s/cs.
c) Conformation to specification.
d) Microexamination of the s/cs.
e) Analysis of crack origin.
f) Conclusion.
g) Corrective action.

→ Insufficient design Criteria.

- Impossibility for making stress Calculation for Complex parts.
- Insufficient Considerations of the types and magnitudes of the loads to which the part will be exposed in service.

B ~~B~~ - Selection of material.

- Inadequacy of tensile data
- Specific characteristics of the material that quantitatively measures its resistance to failure.
- operating Condition. (temp, Corrosion environment) etc.
- Mechanical properties changing with time.
  a) Resistance to wear
  b) Effect of elevated temperature on properties
  c) Resistance to stress corrosion, corrosion, corrosion fatigue and radiation.

C - Imperfections in Materials.

→ internal & Surface imperfection.

decrease the overall strength, provide ~~Rafe~~ Preferential paths for the propagation of cracks, act as notches, serve as preferential pitting type attack or provide path for intergranular Corrosion.

Casting defects - Cold shuts, inclusions, porosity voids, Shrinkage cavities,

forgings -

forging defects - laps, ~~seams~~, seams, shrinkage cavities, flow line pattern, seggregation in the billet,

Rolling defects -

D

D - Deficiencies in processing.

Sometimes failures occur due to Specification of unsuitable processing procedures, incomplete or ambiguous specification, changes made in specifications without complete evaluation

→ Cold forming & related operations.

Such as deep drawing, stretching, expanding reducing and bending, produce residual

Stress Stresses. Surface defects and metallurgical changes caused by processing have influence on fatigue strength, resistance to brittle fracture, Corrosion resistance, anisotropic properties.

- Shearing, blanking & piercing produce local residual stresses.

→ Machining & grinding
Machining introduces residual stress, Severe grinding causes overheating and changes the microstructure.

→ Identification marking - ~~by~~ Marking is given impact indentation, or by electro etching. - The indentation should n't be in the highly stressed region.
- Identification mark by electrical discharge machining, produces fusion and a heat-affected zone, which leads to the stress corrosion cracking.

→ Improper heat treatment - - overheating, undertempering, use of low hardening tempe. Excessive temperature gradients, uses of quenching, tempering, aging condition unsatis- for a specific alloy or part.

Decarburisation during heat treatment, induces failure by a fatigue, because ~~to~~ it decrease the endurance limit of the surface.
b) by distortion of small parts on which the strength is reduced due to decarburisation. ~~It is~~ Decarburisation is detrimental to the service life of springs and small shafts.

→ Acid pickling and electroplating ~~→~~ (especially at low cathode efficiency) are well known for their ability to cause hydrogen charging and hydrogen embrittlement of high strength steels. Chemical cleaning or electrolytic cleaning and etching in which hydrogen is generated produces similar effects.

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Welding - Stress Corrosion Cracking of Welded austenitic stainless steels of boilers, heat exchangers, and pressure vessels

Sensitization & IGC may be reason of failure.

- proper welding condition must be maintained in order to avoid this. proper filler material to be used.

Reworking - Reworking action during some stage of manufacturing.

Errors in Assembly

- Not detected by the manufacturer or purchaser.
- Mostly associated with moving parts of mechanical assemblies, or with electrical assemblies, ~~structure~~
- but structural components (for example small errors in the placement of rivet holes in airplane wings)
- Operator negligence.

Improper Service Condition.

The operation of equipment under abnormally service condition of speed, loading, temperature and chemical environment, without regularly scheduled maintainance, improper inspection and monitoring are ~~the~~ sometimes the prime causes of failure.

- start up and shut down inspection should be proper. Most of the airplanes have crashed during take off or landing.
- Pitting corrosion of Austenitic Stainless steel boilers during shutdown

General procedure of failure Analysis (AKDas) book

Guidelines to reach the root of the cause of failure (Root Cause Analysis)

→ Background information which provides what happened prior to and at the time of failure, the manufacturing history of the part and discussion with eye witness.

→ Visual examination includes a visit to the scene of failure, making sketches, taking measurements, notes and photographs. It helps to select parts to be taken to the investigation agency, examination and understanding.

→ Non-destructive examination to obtain defect-information on the surface as well as at the core of the failed part.

→ Fractographic examination to identify the type and nature of fracture

→ Destructive testing to ensure soundness of the material in conformity with the specification in respect to chemistry, properties of microstructure, etc.

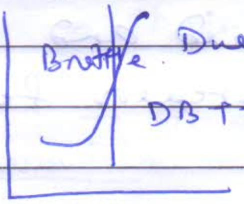
→ Examination of all data to arrive at a conclusion of the cause of failure.

→ Recommendations for its prevention.

Examples.

① Titanic - 3M rivets. - Impact resistance of
1912 binding the plates | the rivets were poor.
↓ loss of 1500 lives. ↓ low quality iron

- 16 components were connected at the ceiling so sequential water filling took place

- 

DBTT should be low.
Addition of Ni, etc.
use alloy steels.

Recommendations - Use alloying elements that decrease the DBTT
- ~~Don't~~ Avoid use ~~too~~ of dissimilar metals
- Avoid use of poor rivets

② St. Francis dam - Los angles city (40 miles
1928
↓ Constructed in Canyon hills
↓ dam failed → 1600 people killed
↓ High water waves.

~~- Regular check up of the dam~~

→ Reason - failed due to residual stresses, poor construction, construction using low quality materials.

→ Recommendation - Regular check up.
- use good quality materials
- Giving a larger factor of safety.

③ Tacoma Narrows Bridge Collapse (1940)
↓ suspension bridge in washington
world's 3rd ~~largest~~ longest suspension bridge.

→ Bridge used to flutter with wind velocity
→ It collapsed at a wind speed (64 km/h)
→ The Cause was aeroelastic flutter.
→ Avoid the suspension bridges

[redacted]

Indian failures

① – Kadalundi train Disaster.

- The railway bridge was around 140 yrs.
- One of the piers settled down the sand in river.
- As soon as the train came near it, the track snapped and the train derailed, the train fell down the river.

→ Recommendation → Never use a structure of high importance without testing it. Always keep an eye on it and test it.

② Bhopal gas disaster :- Union Carbide
1984, a toxic gas release at a union carbide pesticide plant in Bhopal. resulted in 2259 ~~deaths~~ immediate deaths and 16000 deaths following disaster, 558,125 injuries.

- It was caused by methyle-isocyanate, a highly toxic and irritating material. in the making of pesticides, got contaminated with H_2O. This contamination is exothermic and released heat. The inside temperature raised to 200°c. This was beyond the capacity of the plant to sustain the temperature. Therefore, the emergency release systems kicked in, venting the extra pressure which escaped and began to spread.

The gas was heavier than air, it crawled for miles.

③ Rafigan rail bridge Collapse
→ Train fell down due to Plate girder deterioration over time.
→ Bridge was rusty
→ Strength loss with use
→ lost strength of fatigue due
→ Girders were corroded vibrations

Recommendation — Make sure the design is checked against fatigue and steel is coated with anti-corrosion paints.

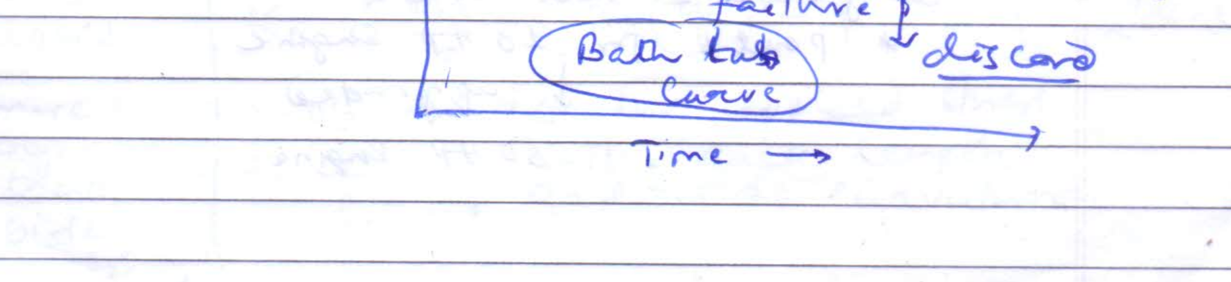
Mechanical Component failure
— Loading Condition.

① Elastic deformation (Unacceptable)
Automotive shaft. → crank shaft in automobiles.

② Plastic deformation (Unacceptable) — shaft - gears teeth twisted

③ Fracture (D, B, F, C) → Creep (boilers)
↓ ↓ → fatigue
Ductile Brittle

④ Loss of dimension beyond acceptable limits, wear & tear, erosion, corrosion.



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(2)

① Importance of FA
② ~~What type of~~ How
② What kind of expertise we need
③ How FA is useful for ensuring the improved reliability, quality and performance of the products

Fundamental sources of failure ③

① Improper design
② Improper selection of material
③ Imperfections in materials. - inclusions
4 ③ Improper manufacturing processes spores.
5 ④ Improper assembly. - leads to imbalance misalignment -
6 ⑤ Improper service conditions
Size & shape
↳ low/high temp.
↳ loading condition.
7 ⑥ Improper maintainance - little lubricants
- Anti-corrosion coatings.

① Deficiencies in design.

⓪ - sizing & shape required for the given service conditions.

a) presence of stress raisers
↳ Mechanical notches
↳

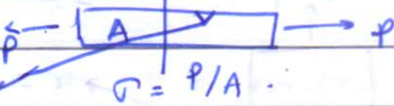
b) Changing the design of the component for a given service condition. without proper consideration to the service conditions (SC)

c) Upgradation a product to the different service conditions
e.g. water & salt-water
* ports for 10 HP engine.
↓ upgraded
50 HP engine.

- Design is developed without full knowledge of stress conditions owing to complexity of geometry.
- Designing without proper assessment of service conditions (Load, Temp & environmental condition)
- Inability to use proper criteria for designing the Engineering Components.
  - Creep - fatigue - overload

a) <u>presence of stress raisers</u> → Intentionally / Unintentionally ↓ imperfections.

No stress raisers



$\sigma = P/A$.

$\sigma_r = P/A$

If some geometrical feature introduced.

↓ localisation of stresses.

