Root cause AC motor failure analysis with focus on shaft failures

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Rotor assemble stresses

Thermal stress
- Thermal overload
- Thermal unbalance
- Excessive rotor losses
- Hot spot
- Sparking
- Ambient

Mechanical stress
- Thermal aging
- Coil movement
- Rotor strikes
- Defective rotor
- Flying objects
- Lugging of leads

Electrical stress
- Dielectric aging
- Tracking
- Corona
- Transients

Environmental stress
- Moisture
- Chemical
- Abrasion
- Damaged parts
- Excessive ambient
- Restricted ventilation

Bearing stresses

Dynamic and static leading
- Radial
- Axial
- Pre-load

Thermal stress
- Friction
- Lubricant
- Ambient

Vibration and shock
- Rotor
- Driven equipment
- System

Electrical currents
- Rotor dissymmetry
- Electrostatic coupling
- Static charges
- AFD’s

Environmental stress
- Condensation
- Foreign materials
- Excessive ambient
- Restricted ventilation

Mechanical stress
- Loss of clearances
- Misalignment
- Shaft/housing fits

Shaft stresses

Mechanical stress
- Overhung load and bending
- Tensional load
- Axial load

Dynamic stress
- Cyclic
- Shock

Residual stress
- Manufacturing processes
- Repair process

Thermal stress
- Temperature gradients
- Rotor bowing

Environmental stress
- Corrosion
- Moisture
- Erosion
- Wear
- Capitation

Electromagnetic stress
- Side loading
- Out of phase reclosing

Stators stresses

Thermal stress
- Thermal aging
- Voltage variation
- Cycling
- Loading
- Ventilation
- Ambient

Magnetic stress
- Rotor pullover
- Noise
- Vibration
- Off magnetic center
- Saturation of lamination
- Circulating currents

Residual stress
- Stress concentrations
- Uneven bar stress

Dynamic stress
- Vibration
- Rotor rub
- Over-speeding
- Cyclic stresses
- Centrifugal force

Environmental stress
- Contamination, abrasion
- Foreign particles
- Restricted ventilation
- Excessive ambient temp

Mechanical stress
- Casting variations
- Loose laminations
- Incorrect shaft/core fit
- Fatigue or part breakage
- Poor rotor to stator geometry
- Material deviations

Other stress
- Misapplications
- Poor design practices
- Manufacturing variation
- Loose bars, core
- Transient torques
- Wrong direction of rotation

