



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

Failure Analysis & Prevention

Fundamental Sources of Failure: Deficient Design

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Fundamental sources of failure

- To have systematic understanding on various factors that can lead to failure of mechanical components :
 - Improper design
 - Improper selection of materials
 - Defects and discontinuities in metal itself
 - Improper processing of materials
 - Poor service conditions
 - Poor assembling
 - Poor maintenance



Deficient design

- The deficiency in design of a component can be in various forms
 - presence of stress raisers owing to sharp change in cross section, various and geometrical features
 - changing the design without proper consideration of its influence on stress distribution especially under high stress areas of the component,
 - duplicating a successful design for more severe loading conditions,



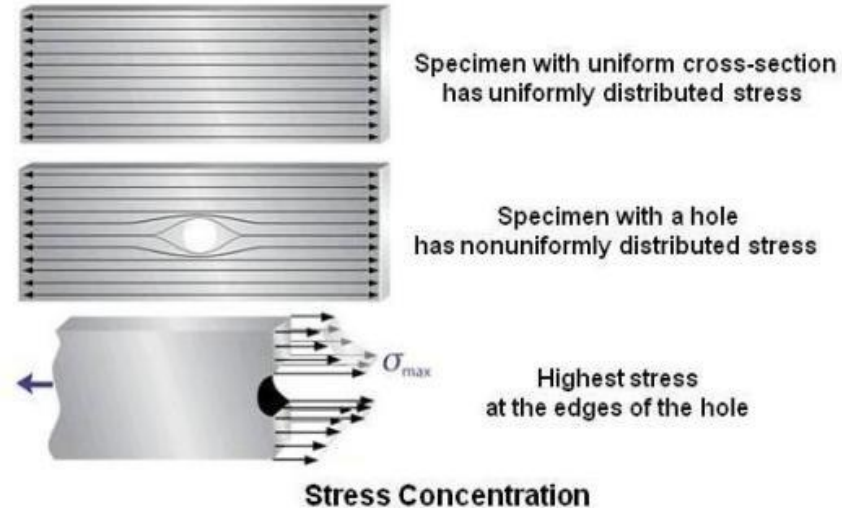
Deficient design

- design is developed without full knowledge of stress conditions owing to complexity of the geometry and
- inability to use proper criteria for designing the engineering components.



Stress raisers

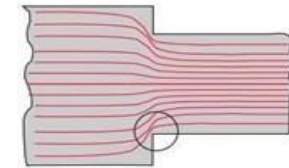
- Basic stress analysis calculations assume that the components are smooth, have a uniform section and no irregularities.
- In practice, virtually all engineering components have at least minimal changes in section and/or shape.
- Shoulders on shafts, oil holes, key ways and screw threads all can change the stress distribution, so that the basic stress analysis equations no longer apply.
- Such discontinuities cause a local increase of stress, referred to as stress concentration



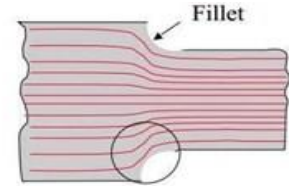
Stress concentration factor

- Stress concentration factor (K_t), is a dimensionless factor
- K_t is used to quantify how concentrated the stress is in a material & defined as the ratio of the highest stress in the element to the reference stress.
- Reference stress is the total stress within an element under the same loading conditions without the stress concentrators.
- Meanings, material is free from holes, cuts, shoulders or narrow passes under given load condition.