↓ stress concentration.

$\sigma_{max} = \frac{P}{A_s}$ ←

<u>$\sigma_{max} > \sigma_{ref}$</u> → $\frac{\sigma_{max}}{\sigma_{ref}}$ = Theoretical stress concentration factor. > 1

example - Threads, holes, rivets.

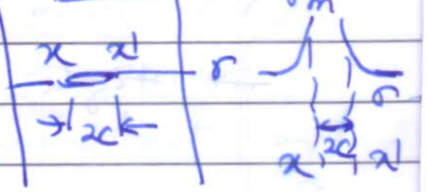
σ_{ref}. reference stress (without any stress raisers)

Geometry of stress raisers.

Surface stress raisers are more dangerous than inside stress raisers

$$\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$



σ_0 → is the applied stress.
a → half crack length.
ρ_t → Radius of curvature.

$\rho_t \downarrow$ ⟵ stress conc^n is high.

$\rho_t \uparrow$ ⟵ stress conc^n is low.

Important in case of brittle materials stress concentration is high.

- To avoid. factors. → fillets, grooves, holes, etc.
  - → size & shape of notches.
    but not on the size & shape of
  - use of narrow notches.
  - → Type of loading
    - Axial
    - Bending
    - Fatigue
    - Torsional.
  - → Metal aspects.
    assumed that material is isotropic and material behaves in linear elastic material.

Axial.

→ radius of crack tip.

ρ_t.

If material is brittle, $\rho_t = 0.5$, crack doesn't blunt.

If m/l is ductile, the crack blunts ρ_t increases, stress concentration gets reduced.

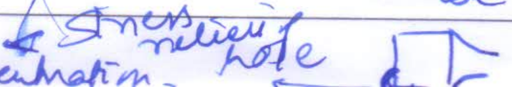
— In case of torsional loading, the stresses are more at the surface than at the core, implies that torsional and bending stresses are more harmful than the axial loading.

→ High yield strength material are more harmful.

→ The change in cross sectional shouldn't be sharp but it should be gradual.

gives less stress concentration.

Stress relief hole



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Geometrical features. (role of stress raisers)

- Design Criteria - fatigue, creep, Uniaxial.
- Type of Load - Axial,
- Material features - σ_y, σ_{UTS}.
- Metallurgical features - needles, platelets, lamellas. (morphology of microconstituents) easily nucleate the cracks.
- Calculate the maximum stress by taking into the stress raisers.
- fracture analysis - High strength, High hardness, Low ductility
  fracture mechanics. $K_{IC} = \sigma\sqrt{\pi c}$.

Case study — Lect-4. (Deficiencies in design) Page-1, ASM Handbook

b) Changing / Upgradation of a part to more severe condition.

- Unsuitability of the metal/alloy to the new application. + Good record at RT. If we ~~apply~~ use it at low temp (−22°C) or Chemical industry (high temp), the behaviour will be different.
- Heat treatment requirements. for steel - ~~Tempered~~ Quenched + tempered.
  If the same part to be used at high temperature → it will lead to over tempering → loss in toughness.
- Improper stress relieving.
- Size/shape requirements for the new service condition. (high load), the size and notch of stress raisers play an important role. Loading distribution also changes for the new condition. Tensile stress may convert to torsional stress condition.
- Plane stress may change to plane strain.

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- Upgradation of a product to a different service condition
  - Designing should be done as per the new condition.

These arise
↓
due to complexity of design.

→ Stress distribution, corrosion environment – Effect of environment
→ Improper distribution of load during service.
→ Inability to

Calculate the stresses which will be acting on the components.

↓ ~~Material~~

② <u>Improper Selection of Material</u> – ~~Selection of Material for application~~

Each metal have different Physical & Mechanical properties

A $\sigma_{ys}\uparrow$ % El ↓.

B $\sigma_{ys}\downarrow$ % El ↑. etc.

We need to consider the expected failure ~~examination~~ mechanism.
- Ductile fracture
- Brittle fracture
- → Creep.
- → Fatigue.
- → Corrosion
- – Wear
- – Erosion
- – Wear.

~~The size and shape of the stress raisers.~~

- If failure is expected to occur by excessive plastic deformation at room temp. and high temperature, then the yield strength and creep respectively become important criterion of design.
- If failure is expected to occur by fracture under overloads, fluctuating loads, and impact loads then UTS, Endurance strength and impact strength respectively become the

design Criteria.

Characteristics of materials required for the selection.

Failure mechanism	Selection Criteria.
Ductile fracture	yield strength (tension, compression)
Brittle	fracture toughness (K_{IC}) Notch toughness ductility DBTT.
fatigue	Endurance limit/ Fatigue strength with stress raiser, hardness
Thermal fatigue	Ductility, peak plastic strain. (under operating condition)
Creep	Creep rate at given temperature
plastic deformation (change in cross section)	yield strength.
SCC (tensile load under corrosive environment)	K_{ISCC}, Corrosion resistance to specific environment

Imperfection in base metal itself.

- * Perfect metal & Alloy not possible
- * Live with imperfections

Some are favourable. / Some are not.

- point defect } ① Crystallographic Vacancy & dislocation
- line defect
- surface defect - Microscopic.
- volume defect - - Macroscopic

Point defects (Vacancies) → Vacancy

- Interstitial impurity
- self-interstitial.
- Substitutional impurity
- frenkel/ Schottky defect

$$\frac{n}{N} = e^{-H_f/RT}.$$

Dislocations - ⊥ + edge
T - edge,
screw
Q.C.

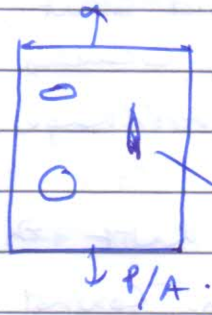
Some phases in localised way.

② Microscopic - bands, Seggregation, Unfavourable grain Orientation
Grain boundary | Orientation.
high low.
direction of loading/grains are unfavourable Oriented.

③ Macroscopic or Volume defect - Pores, Inclusions, Cracks.

Cracks at S/C and internal Cracks in the form of ~~[illegible]~~ pores, inclusions.

In Al-Si alloy Si exists in the form of inclusion.



- Area gets reduced.
- Nominal Stress increased.
→ Act as stress Concentrators. (tip radius)

Lower radius, → higher is the stress Concentration.

Due to presence of defects, the Area ↓ Stress ↑s.

~~Di~~ Favourable imperfects

→ ~~Di~~ Vacancies - Diffusion, Thermal & Electrical resistivity.
→ Dislocation density → increases the strain hardening. → yield Strength increases.
→ GB strengthening.
→ ~~Electrical~~
→ Fe - Cr, Ni, Cr, Mo.
Al - Mg, Si

Micro - Not detected. - NDT.
Macro - Detected by NDT.

Origin of Microscopic imperfection. -
→ Dissolved unfavourable gases H_2, N_2, O_2 etc,
→ Inclusions of oxides nitrodes, slag, FeS
- High aspect-ratio micro-constituents.
- Heterogeneity in Chemical Composition.
e.g Seggregation or selective depletion of few elements

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- Varying metallurgical structures due to varying thermal cycles and deformation by metal during its production
- Unfavourable morphology – Banded, laminated, plates, needle shape structures.

Origin:

Macroscopic features

- Ingot of base metal: Cold shut, inclusion, pores, shrinkage voids, cracks (hot/cold)
- forging: laps, seams, shrinkage, cavities flowline pattern.
- These features may be left in base metals due to improper quality control in place.
  - S/c defects – Cracks, open holes, blisters, laps, etc
  - Sub-surface – Blow holes, pores, piping defects, cold shut, lack penetration.

→ These macroscopic features increase the stress and cause failure.

Effect of imperfections.

- Micro-constituents
  - Varying mechanical properties (due to localised hardening/softening)
  - Reduce tolerance to crack nucleation (for hard and brittle metals)
  - Sources of stress concentration as notches e.g. banded structure, needles and laminates.
  - Delayed cracks (due to dissolved hydrogen in steel)
  - Reduced corrosion resistance due to increased galvanic cell formation tendency like in castings owing to segregation.

~~Effects of~~

Case-study (forged Connecting rod).

→ Medium carbon steel Connecting rod 50% P, 50% ~~F~~: failed

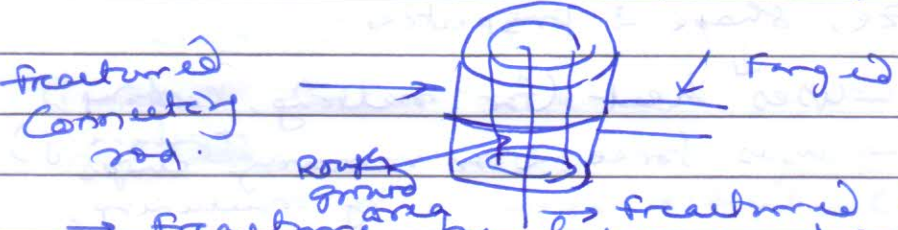
→ Composition within limits

→ No metallurgical imperfection

→ Hardness was 140 BHN instead of 160 - 205 BHN.

→ Metallography - Unused showed homogen. pearlite with equal F/P showed proper HT.

→ failed one showed banded structure near feed marks. (bands of ferrite)



→ Fracture by fatigue - beach structure.

→ The banded structure fell at the high stress zone.

→ Fracture started from transition in cross section.

- Beach marks indicated fatigue fracture with Smooth region of Crack initiation.

- No plastic deformation - Supporting fatigue failure.

→ Die-penetrant test showed fatigue cracks.

Reason. Findings

- Notch sensitive banded structure in high stress area - lead to nucleation & growth of crack.

- Rough ground marks stress raiser

- Low hardness at the crack initiation site.

Recommendation:- Control of microstructure hardness and to finish in critical areas.

~~support~~ - Uniform micro structure to avoid stress concentration

[redacted]

Failures caused by Improper Manufacturing process/conditioning

Improper Manufacturing leads to failure

- General factors
- Specific factors to each process

General factors

- Proper procedure not followed
- General procedure must be following.

Size, shape & properties.