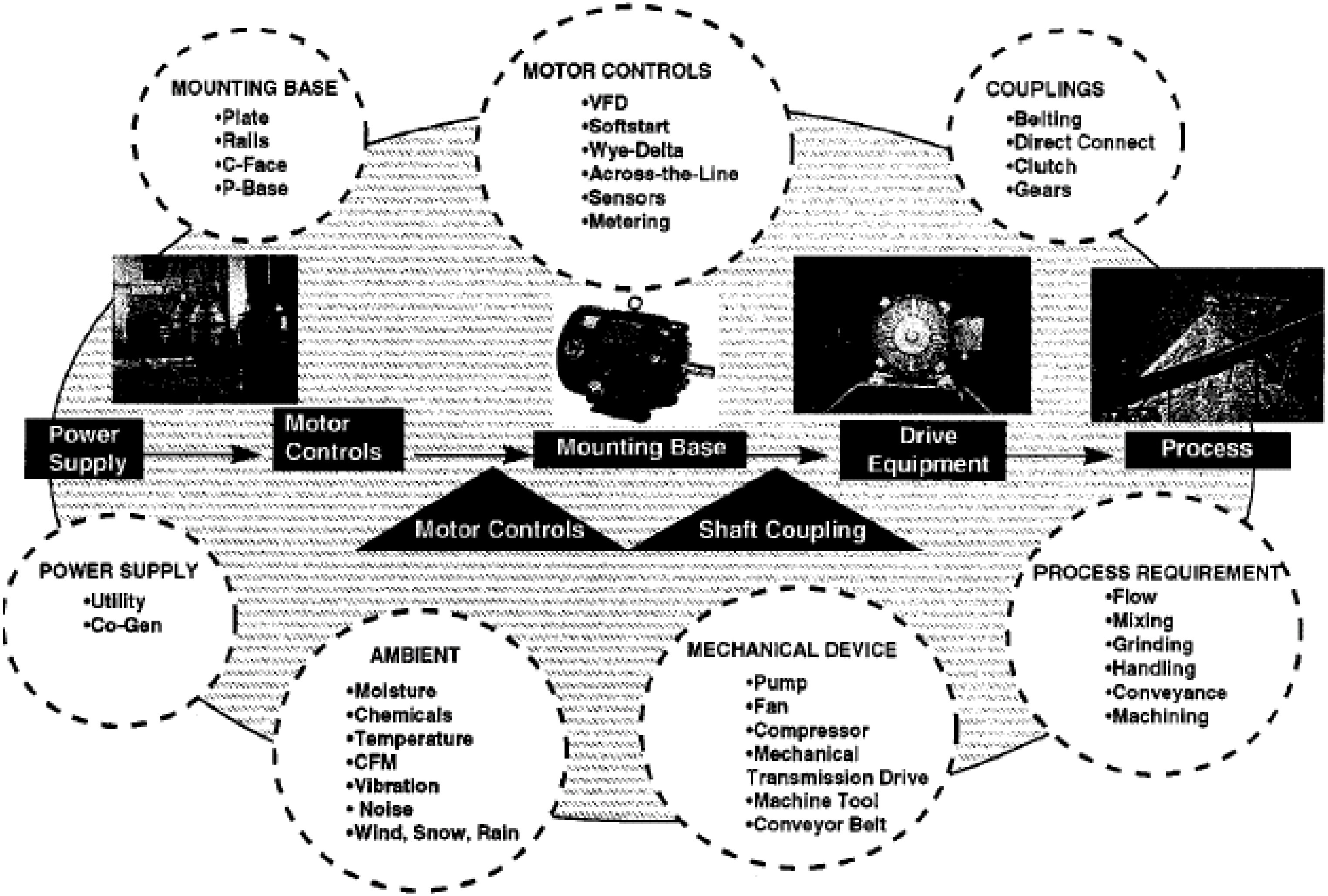
Motor component/stresses

Type of stress	Stator winding	Rotor assembly	Bearings	Shaft
Thermal	✓	✓	✓	✓
Electrical /dielectric	✓	✓	✓	
Mechanical	✓	✓	✓	✓
Dynamic		✓	✓	✓
Shear				✓
Vibration/shock	✓	✓	✓	✓
Residual		✓		✓
Electro-magnetic	✓	✓	✓	✓
Environmental	✓	✓	✓	✓

Summary of methodology for analysis

Motor component	Failure mode/class	Failure pattern
Stator winding	• Turn to turn • Phase to phase • Phase to ground • Coil to coil • Open circuit	• Symmetrical • Single phased • Non-symmetrical & grounded • Non-symmetrical & no ground
Rotor assembly	• Shaft • Bearing • Lamination • Squirrel cage • Vent. System	• Thermal • Magnetic • Residual • Dynamic • Mechanical • Environmental

The typical system



Summary of methodology for analysis

Motor component	Failure mode/class	Failure pattern
Ball bearings	• Fatigue spalling • Fretting • Smearing • Skidding, wear • Lubrication failure • Electric pitting • Fluting • Cracks, seizures	• Thermal • Vibration & noise • Lubricant quality • Mounting/fits • Contamination • Mechanical damage • Electrical damage • Load pattern
Shaft	• Overload • Fatigue • Corrosion	• Ductile, brittle • Beach marks • Conchoidal marks • Chevron marks • Ratchet marks • Cup/cone, shear lips • Fretting

Checklist for evaluating assembly conditions

- Is there any sign of moisture present on the stator, rotating assembly, bearing system, or any other parts?
- Are there any signs of movement between rotor and shaft or bar and lamination?
- Is the lubrication system as intended or has there been lubricant leakage or deterioration?
- Are there any signs of stalled or locked rotor?
- Was the rotor turning during the failure?
- What was the direction of rotation and does it agree with the fan arrangement?
- Are any mechanical parts missing?
  such as balance weights, bolts, rotor teeth, fan blades, etc.,
- or has any contact occurred between rotating parts that should maintain a clearance?

Checklist for evaluating assembly conditions

- What is the condition of the coupling device, driven equipment, mounting base, and other related equipment?
- What is the condition of the bearing bore, shaft journal, seals, shaft extension, keyways, and bearing caps.
- Is the motor mounted, aligned, and coupled correctly?
- Is the ambient usual or unusual?
- Do the stress risers show signs of weakness or cracking?