$$K = \frac{\sigma_{\max}}{\sigma_{\text{ref}}}$$



Abrupt change
Stress "flow lines" crowd
High stress concentration



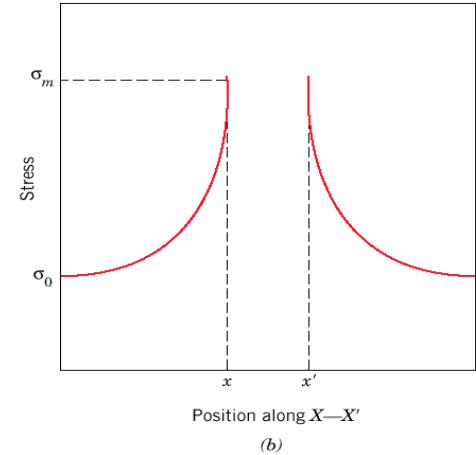
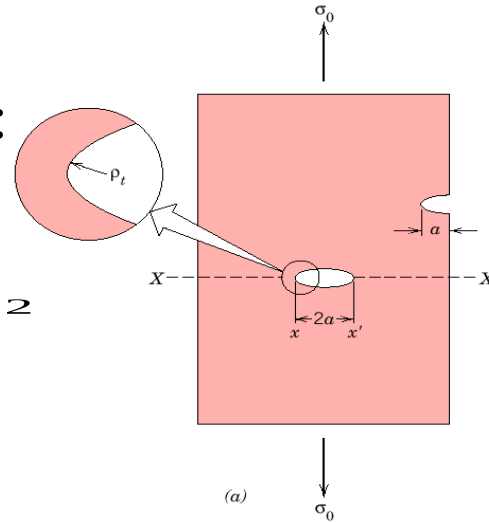
Smoothen change
"Flow lines" less crowded
Lower stress concentration



Stress Concentration (SC)

Crack perpendicular to applied stress:
maximum stress near crack tip $\rightarrow$

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



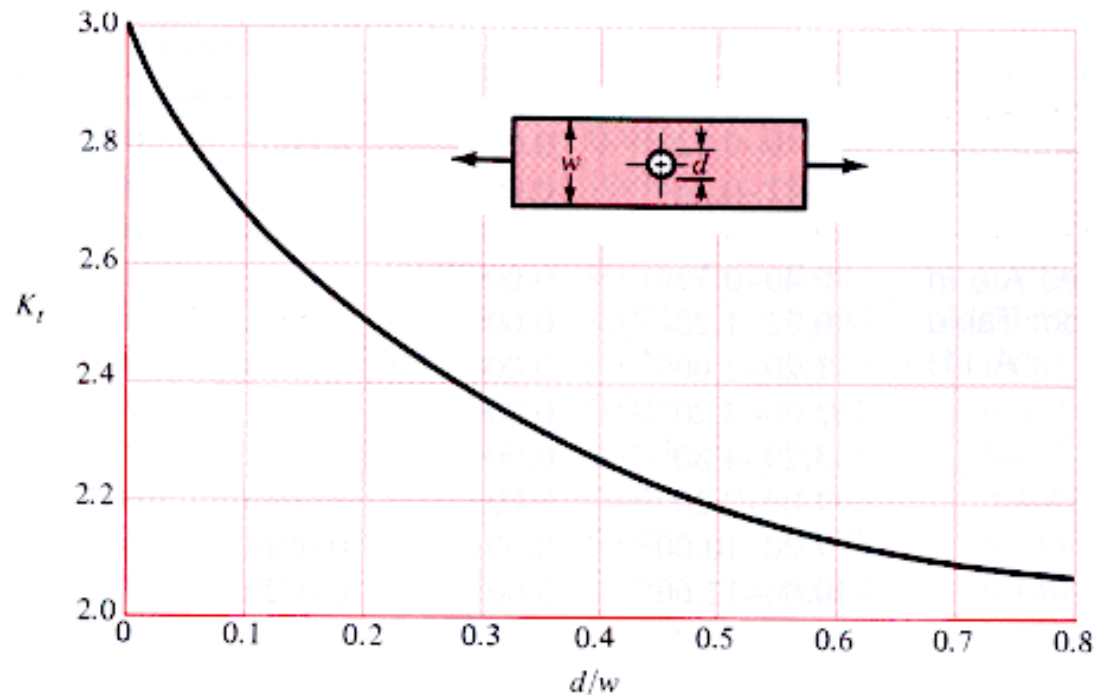
σ_0 = applied stress; a = half-length of crack;

ρ_t = radius of curvature of crack tip.