↓

- uses heat (for melting, casting, machining)
- uses force (for removing chips by machining, solid state joining, bulk deformation process) (Rolling, forging, extrusion)
  - micro level deformation.
  -  Ultrasonic welding.
  - Explosive welding.
  - Diffusion bonding.
- uses heating / controlled cooling
  - Heat treatment - to gives proper microstructure

Taking these factors into consideration.
the manufacturing process is established.

Example - Casting

Melt → Melt treatment - Pouring - solidification - cleaning.

Example Welding (fusion welding)

Edge preparation + cleaning + suitable welding process (Gas arc welding) + suitable process parameters + chipping + cleaning.

Process = Process Parameters , Secondary treatment-

↓

These should be very specific. and strictly followed. to get desired shape, size & properties.

General factors / General Causes to ~~defective~~ manufacturing

- Unsuitable specifications. in mfring procedure.
  - Suitable melting facility
  - Process parameters
- Incomplete + Non clarity in specification.
- changes in specification without proper evaluation of the conditions.
- failure to follow the specified procedure.
- Inadvertant error on the part of error.
- Accidental damage.

If General factors are not followed, it can lead to - Discontinuity of product.

- Large defects cracks, pores blowholes etc.
- Unfavourable properties.
- Unfavourable metallurgical changes - softening/ hardening

↓

increased cracking tendency.

Effects.

These lead to.

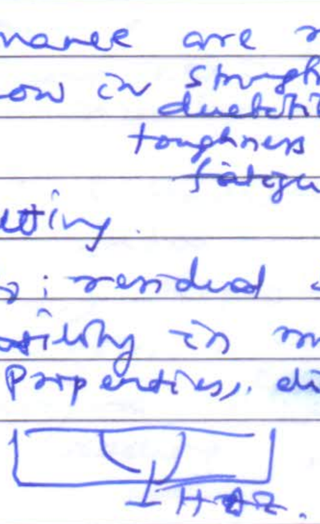
- Stress raisers
- ↓ Mechanical properties.
- ↑ Sensitivity to cracking.

Manufacturing and performance are related.

Casting - As-cast (dendrite) - Low in strength, ductility, toughness & fatigue strength

Welding (fusion) - Partial melting

leads to: residual stresses, variability in mechanical properties, distortion



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Machining - Mechanical force applied by shearing. Thin deformed layer at surface → ↑ TS ↑ Fatigue strength.

Forming - Deformation is accompanied by work hardening. ↓ ductility ↓ Toughness
(Low temperatures ↑ strength ↑ Hardness.
If deformation is carried out at high temperature, without much adverse effect on mechanical properties.

Specific factors

↳ Casting, welding, machining, forming processes.
(deformation

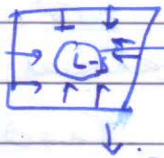
Casting (dendritic structure) - * Metal + gases → slag.
↓
flux.
↓
Slag inclusion
Flux inclusion.

* Pores.

* Alloying Seggregation. tendency.
↓
- Metallurgical Variations.
- Galvanic cell
- Corrosion tendency.
- Solidification cracking.
- Coring.

* Non uniform Cooling - Variation in micro structure.

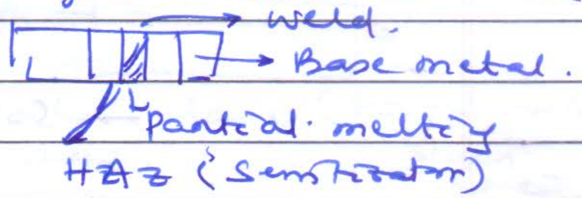

→ High hardenability (hot spots)



→ shrinkage cavity
↓
It is avoided by directional solidification
(chills / chaplets / Riser)

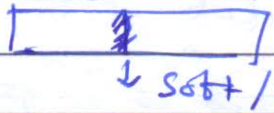
Casting - ~~Poor~~ Dendritic Structure
- Poor in hardness, strength, toughness & ductility.
- Scope for internal defects
- Heterogenity in Composition & Property

Welding — Edges are brought to molten state.



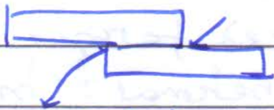
→ If procedure is not followed.
post weld heat treatment - is not done.
↓
Lead to fracture

- Joining in solid state. (mechanical deformation at the edge is achieved)
2 category
Micro: Ultrasonic, explosive.
Macro scale deformation: friction welding, friction stir welding



⇓
- should be modified.

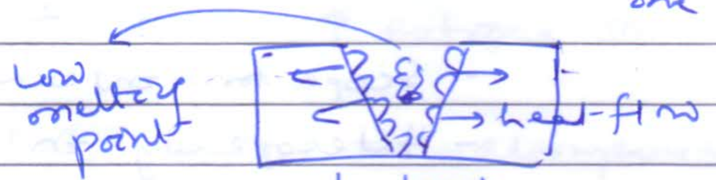
- Solid - liquid based process (brazing & soldering)



Joints are weak
Can not take high load & high temp.
useful for electronic circuit which doesn't require high temp & high load.

- ~~Liquation~~ Liquation Cracking
(Cracking next to fusion boundary).
- HAZ.
- H_2 in HAZ. (Hydrogen induced Cracking)
- Gases (O_2, N_2) promotes inclusions & delayed cracking.
- Stress Corrosion Cracking.

→ Segregation of alloying elements at the centre of fusion zone



↓ leads
Solidification crack

→ Solid state joining.
- cleanroom.
- limited metallurgical bonding.
due to lack of deformation and fusion.
- Hard / soft zones

Machining

Shear stress. ← - Mechanical shearing: Compressive residual stress at the surface so improved fatigue and tensile properties.

- Thermal: melting and ablation. re-cast layer, heat-affected zone may cause abrupt change in properties as per metal system.

- Chemical: Electrolytic - No residual stress so lower fatigue and tensile properties w.r.t sheared surfaces.

a) Laser beam
b) Flame cutting
c) Electron beam
d) Plasma arc
e) Electric discharge
↓
HAZ.
↓ in the near surface layer.

No deformed layer
No residual stress.

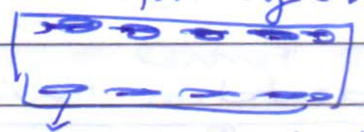
failure of machined surfaces.

- irregular surfaces and feed marks.
- Hard Spot formation.
- Localized softening.
- Cast layer with cracks with hardened steel reduces fatigue and tensile strength.

Thermal.

① white layer (tough marks as stress conc^n).
② HAZ.
③ Bulk material.

forming:
- Hot (Strength by grain refinement -
- Cold. (Strength). by work hardening)
  - Non uniformity deformation
  - Non uniformity in microstructure



- decreased ductility,
- banded Structure.
- defects.

failures in deformation based processes.

Cold forming

- Reduced toughness
- Increased notches sensitivity
- Surface Cracking (
- Unfavourable grain flow pattern, stronger in longitudinal direction.
- These reduce fatigue, corrosion and increase brittle fracture resistence.
- Residual Stress due to localized differential deformation :-
  - anisotropic mechanical properties
  - localised loss of ductility.
- Increased DBTT (Steel)

Hot forming
— Doesn't cause much problem.
- they gain strength from the grain refinement.
- Oxidation tendency become at high temp.
  ↓
  Poor surface finish.
- Poor dimensional control.
- Differential contraction during cooling.

Failures caused by
2 Steps related to manufacturing
— ① ~~bench marks~~. Indentation.
↓ ↓
→ ↑ Mechanical properties.
② (~~Heat treatment~~ Improper conditions to ~~expose~~ remove residual processes)

① Indentation Marks.
① — Mechanical based
- Indentation (using punches)
  ↓
  Heavy section.
- Embossing
  ↓
  Sheet metal.

② — Electrochemical Etching. (Numbers / letters) - controlled removal material.

Mechanical based
- Displacement of metal sidewise caused by the plastic deformation of material by punch.

→ Displaced material. (hardened material)
↓
If they are present at the high stress region (e.g. ~~shafts~~)
↓
they will act as stress raiser
↓
easily initiate cracks. (e.g. indentation at s/c of shaft)

due to
2 factors < Stress Concentration. } They will
Hardening of metal. } lead to
lastly nucleation
~~gon~~ of crack

e.g Shafts and Springs at the surfaces.
where surfaces stresses are higher.

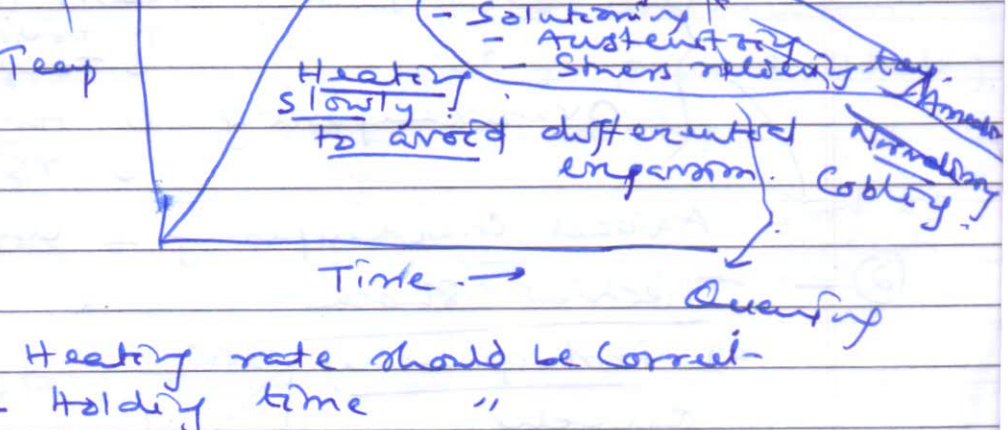
- Stress Concentration are ~~dangest~~ more harmful in dynamic loading (Fatigue or impact loading).

Failure due to ~~str~~ indentation are more important in HAZ and hardened Steel (HRC >50) because these materials have low ductility (don't give localised yielding) and there is no stress relief.

② HEAT Treatment-

1. Normal heat treatment -
   - * ↑ mechanical - Control of Structure.
   - * ↓ Residual Stresses
   - * ↑ stability in term of properties/ Uniformity/ dimensional Stability.

Procedure



{ - Heating rate should be correct-
- Holding time "
- Holding temp "
- - Cooling rate. "

Inappropriate in any of these factors will lead to failure.