Methodology checklist : Appearance of motor and system

- Does the motor exhibit any foreign material?
- Are there any signs of blocked ventilation passages?
- Are there signs of overheating exhibited by insulation, lamination, bars, bearings, lubricant, painted surfaces, etc.?
- Has the rotor lamination or shaft rubbed? Record all locations of rotor and stator contact.
- Are the top-sticks, coils, or coil bracing loose?
- Are the rotor cooling passages free and clear of clogging debris?
- What is the physical location of the winding failure?
- Is it on the connection end or opposite connection end?
- If the motor is mounted horizontally, where is the failure with respect to the clock?
- Which phase or phases failed?
- Which group of coils failed?Was the failure in the first turn or first coil?
- Are the bearings free to rotate and operate as intended?

Methodology checklist : Application considerations

- What are the load characteristics of the driven equipment and the loading at time of failure?
- What is the operating sequence during starting?
- Does the load cycle or pulsate?
- What is the voltage during starting and operation?
- Is there a potential for transients?
- Was the voltage balanced between phases?
- How long does it take for the unit to accelerate to speed?
- Have any other motors or equipment failed on this application?
- How many other units are successfully running?
- How long has the unit been in service?
- Did the unit fail on starting or while operating?

Methodology checklist : Application considerations

- How often is the unit starting, and is this a manual or automatic operation?
- Is it part winding, wye-delta, or variable-frequency drive (VFD), or across the line?
- What type of protection is provided?
- What removed or tripped the unit from the line?
- Where is the unit located and what are the normal environmental conditions?
- What was the environment at time of failure?
- What was the ambient temperature, at time of failure, around the motor?
- Is there any recalculation of air?
- Is the exchange of cooling air adequate?
- Was power supplied by a VFD?
- What is the distance between the VFD and the motor?
- How would you describe the driven load method of coupling and mounting?

Methodology checklist : Maintenance history

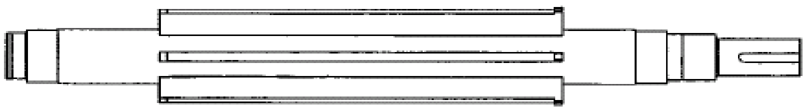
An understanding of the past performance of the motor can give a good indication as to the cause of the problem.

- How long has the motor been in service?
- Have any other motor failures been recorded and what was the nature of the failures?
- What failures of the driven equipment have occurred?
- Was any welding done?
- When was the last time any service or maintenance was performed?
- What operating levels (temperature, vibration, noise, insulation, etc.) were observed prior to the failure?
- What comments were received from the equipment operator regarding the failure or past failures?

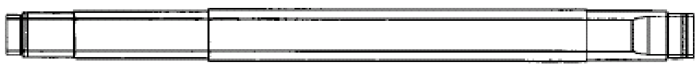
Methodology checklist : Maintenance history

- How long was the unit in storage or sitting idle prior to starting?
- What were the storage conditions?
- How often is the unit started?
- Were there shutdowns?
- Were correct lubrication procedures utilized?
- Have there been any changes made to surrounding equipment?
- What procedures were used in adjusting belt tensions?
- Are the pulleys positioned on the shaft correctly and as close to the motor bearing as possible?

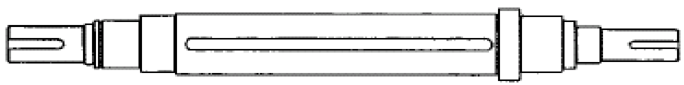
Cause, analysis and prevention of motor shaft failures



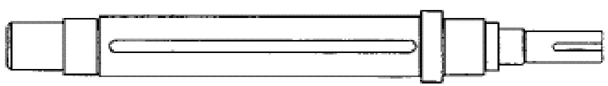
Large motor spider shaft



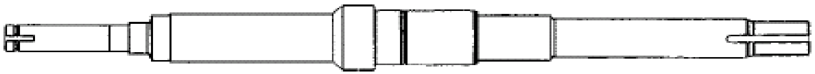
Vertical motor hollow shaft for pumps



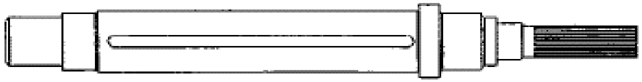
Totally enclosed fan-cooled shaft



Open drip-proof shaft



Close-coupled shaft for pump



Splined or geared take-off shaft

1. Motor shaft materials

AISI	Material	Application	Tensile stress	Yield stress
1045	Hot roll carbon	General purpose	586MPa	310MPa
4142	Cr-Mo	High stress	690MPa	517MPa
416	Stainless	Corrosive environment	483MPa	276MPa
1144	Cold draw carbon	General purpose small motor	745MPa	620MPa