Stress concentration factor $\rightarrow K_t = \frac{\sigma_m}{\sigma_o} \approx 2 \left(\frac{a}{\rho_t} \right)^{1/2}$

Size effect

Bar in tension or simple compression with a transverse hole. $\sigma_0 = F/A$, where $A = (w - d)t$ and t is the thickness.



Factors affecting SC

- Function of the geometry or shape of the part, but not its size / material
- Type of loading (axial, bending or torsional)
- Geometry of stress raiser (fillet radius, notch, hole)
- Typically assumes a linear elastic, homogeneous, isotropic material



Reducing SC

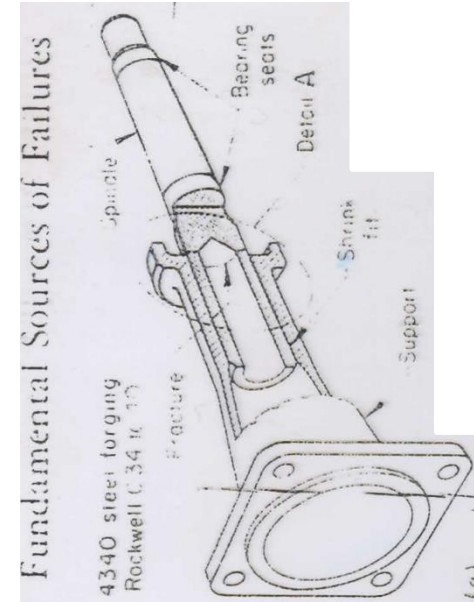
- Providing a fillet radius so that the cross-section may change gradually Using an elliptical fillet
- Using a number of small notches rather than a long one, if a notch is unavoidable
- Using narrow notches rather than wide notches, if a projection is unavoidable
- Using stress-relieving grooves

FA for failures due to SC

- Needs information on design aspect
- Understand design criteria
- Size and shape of geometrical feature at the location of failure if any
- Type of loading
- Mechanical (hardness, toughness, ductility)
- Metallurgical properties (high aspect ratio feature e.g. needles, lamellas)
- Stress analysis

Change in design: Case study of changing the design without proper consideration

- Fatigue fracture of hardened 4340 steel spindle of a vehicle
- Spindle drawing had weight reducing hole but without depth
- Lead to drilling of hole to a greater depth caused fracture after 1400 miles
- **Materials:** Annealed/normalized AISI 4340 forging and tempered to final hardness RC 34 to 40 and then finished machined in critical areas and shot peened before assembly.



Deficient design: change

Macro-examination:

fracture extended radially from the bottom of drilled weight reducing hole to periphery of spindle. No service damage or materials defect that could be related to failure (A)



- Appearance of fracture surface is typical fatigue fracture, with cyclic one way bending , low to moderate overload, high stress concentration
- Location and orientation clamshell marks suggest fracture origin at periphery of weight reducing hole (arrow)
- Entire bottom surface of hole shows deep scored drilling tool marks