Defects in heat treatment-

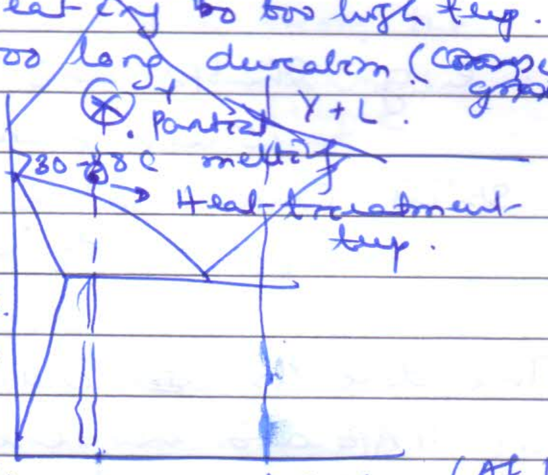
① Over heating

a) Heating to too high temp.
b) too long duration (coarse grain).

a) Partial melting of Low MP phase
b) Coarse grain.
c) Oxidation.

a) De Carburisation.
↓
↓ Hardness
↓ yield strength.

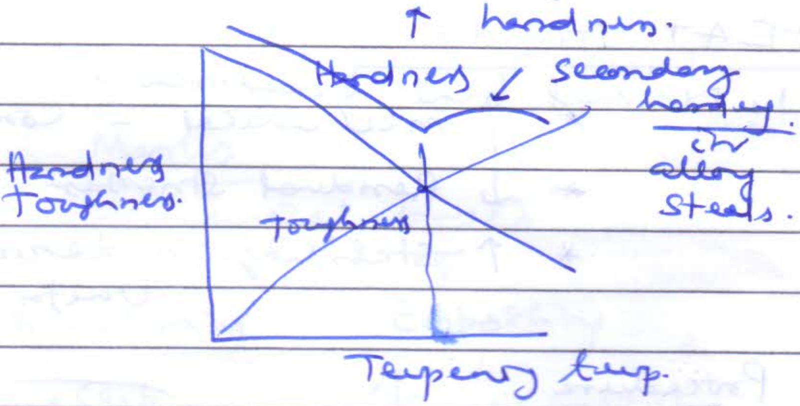
b) Spheroidization Fe_3C, C.
leads to softening.



(At Low temp it will undergo Partial melting)
(partial melting)

a) ~~Prolonged heating~~.

Quenched steel. ↓ toughness.
↑ hardness.



Under tempering means ~~too...~~
↑ Hardness.
↓ Toughness.

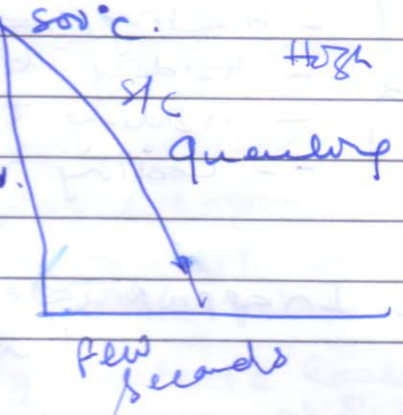
Over tempering ↓ Hardness
↓ TS.

Avoid Overtempering & Undertempering.

②— Thermal Shock

a) fast quenching

Quenching leads to quench cracks.



High temperature gradient at S/c & core will lead to quenching cracks.

b) Suitable of the type of heat treatment.
A, N, Q, tempering, Austenitizing temp.

- ~~High~~

- Improper Assembly

Various the parts are brought together & joined by Mechanical or thermal
↓
brazing
soldering
welding.

- Proper position & they should maintain the constant relative movement
- Main sources are
  - Ambiguity in assembling / Not clear
    - Proper procedure to be followed.
  - Insufficient or improperpriate procedure.
  - Misalignment - (to imbalance the force distribution e.g. gear & shaft)
  - ~~Ieep~~ Poor workmanship.
    etc..
  - Accidental error on part of operator (inadvertent error)

These are to be avoided.

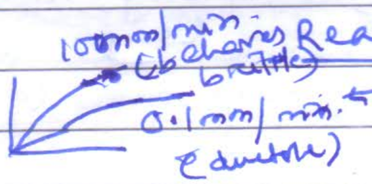
||

A proper procedure to be followed.

- Example - Tightening of Car wheels.
  Tightening of nuts are done in a particular sequence, how much torque is to be applied for nuts.
- Example - Gear teeths flatness.

Improper Service Condition.

Lots of variables.



Reasons. → - Rate of loading
- Type of forces
- Magnitude of load
- Temp. (Normal, Low, high)
- Unfavourable Environment (Dry, Moist, Seawater Corrosive environment)
- ✓ Wear (Adhesive, Abrasive, Erosion, Cavitation)

Based on ~~Optimum~~ Estimated failure mechanism. → Suitable material & design criteria

Example

~~It~~ - QTT - 400°C → Service temp 300°C
If Service temp 400°C
↓
It will cause Over tempering.

- Mild steel weld joint - upto -25°C
If temp < -20°C
It will cause brittle fracture.
- Titanic failure. (Change in temperature conditions)
-
- Normal inspection & ~~fracture~~ maintenance
- Suitable repair is to be done.

Example

Boiler tubes → start ups and shut downs.

✓ Start up is critical for a component.

✓ Pitting corrosion in super heated tubes of boiler during several annually shut down.

(50mm × 4.12mm)

~~was~~ - The boiler tubes were operating at 400°C and 650 psi for 2 years.

- The life period was 15 years.
- During hydrostatic testing during maintenance, it failed. tube

Investigation. — hot wate — Medium carbon

Starting material - ~~mild~~ steel. steel

* Visual - Black adherent - magnetic scale (internal s/c) with localised presence of powdery, loose, non-magnetic black scale showed pits like on removal.

* Analysis of deposite. XRD showed Fe_3O_4 (black iron oxides), Fe_2O_3 (red dust), FeO (without - chlorides)

* Metallography - Normal medium carbon steel structure, no segregation ~~of~~ in ~~micro~~ the microstructure.

Analysis.

- Absence of chloride showed no HCl effect - used for cleaning of tubes. ~~[illegible]~~
- Fe_3O_4 formation suggest - presence of little oxygen for pitting.
- Fe_2O_3 from loose, powdery non-magnetic brown deposits suggests pitting caused by presence of excess oxygen.

Observed in normal moist condition.

- During shut down of 15 days annual overhaul for requisite repairs.
- Oxygen rich condensate caused pitting in low points bend regions.

during overhaul period

CO_2 dissolved water gets

Condensed at the lower point bend regions during maintenance

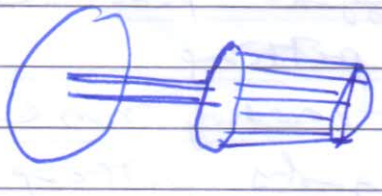
Improper maintainance

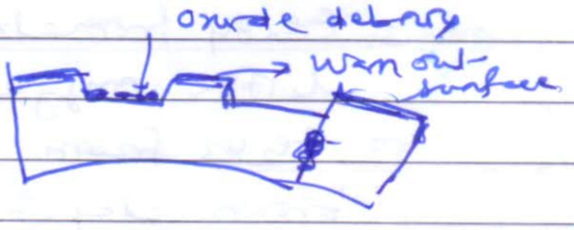
- A well developed and clear maintenance plan with steps for maintainance, including what, when, where, who and how, is specified explicitly (very clearly)

- lack of information on proper schedule of maintainance, procedure of the maintainance frequently causes premature failure of moving components (where lubrication is important)

S Example Splined end of 4350 steel drive shaft

- failed after 700 - 900 hr.
- shaft of 4350 hardness. HRC 34-38
- Case harded to HRC 48-52. minimum depth 780 micron.
- Counter surface C 58-62 with MoS_2 coating





Observation

1. Oxidised debris at the root area
2. No residual lubricant on splined shaft
3. MPT showed no surface defects
4. Chemistry & metallurgy as expected

Conclusion - failed due to excessive wear due to breaking down of lubricating film.

Recommendation - lubrication after each 300 hrs and hardness increased from 48-53 to 58-63 RC.

Toughness & fracture Mechanics.

Toughness is the capacity of a material to absorb energy by deforming plastically before fracture. It is determined by the combined strength and ductility of a material and usually is measured by the amount of work absorbed during the propagation of a crack through a structural member or a standard specimen.

The consideration of toughness during design

1. permit selection of materials with low probability of failure by fracture.
2. Establishing the conditions for failure.

Toughness measurement are done by 2 types.

1. Standard tensile specimens :- Area under a standard tension stress - strain curve taken to fracture.

2. Notched or pre cracked :- Measured by fracture of pre-cracked specimens to measures the resistance to rapid crack propagation.

Notch toughness - Measured by testing a prescribed notched-bar specimen at known temperature in a single blow pendulum type impact machine.

↓ Charpy
↓ Izod.

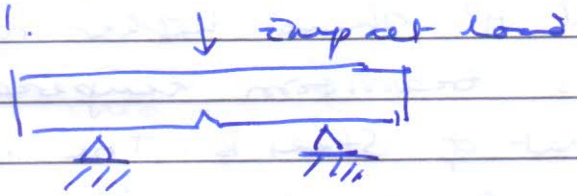
Notch toughness measurement by ~~t~~ Charpy & Izod developed during World war-2 due to failure of 250 welded transport ships.

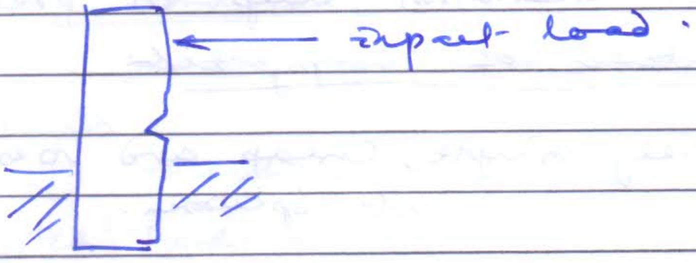
19 of which broke into 2 pieces.

Charpy

Square Cross Section - 10 mm × 10 mm.
45° V-notch.
2 mm deep with a 0.25 mm root radius.