2. The tools of shaft failure analysis

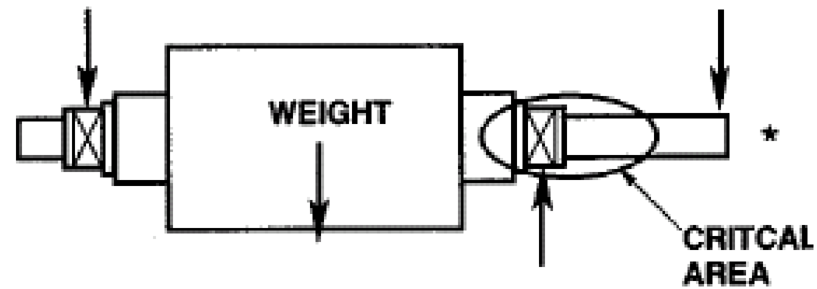
The ability to properly characterize the microstructure and the surface topology of a failed shaft are critical steps in analyzing failures.

- Visual inspection
- Optical microscope
- Scanning electron microscope
- Transmission electron microscope
- Metallurgical analysis

3. The causes of motor shaft failure

Cause of shaft failure	Percent
Corrosion	29%
Fatigue	25%
Brittle fracture	16%
Overload	11%
High-temperature corrosion	7%
Stress corrosion fatigue/hydrogen embitterment	6%
Creep	3%
Wear, abrasion and erosion	3%

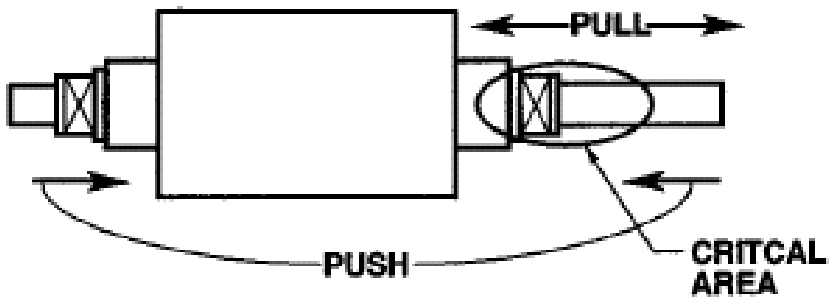
4. Typical motor shaft loading



Overhung load.

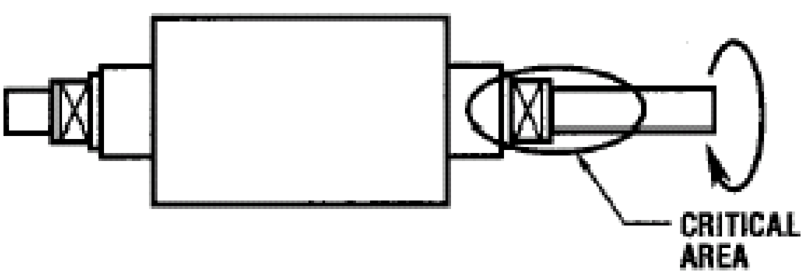
Failure mode: Bending fatigue and shaft rub

The force may be in any direction of the 360 .



Axial load.