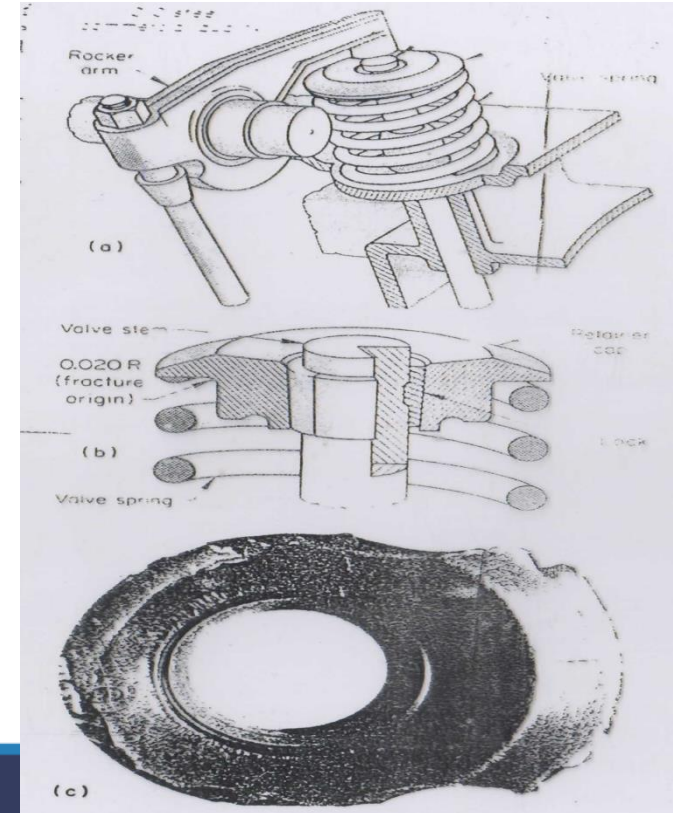
Design change case study

- Conformance to specification:
 - **chemical analysis** confirmed AISI 4340.
 - **NDT** did not revealed any internal dis-continuity
 - **Hardness** was in range of 38-40 RC
 - **Microstructure**: Normal tempered martensite as expected without any decarburization, inclusion and other abnormalities
- Conclusion:
 - Fracture by fatigue due to presence of circumferential notch at highly stressed area.
 - Notch presence was estimated to equivalent to 40% reduction in strength of spindle.
 - Variation in depth occurred due to missing hole depth info in drawing.
- Corrective action: Hole depth to keep it about 25 mm away from high stress area where change in cross section was taking place.

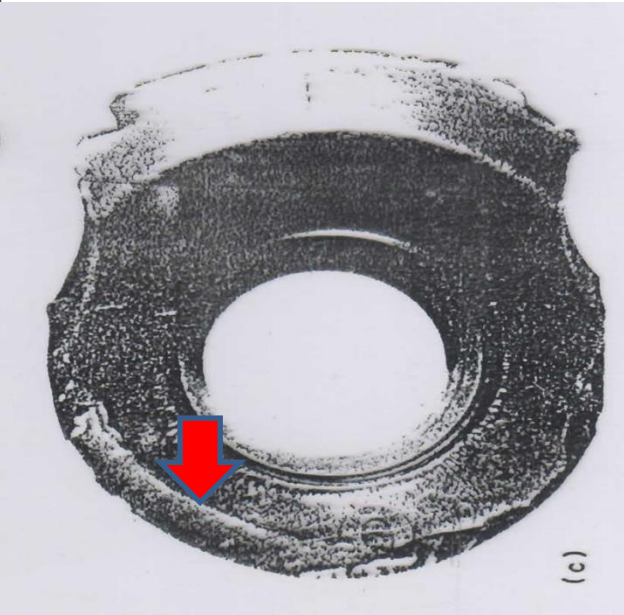


Upgrading of a part: Premature failure of AISI 1010 steel valve spring retainer of an engine during trial

- Retainer cap failed during 8 cylinder automobile qualification run
- Cap broke off before trial run of 200 hrs at 4100 to 4600 rpm after 26 millions of cycles
- Test simulates continuous running of engine for 200 hr at 140 miles/h
- Manufacturing: made from 16 mm cold drawn 1010 steel in annealed condition
 - Forging and then trimming
 - Case hardening: carbo-nitriding for 30 min at 843 °C and oil quenching
 - Tempering at 260 °C
 - Case depth 0.025 to 0.25 mm, HRB 86 min.