The Specimen is supported ~~by a~~ as a beam in horizontal position and loaded behind the notch by impact of a heavy swinging pendulum at impact velocity 5 m s^{-1}. The Specimen is forced to bend and fracture at a high strain rate 10^{-3} s^{-1}.





The Specimen is thick enough to ensure a high plane-strain loading & triaxiality stre
The Standard Charpy V-notch Specimen provides a severe test for brittle fracture.

Information from Notch toughness

→ Measures the energy absorbed in fracturing the specimen.. After breaking, the test bar, the pendulum rebounds to a height, which decreases as the energy absorbed in fracture increases. Expressed in Joules.

- Examination of fracture surface
  Fibrous (Shear fracture) Dull
  Granular (Cleavage fracture) High reflectivity (Bright)

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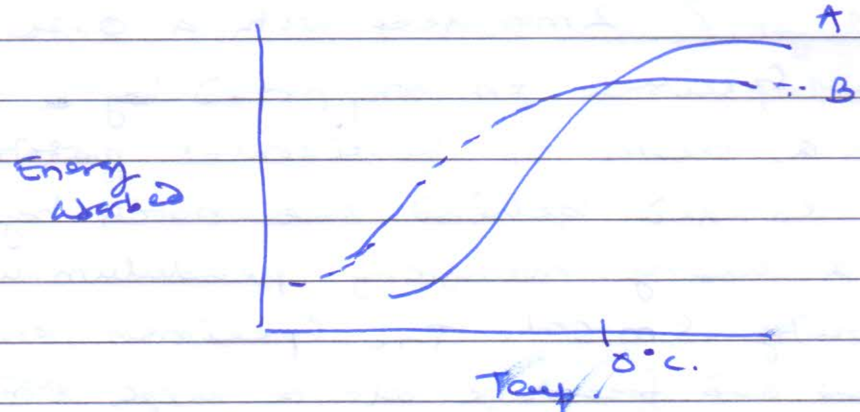
- Ductility - indicated by percentage contraction of the specimen at the notch.

- Determination of DBTT.



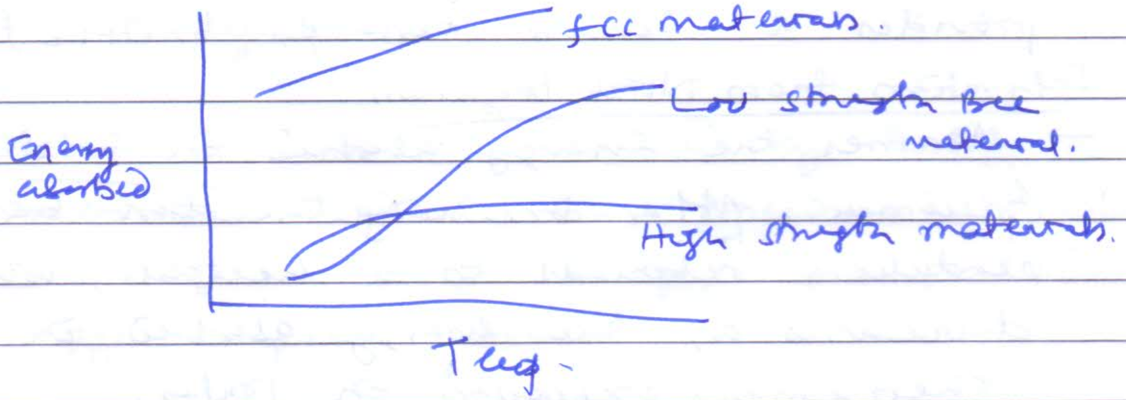
Steel 'A' shows higher notch toughness yet its transition temperature is higher than that of Steel B. The material with the lowest transition temp is preferred.

Advantages of Charpy test

- Relatively simple, cheap and uses small test specimen.

- Comparison of alloys and their heat-treatment.

- Used for quality control.



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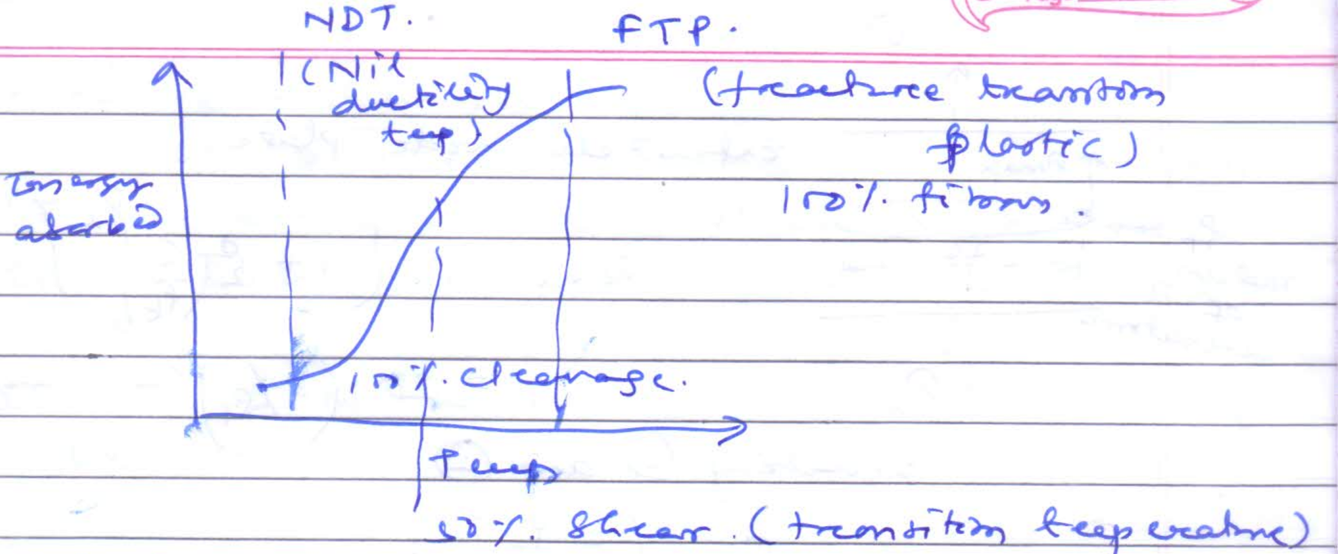


factors affecting Notch toughness

- Chemical Composition.
- physical properties. (Hardness, microstructure, grain size, homogeu method of fd wo Rolling direction Hot or Cold working temp).

Chemical {
- Alloying elements
- Gas content.
- Impurities.

fracture toughness

~~It was observed that theoretical cohesive strength~~ :

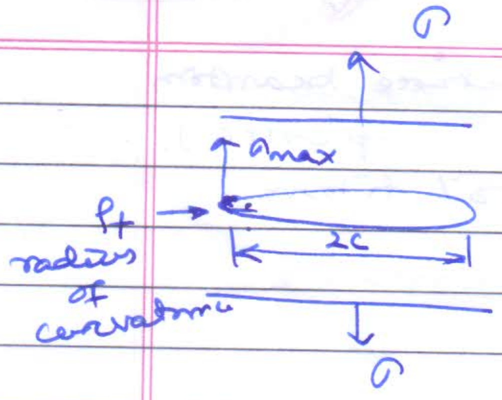
The investigations of brittle fractures by notch toughness tests led to development of new methods of notch toughness. But none of the methods gave rise to material constant. These parameters are affected by the size, shape, and notch. So a new parameter was introduced - called fracture toughness. This is based on the fracture mechanics approach.

Theoretical Cohesive strength of material

$$\Rightarrow \sigma_{max} = \left(\frac{E\gamma_s}{a_0}\right)^{1/2} \quad \text{---} ①$$

fracture strength are 10 to 1000 times lower than the theoretical value.

~~Due to~~ So the presence of Cracks are inevitable.



Infinitely wide plate.

$$\sigma_{max} = \sigma\left[1 + 2\left(\frac{c}{\rho_t}\right)^{1/2}\right]$$

$$= 2\sigma\left(c/\rho_t\right)^{1/2} \quad \text{—②}$$

Equating ① and ②

$$\sigma_f = \left(\frac{E\gamma_s\rho_t}{4a_0c}\right)$$

Assuming the sharpest possible crack

$$\rho_t = a_0.$$

$$\Rightarrow \sigma_f = \left(\frac{E\gamma_s}{4c}\right)^{1/2}$$

The first explation of discrepancy between observed fracture strength of crystals and the theoretical cohesive strength was proposed by Griffith.

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

For a thick plate (brittle)

$$\sigma_f = \left[\frac{2E\gamma_c}{(1-\gamma^2)\cdot\pi c}\right]^{1/2}.$$

For thick plate (elastic + plastic)

$$\sigma_f = \left[\frac{2E(\gamma_s+\gamma_p)}{\pi c}\right]^{1/2}$$

$$= \left[\frac{E\gamma_p}{c}\right]^{1/2}$$

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fracture mechanics approach

It provides a quantitative framework for evaluating structural reliability in terms of applied stress, crack length, and stress intensity factor.

~~It~~ The LEFM approach is based on 3 major assumption.

- Cracks and similar flaws are inherently present in parts
- A crack is a flat, internal free surface in a linear elastic stress field. (LEFM)
- The quantity of stored energy released from a cracking specimen or part during crack propagation is a basic material property, independent of specimen or part size

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cos\theta/2 \left(1 + \sin\theta/2 \cdot \sin 3\theta/2\right)$$

$$\sigma_x = \frac{K}{\sqrt{2\pi r}} \cos\theta/2 \left(1 - \sin\theta/2 \cdot \sin 3\theta/2\right)$$

σ_y is the stress perpendicular to the crack plane.

σ_x is the stress perpendicular to the ~~Cr~~ crack tip.