Failure mode: Bearing failure

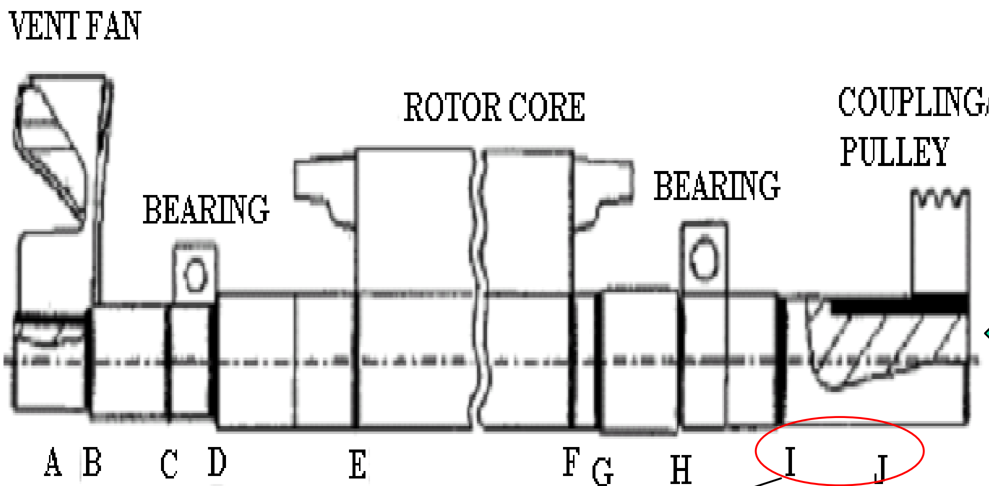


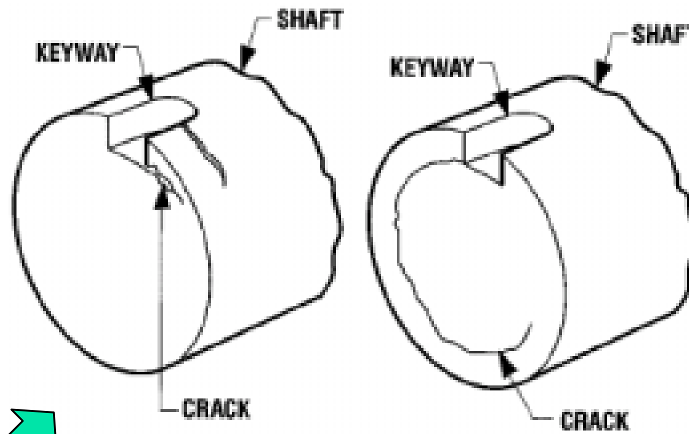
Torsion load.

Failure mode: Torsion failure

5. Areas of highest concentration

Stress raiser will exist at the **surface discontinuity**, such as bearing shoulders, snap ring grooves, keyways, shaft threads or holes.



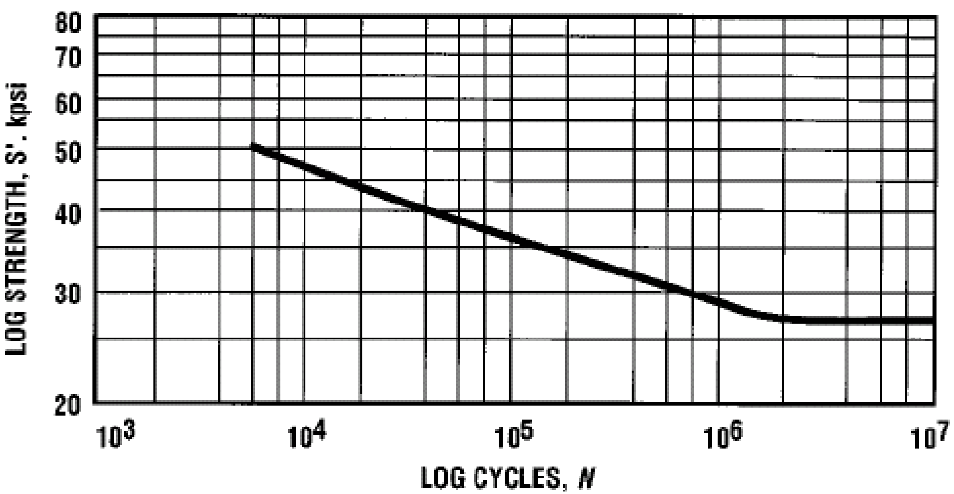


Peeling-type cracks in shafts usually originate at the keyway.

The most common area for shaft damage

6. Shaft failures for motors

Failure mode	Cause
Overload	High impact loading(quick stop or jam)
Fatigue	Excessive rotary bending, such as overhung load, high torsional load or damage causing stress raisers
Corrosion	Wear pitting, fretting, and/or cavitations can result in a fatigue failure if severe enough



S-N diagram for 1040 steel

Understanding **fatigue strength** and **endurance limits** is important because most shaft failures are related to fatigue associated with **cyclic loading**.

7. Defining the fatigue process

The failure process

- The fatigue leads to an initial crack on the surface of the part.
- The crack or cracks propagate until the remaining shaft cross section is too weak to carry the load.
- A sudden fracture of the remaining area occurs.