Deficient design: upgrading



- **Macroscopy:** flange broke off from the cap periphery
- Smooth area on fracture surface in characteristics fatigue fracture with brightness (at arrow)
- Fracture initiated at outside region of the cap along the sharp fillet
- Irregular, rugged areas correspond to final fracture
- No sign of plastic deformation or shear lips
- **Metallography:.**

Conformance

- Conformance to specification:
 - **chemical analysis** confirmed AISI 1010 (0.11 C, 0.48 Mn).
 - **Microscopy**: case depth 0.2 mm
 - **Hardness** was in range of 84 HRB slightly below than specified 86 units
 - **Microstructure**: Normal F & P structure as expected without any inclusion and other abnormalities
- Conclusion:
 - Fracture initiated and propagated by fatigue mechanical before final brittle fracture due to sharp fillet between pilot and flange
 - No significant material and manufacturing problems were found
- Corrective action: Design of cap fillet radius increased from 0.5 to 1.25 mm for better stress distribution. Increased fillet radius eased manufacturing also.



Deficient design

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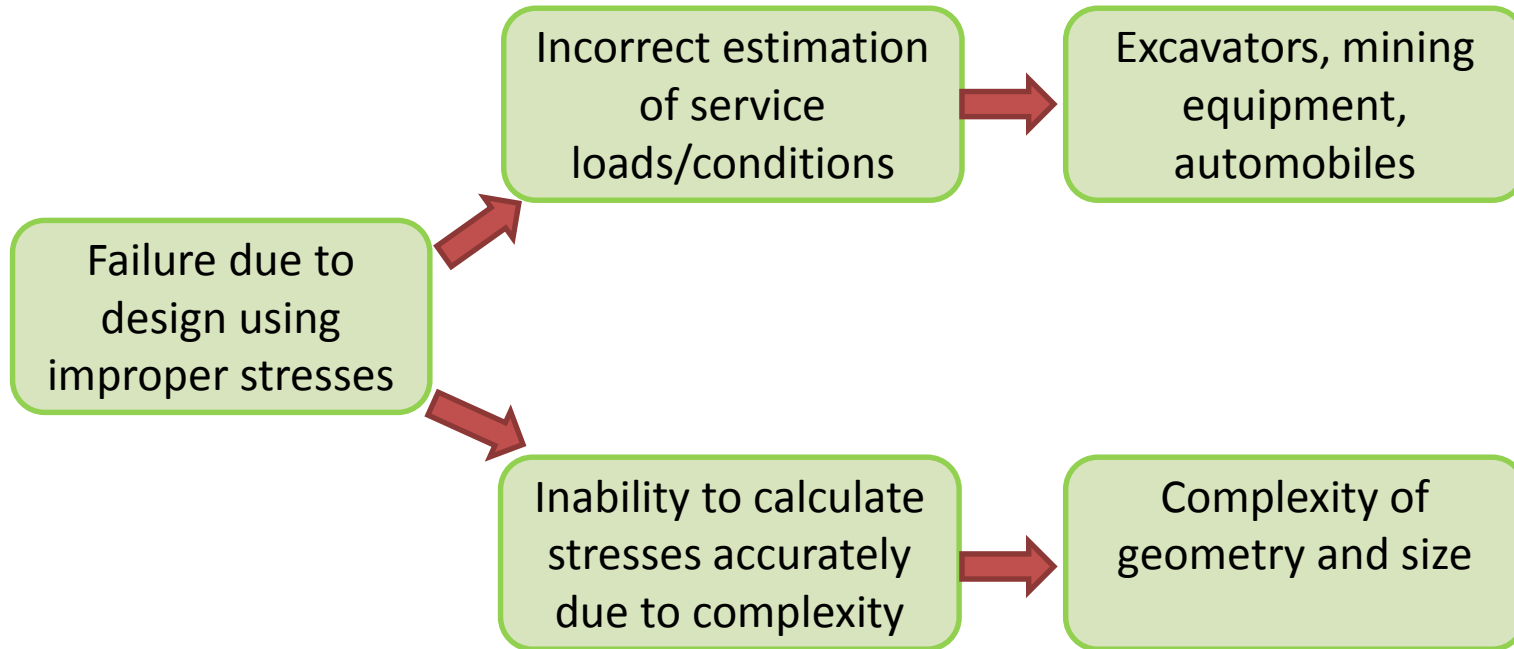