Streess intensity factor

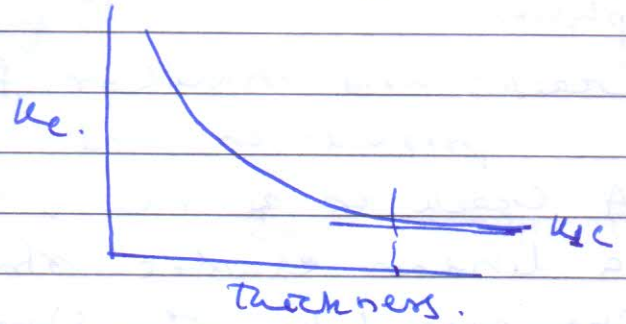
Rapid crack propagation is controlled by a material constant, called critical stress intensity factor (K_c). It is that value of stress-intensity factor, K at which crack propagation becomes rapid. The greater the value of K_c, greater the resistance ~~and~~ to brittle fracture.

It is also called plane strain fracture toughness

$K_C^2 = E G_C$. Unit of K_c = MPa$\sqrt{m}$.

G_c is the energy required for rapid crack propagation.

or Critical strain energy release rate for unstable crack propagation. (MJ/m^2)

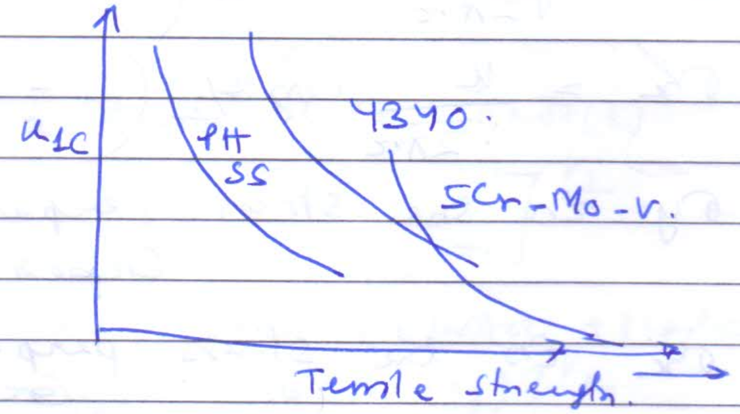


K_{1C} - Plane strain fracture toughness. is independent of thickness.

K_{1C} is determined by bend specimens and CT specimens. (Compact - tension)

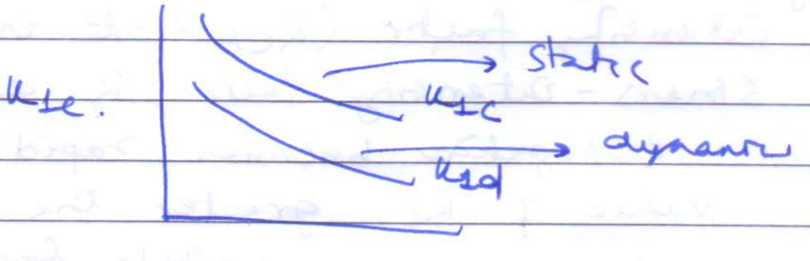
factors affecting K_{1C}

1. Effect of Material Strength - If strength (TS) increases, the fracture toughness decreases



2. Effect of loading rate.

$\frac{dK}{dt}$ should be in the range 0.55 to 2.75 Mpa m^{-1}/s^{-1}



Q. 1. A Structural Component of an engineering design loaded in plane strain Condition must support 250 MPa load in tension. If the alloy used for this application is to be used without fail, calulate the length of the largest internal flaw that the alloy can withstand.

0.2% Proof stress (~~0.2%~~) ~~in~~ (MPa) = 503 ~~MPa~~.
Tensile strength (MPa) = 572
Shear strength (MPa) = 331
% elongation = 11
Vickers hardness (HV) = 175
K_{IC} MPa$\sqrt{m}$ = 25
Fatigue strength (MPa) = 159.

Q. 2. ~~Discuss~~ List the fundamental sources of failure. Discuss ~~the~~ how the imperfections in materials, as a source of failure.

Q. 3. Discuss the guidelines to reach the root Cause of failure.

Q. 4. What is failure analysis. ~~What are the~~ Describe the Conditions to know whether a Component has failed.

Q. 5*. Thin walled pressure vessels are to be made either from material A or Material B. If the applied stress is 1.2 times higher ~~than~~ when material 'A' is used and $(K_{IC})_A = 0.6 (K_{IC})_B$ which material is to be used for pressure vessel. Explain with Crack length Calculation.

Q. 6.

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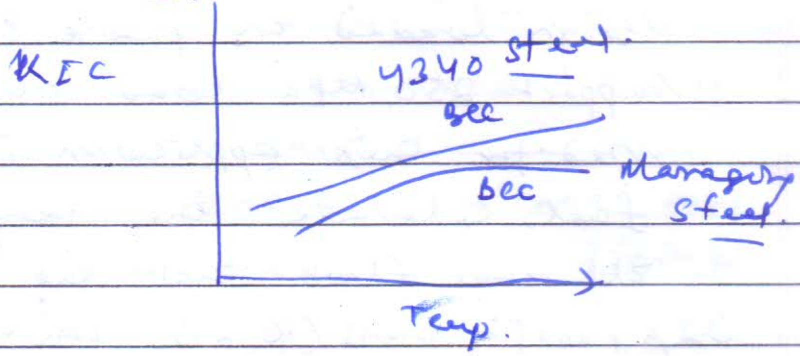
3. Effect of test temp.



Reverse trend is shown by Al alloys.

~~High temperature and low~~

5. High and low temperature failures.
Mechanisms of and the influence of structural and environmental parameters on failures.
Identification of types of failures.

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- Ductile & brittle.
- Fatigue failures.
- Stress Corrosion Cracking.

<u>Classification</u>: (Macroscopic scale)

- Ductile & brittle
- Fatigue
- ~~Stress corrosion cracking~~. combined effects of stress and environment.

Assignment
- → SCC
- → Liquid metal embrittlement.
- → Interstitial embrittlement.
- → Corrosion fatigue. → Same as fatigue.

<u>Ductile</u>

Gross plastic deformation.
gray, fibrous.
in appearance.
microscopic.
- flat faced (Square)
  - → produced under plain strain condition of ductile material.
  - — Perpendicular to the direction of loading.
  - — Equiaxed dimples.
- Shear-face (slant).
  - → plane stress. (thin section).
  - → 45% to the tensile axis.
  - → Elongated dimples.

<u>Brittle</u>

1 Less plastic deformation
2 Bright-, granular appearance.
3 - produced under plane-strain
4. Perpendicular to the direction of loading.
5. Chevron pattern may be present at the Origin.

6. Intergranular or transgranular.

Transgranular fractures are by microvoid coalescence cleavage, quasicleavage. Intergranular fracture are by GB separation, with or without microvoid coalescence.

Examples
Leaf springs
Air craft wings.

→ **fatigue fractures**

Occurs due to the combined action of cyclic stress, tensile stress and plastic strain.

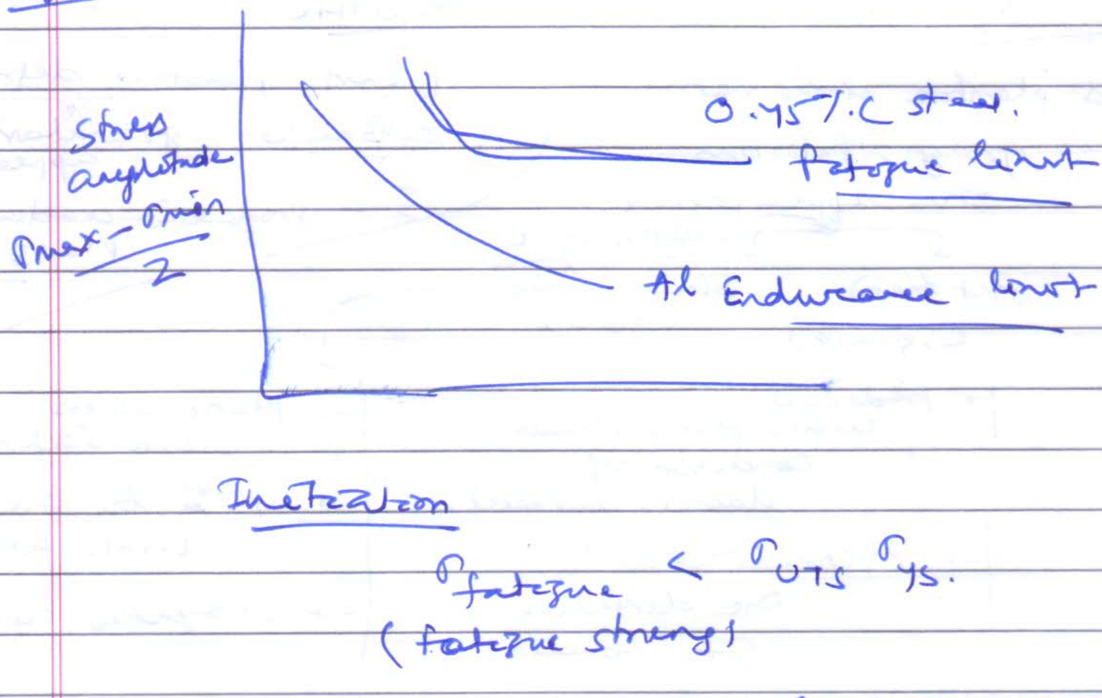
- Result from cyclic loading.
- Appear brittle in microscopic scale.
- Beach marks.

On a microscopic scale it consists of 3 parts.

3 stages.

- Initial fatigue damage leading to crack initiation
- Crack propagation until the remaining uncracked cross section of a part
- Final sudden fracture.

Types

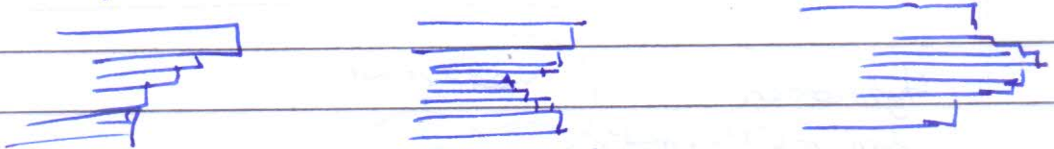


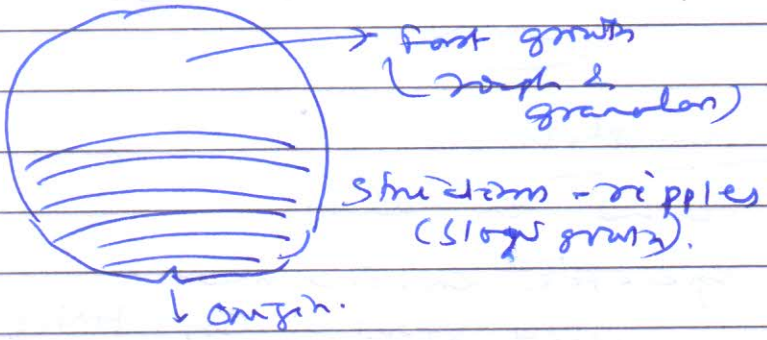
Initiation

$\sigma_{fatigue} < \sigma_{UTS}\ \sigma_{YS}$.
(fatigue strength)

→ Occurs due to microscopic plastic deformation in localised scale during stress reversals.