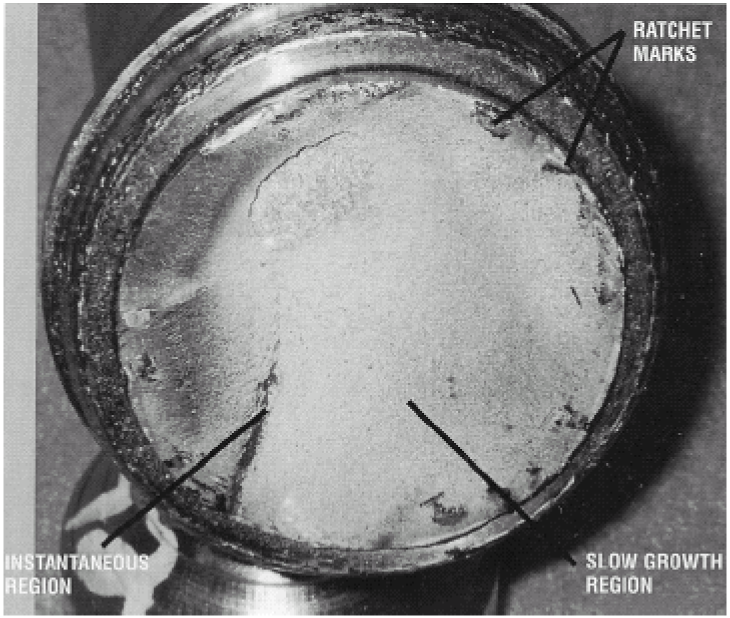
8. Appearance of fatigue fractures

The appearance of the shaft is influenced by various types of cracks, beach marks, conchoidal marks, radial marks, chevron marks, ratchet marks, cup and cone shapes, shear lip, and whole host of other topologies

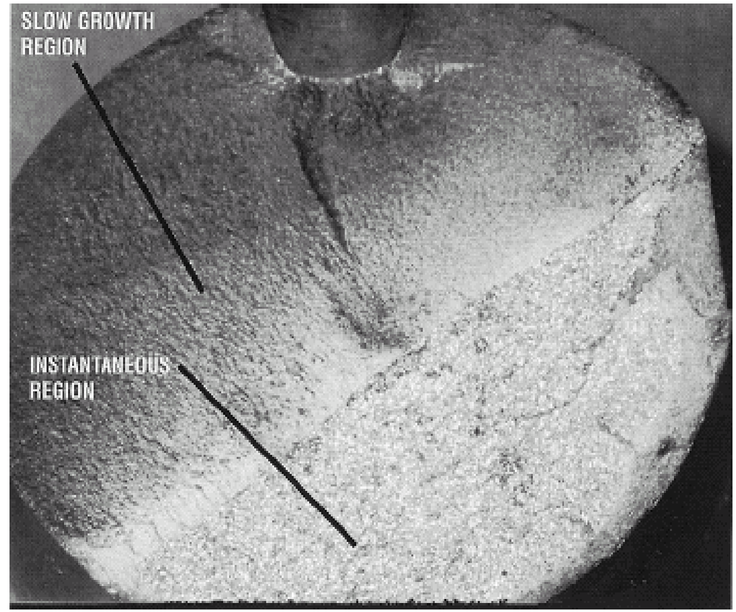
Region B of fracture zone, **instantaneous zone** with minimal plastic deformation

Region A of fracture zone, **slow growth** evidenced by conchoidal marks

Surface of a fatigue fracture displaying two distinct regions



View of slow growth and instantaneous regions of the shoulder



Initiation sites originated at the root of the keyway

9. Surface finish effects

Finishing operation	Surface finish (μm)	Fatigue life (cycles)
Lathe	2.667	24,000
Partly hand polished	0.125	91,000
Hand polished	0.127	137,000
Ground	0.178	247,000
Ground and polished	0.051	234,000

10. Residual stress failures

- These stresses are independent of external loading on the shaft.
- Many manufacturing or repair operations can affect the amount of residual stress.

- In addition to the above mechanical processes, **thermal processes** that introduce **residual stress** include:

- drawing
- bending
- straightening
- machining
- grinding
- surface rolling
- shot blasting or peening
- polishing
- hot rolling
- welding
- torch cutting
- heat treating

10. Miscellaneous

There is a broad category of shaft failures or motor failures that does not result in the shaft breaking.