Deficient design

- design is developed without full knowledge of stress conditions owing to complexity of the geometry and
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Difficulty in assessment of stress conditions



Improper selection of material

- Selection of a material for design (in light of operating conditions) should be based on expected failure mechanisms such as
 - ductile fracture
 - brittle fracture
 - creep
 - fatigue
 - corrosion
 - wear etc.



Improper selection of material

- If failure of a component is expected to occur by excessive **plastic deformation at room temperature and high temperature conditions** then **yield strength and creep** respectively become important criterion for design.
- Similarly, if failure of a component is expected to occur by **fracture under overloads, fluctuating loads and impact loads** then **ultimate strength, endurance strength and impact strength** respectively should be considered.



Few Selected Criterion

Failure mechanism	Design criteria
Ductile fracture	Yield strength (tension, compression etc.)
Brittle fracture	Fracture toughness (K_{1c}), notch toughness, ductility, DBTT
Fatigue	Endurance limit / fatigue strength with stress raiser, hardness
Thermal fatigue	Ductility, peak plastic strain (under operating conditions)
Creep	Creep rate at given temperature
Plastic deform.	Yield strength
SCC	K_{1SCC} , corrosion resistance to sp. environment



Improper selection of material

- Deficient material selection can occur due to
 - Over-reliance on tensile data for selection of material and
 - inability to select of metal in light of the expected failure mechanism to develop criteria for the design purpose.

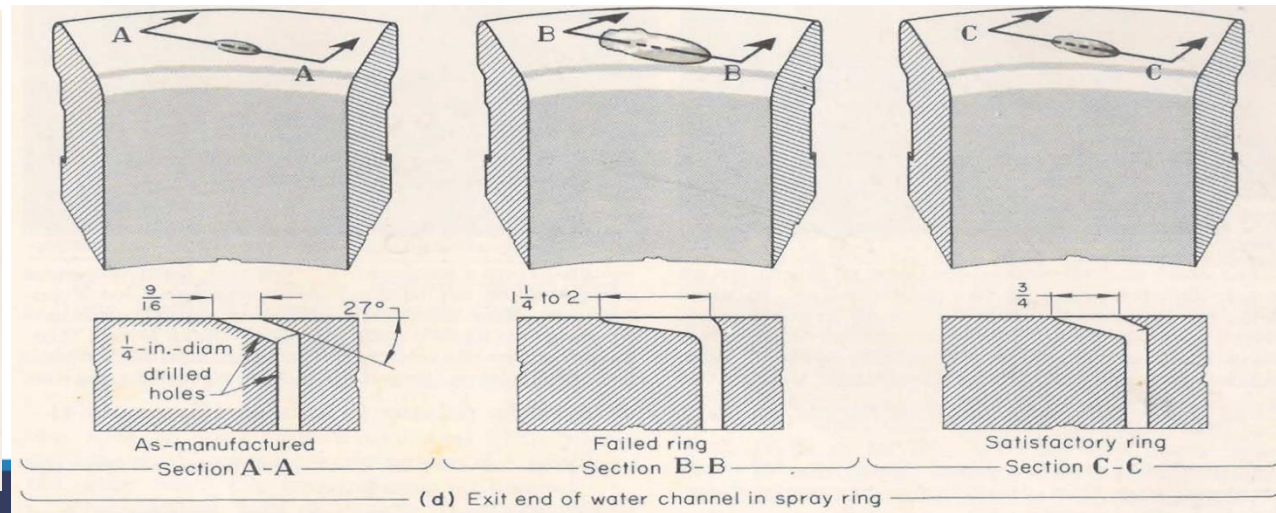
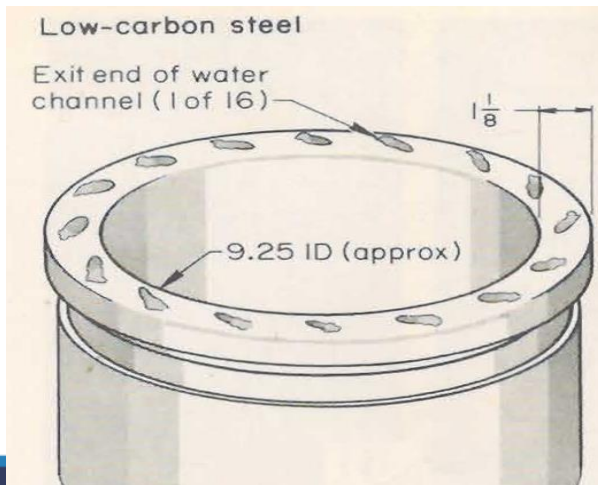