Slip starts at the s/c



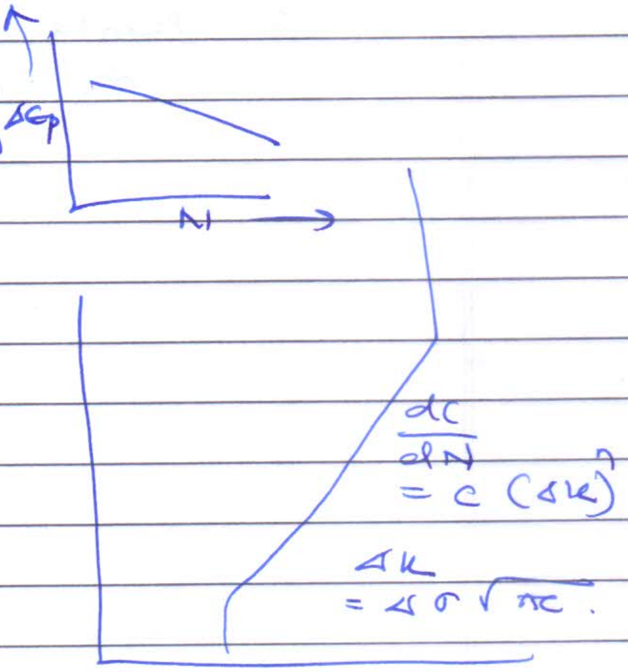


Low cycle fatigue

High cycle fatigue.

→ 10^5
- thermal origin.
- pressure vessels
turbines.

Crack growth rate.



factors

frequency - has small effect
form of strength - No effect
Environment - marked effect.
Thickness - thinner material show low crack growth rate.
Temperat → ↑ c ".

Prevention - shot pinning - compressive stress.
- Carburising & Nitriding.
- fine grain size.
- Avoidance of stress concentration.
(Highly polished s/c)

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Stress Corrosion Cracking

Characteristics

1. Found in alloys
2. Specific environment
   - Mild steel - Conc HNO_3, OH^-
   - Stainless steel - Cl^-
3. Tensile component of stress & Residual stresses.
   - → Season cracking of Brass
     Cold drawn cartridge cases of α- Brass in Ammonia.
   - → Caustic embrittlement of boilers.
     Boiler water treated with $NaOH$ to control pH.

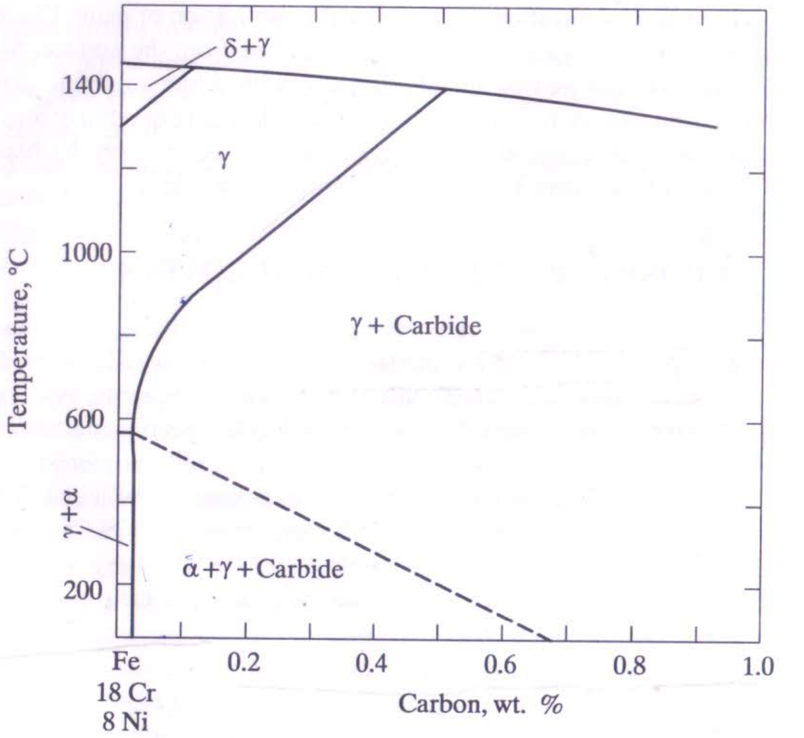

Figure 6.11 The pseudo-binary phase diagram for an 18/8 stainless steel as a function of carbon content. The precipitation of the α phase below the dotted line rarely occurs.

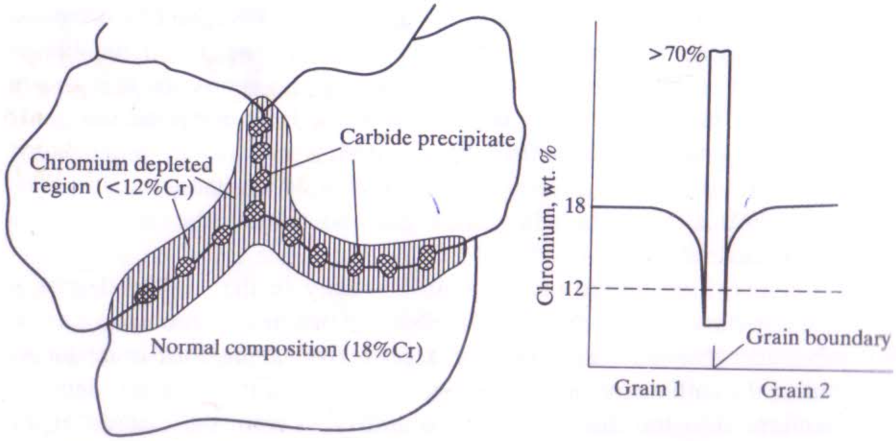

Figure 6.12 Chromium carbide precipitation at a grain boundary and the composition profile near the boundary.

A sensitized steel can be restored to its original state of excellent corrosion resistance in the following ways.

1. The steel is reheated into the single austenitic region, Fig. 6.11, and then *quenched*. The carbides go into solution during austenitizing and have no time to reprecipitate during quenching. This procedure cannot be adopted, if the steel is to be used in service at temperatures between 500 and 800°C, as grain boundary precipitation will again occur during service.
2. A *low carbon grade* of stainless steel such as 304L or 316L can be used. In these grades, the carbon content is limited to a maximum of 0.03%. So, there is no precipitation of carbides, note the solubility of carbon in austenite in the phase diagram in Fig. 6.11.
3. The *stabilized grades* 321 and 347 can be used. In type 321, titanium greater than 5 times the wt%C is added. In type 347, niobium greater than 10 times the wt%C is present. Both titanium and niobium form more stable carbides than chromium, recall the carbide stability scale given on p. 107. So, carbon combines preferentially with titanium or niobium. Chromium remains in solution and sensitization does not occur.

Ti Nb

The above description is valid for austenitic stainless steels. Because of the low solubility of carbon in ferrite, ferritic stainless steels sensitize much more rapidly and at lower temperatures. Here, the intergranular corrosion cannot be prevented, by a solutionizing treatment and water quenching. They must be annealed at about 800°C to replenish the Cr-depleted regions near the grain boundaries by diffusion of Cr from the interior of the grains. Reducing C to 0.03% is also not applicable here. *Duplex stainless steels*, which contain metastable ferrite within the austenite grains, are known to be remarkably resistant to intergranular corrosion.

304 - 18-8 - 0.08
304L - 0.03
316 - - 2 Mo
321 - - 5 times Ti
347 - - 10 times Nb.

6.9 STRESS CORROSION CRACKING

Stress corrosion cracking (SCC) refers to the cracking of a material under static load by the combined action of a stress and a corrosive environment. The related phenomenon of hydrogen cracking or hydrogen embrittlement is due to the absorption of atomic hydrogen into the metal.

General characteristics The experimentally known characteristics of stress corrosion cracking are summarized below.

1. Stress corrosion cracking is found in *alloys* and not in pure metals. However, there is some uncertainty as to what level of purity can be classified as "pure"!
2. SCC occurs only in a *specific environment* for a given alloy. Some examples of environments and the corresponding alloys are given below.

Alloy	Environment
Mild steel	Conc. NO_3^-, OH^-
High strength steel (T.S. > 1200 MPa)	H_2O
Stainless steel	Cl^-
α-brass	Traces of NH_3 or NH_4^+
Aluminium alloys	H_2O, NaCl solutions

3. The presence of a *tensile component* of stress is necessary. The stress may be externally applied. Or it can be residual stresses in the alloy. Early examples of SCC were due to residual stresses: the *season cracking* of brass and the *caustic embrittlement* of boilers. When cold drawn cartridge cases of α-brass are exposed to traces of ammonia in the atmosphere, they crack spontaneously. When the cold worked brass is given a stress-relieving anneal at 250–300°C, the susceptibility to SCC disappears. Boiler water is treated with NaOH to control *pH*. In the crevices between bolts and the boiler plates, evaporation results in a concentration of OH^- ions, leading to SCC of the bolts having residual stresses induced by plastic deformation during tightening. Welded boilers are also prone to SCC, in the presence of residual welding stresses.
4. The cracks in SCC move on a very narrow front. In hydrogen cracking, the cracks are known as *hairline cracks* often difficult to identify. If cracking is due to anodic dissolution at the crack tip, extremely localized corrosion must be taking place.
5. The crack path is often *intergranular* in SCC, Fig. 6.13. Transgranular crack propagation, i.e. propagation across the grains, has also been found in some cases.