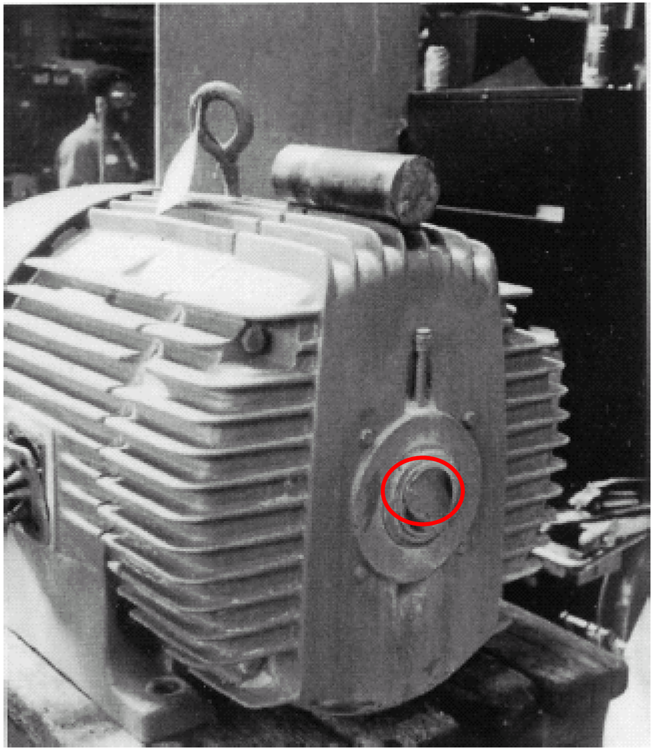
- bending or deflection causing interference with stationary parts
- incorrect shaft size causing interference, run out or incorrect fits
- residual stress causing a change in shaft geometry
- material problems
- excessive corrosion and wear
- excessive vibration caused by electrical or mechanical imbalance

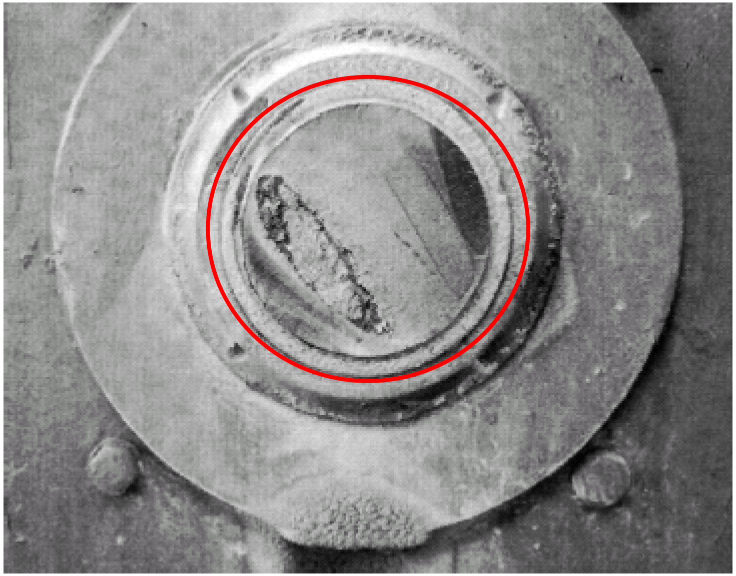
11. Prevention

Several practices will minimize the probability of a premature shaft failure.

- Be sure that the application and the possible loading on the motor are well understood and communicated. It is imperative to know if there is an overhung load. The environmental conditions are also critical.
- The motor manufacturer must be sure that proper materials are selected. For the most part, steel with the properties of hot rolled 1045 steel is adequate.
- The manufacturing processes are critical. During the processing of the shaft, care must be taken not to introduce stress raisers and to achieve the required shaft finish.
- The installation phase and operation phases are also critical. Care must be taken not to damage the shaft when coupling it to the driven equipment. For belt-driven loads, remember the moment principle (force distance) in placement of the pulley.