Improper material selection

Failure of carbon steel of spray ring

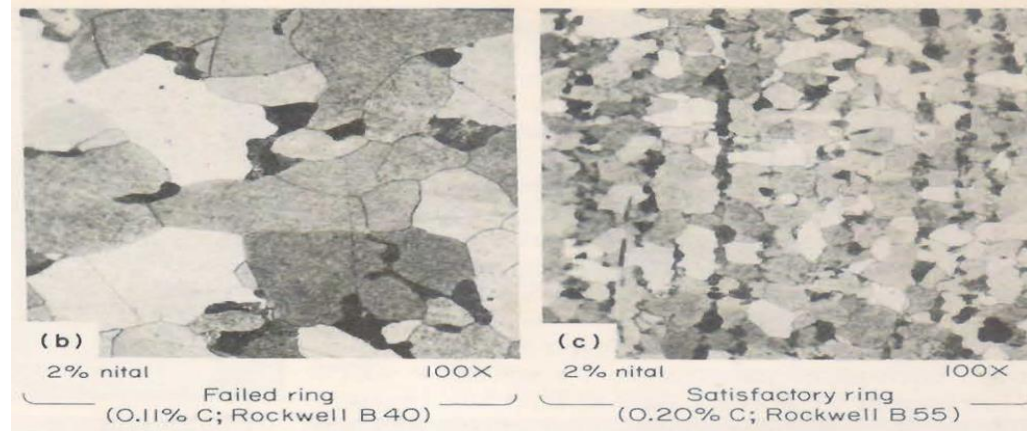
Failed pre-maturely within 4-5 months as compared other doing well for last 4 years.

Failure judged from drop in curing temperature ($177-182^{\circ}\text{C}$) being done through hot water sprays at 193°C



Carbon steel spray ring failure

- Examination: pits with irregular shaped opening of spray nozzle without corrosion
- Chemical analysis: 0.11 C lower as compared to satisfactory performing ring 0.2C while same other residual elements
- Metallography: satisfactory ring: fine pearlite ferrite with stringer of pearlite and hardness HRB 55 while failed one had coarse ferrite and pearlite with hardness of HRB 40



Carbon steel spray ring failure

- **Conclusions:**
 - Failure of desired curing temperature was due to enlargement of opening of spray ring which in turn increased agitation, reduced velocity that led to lower heat transfer
 - Erosion caused pitting due to cavitation
 - Low carbon, low hardness and coarse grain size reduced erosion resistance
- **Corrective action**
 - Replace the steel with proper composition with sub-critical annealing so that final grain size not more than ASTM 7 and min. HRB 55.
 - Thereafter, no further failure of spray rings was observed.