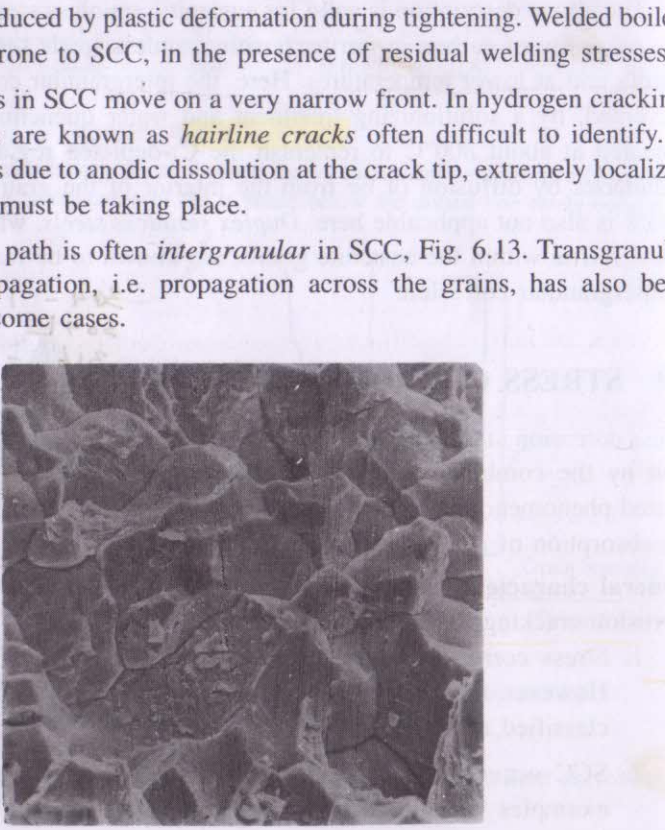

Figure 6.13 Intergranular fracture in stress corrosion cracking.

6. Many of the alloys which are susceptible to SCC form passive films. Examples are aluminium alloys and stainless steels. However, this is not always the case.
7. Cracking consists of two stages: (i) *initiation* and (ii) *propagation*. Titanium alloys are immune to crack initiation in chloride solutions. But when the alloys are precracked, crack propagation is found to occur.

Mechanisms of crack growth In the electrochemical mechanism, corrosion by anodic dissolution is believed to occur at the crack tip. In alloys that form a passive film, the crack tip is not covered by the film, because the plastic deformation at the tip exposes fresh metal or the stress concentration at the tip is sufficient to break the brittle oxide film. An active-passive cell is set up between the tip and the crack faces that are covered with the film. Only a very small area of the tip is exposed, resulting in a high current density at the tip.

Intergranular corrosion is due to the galvanic cells set up at the grain boundaries by segregation or precipitation. In this mechanism, cathodic protection should be effective in preventing SCC, as is found in some cases.

In hydrogen cracking, the adsorption of atomic hydrogen at the crack tip faces can lower the surface energy γ in the Griffith equation (5.6). This explanation is probably valid for the time-dependent cracking observed in non-metallic materials, where an electrochemical mechanism is not possible. In ductile alloys, γ_p is much larger than γ and an adsorption mechanism is unlikely. Hydrogen atoms presumably diffuse into the metal near the crack tip and *lock up the mobile dislocations* thus preventing plastic flow. The yield strength increases locally and the lack of plastic flow at the tip causes embrittlement.

??

$\sigma_f = \sqrt{\frac{2\gamma Y}{\pi c}}$

Alternatively, supersaturated hydrogen atoms can precipitate as H_2 molecules at a crack nucleus or interface. The stresses from the build-up of hydrogen pressure can induce the nucleation and/or growth of cracks. At room temperature, hydrogen being a small interstitial atom can diffuse over a number of interatomic distances in a matter of seconds. A high hydrogen overvoltage slows down the combination of hydrogen atoms into molecular hydrogen, thus facilitating their inward diffusion. Sulphur containing oil increases the hydrogen overvoltage and thereby causes embrittlement of oil pipelines.

The stress intensity factor K_{Iscc} The time dependent fracture under a corrosive environment has been studied experimentally by measuring the stress intensity factor K_I. After precracking, a cantilever specimen that is surrounded by the corrosive environment is subjected to a constant load. The measured time for fracture is plotted in Fig. 6.14 as a function of K_I. If the applied stress corresponds to K_{Ic}, fast fracture occurs instantly. When $K_I < K_{Ic}$, fracture occurs after a delay period, during which the crack grows slowly. When the stress intensity factor is below a critical value known as K_{Iscc}, no fracture occurs even after prolonged holding, see Fig. 6.14.

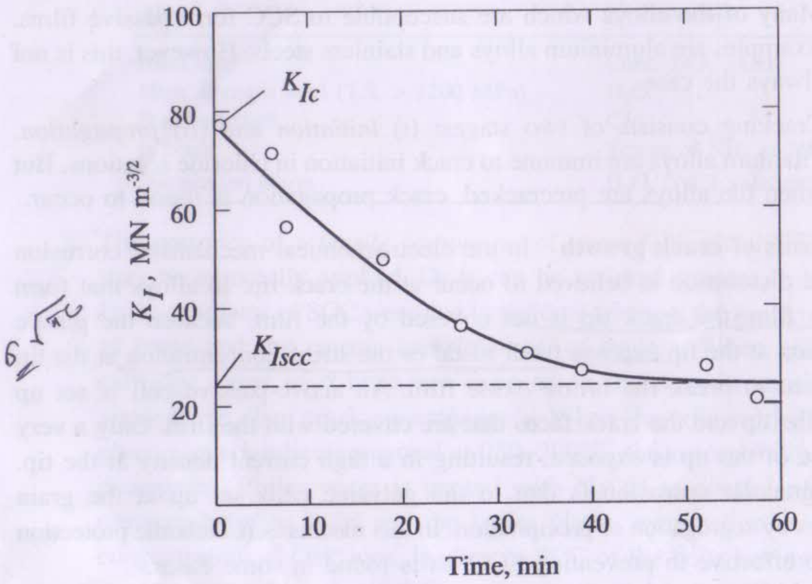

Figure 6.14 The critical stress intensity factor decreases with increasing time in a corrosive environment, reaching a constant value of $K_{\rm Iscc}$, below which no cracking occurs.

Figure 6.15 shows the measured rates of crack growth as a function of K_I. Below $K_{\rm Iscc}$, the crack growth rate is zero. Above $K_{\rm Iscc}$, in region II, the crack grows at a constant rate independent of K_I. The growth rate is probably controlled by an electrochemical process in this region. Region III corresponds to fast growth that culminates in fracture.

The energy balance for crack growth in the Griffith equation (5.6) needs to be modified to take into account the electrochemical energy released at the crack tip due to anodic dissolution. For unit extension of the crack, we can write the condition for spontaneous growth as:

$$\underbrace{\underset{\text{of the crack}}{\text{surface energy}} + \underset{\text{at the tip}}{\text{plastic work}}}_{2\gamma_p} = \underset{\pi\sigma^2 c/Y}{\underset{\text{released}}{\text{elastic energy}}} + \underset{(nF\rho\delta/M)\varepsilon}{\underset{\text{energy released}}{\text{electrochemical}}}$$

where σ is the tensile stress,

c is half-length of the crack,

Y is Young's modulus of the alloy,

n is the number of electrons taking part in the anodic reaction,

F is Faraday's constant,

ρ is the density of the alloy,

δ is the opening at the crack tip,

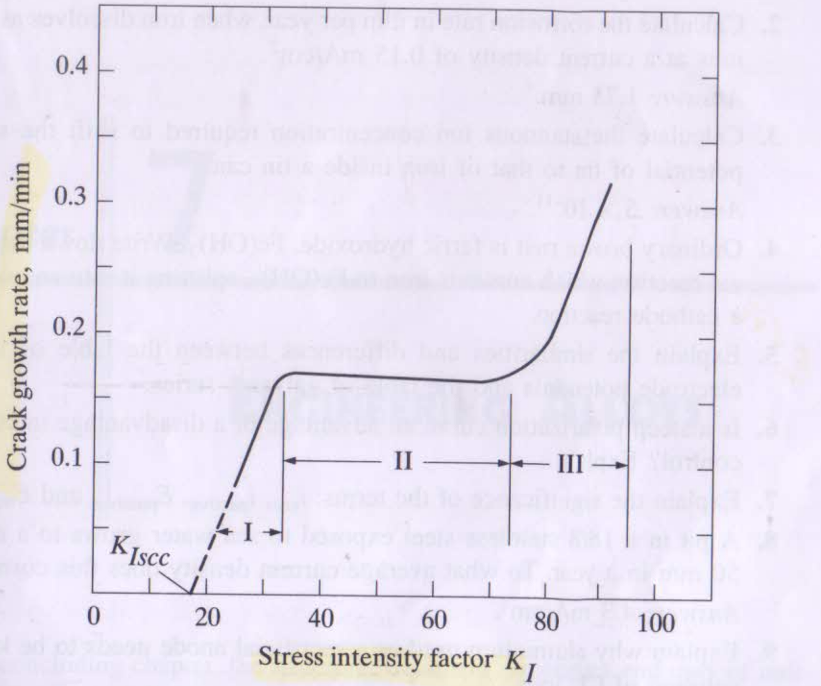

Figure 6.15 The crack growth rate in a Ni-Cr-Mo steel in a NaCl environment as a function of the stress intensity factor, depicting the three stages.

Rewriting the critical condition in terms of $K_{\rm Iscc}$, we have

$$K_{\rm Iscc} = [2\gamma_p Y - (nF\rho\delta/M)\varepsilon]^{1/2} \tag{6.6}$$

Equation (6.6) shows that $K_{\rm Iscc}$ decreases with an increase in yield strength (which decreases γ_p) and with an increase in the corrosion tendency as given by ε.

SUGGESTED READINGS

Jones, D.A., *Principles and Prevention of Corrosion*, Prentice Hall, New Jersey (1996).

Uhlig, H.H., *Corrosion and Corrosion Control*, John Wiley, New York (1971).

QUESTIONS

1. Calculate the amount of zinc (anode) that corrodes, when a current of