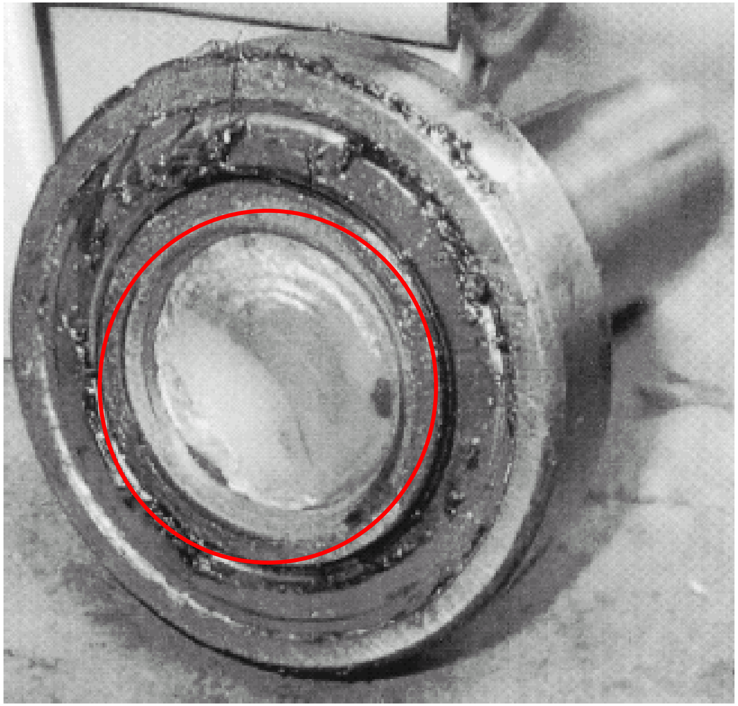
The most common shaft failures : Common shaft failures

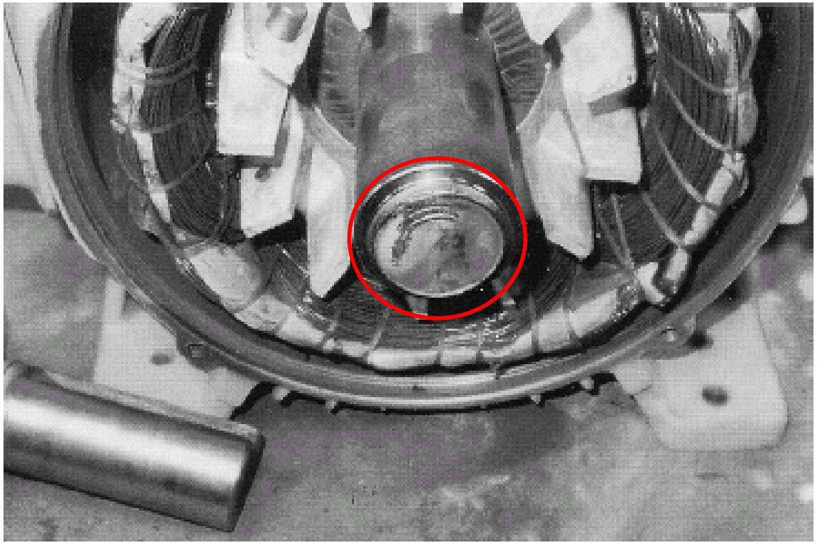




1045 carbon steel motor shafts that failed due to rotational bending fatigue. The point of failure was at the shoulder of the customer take-off end

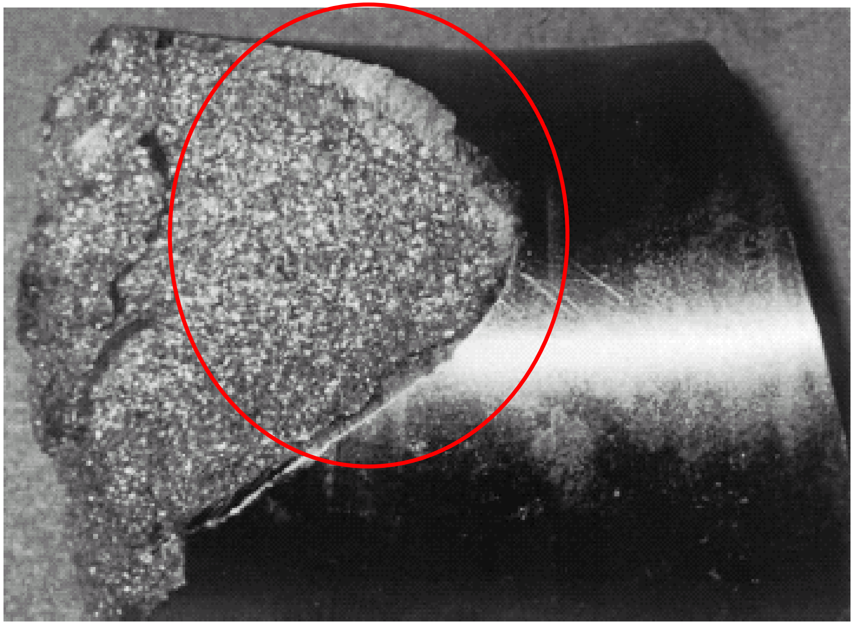
The most common shaft failures : Common shaft failures

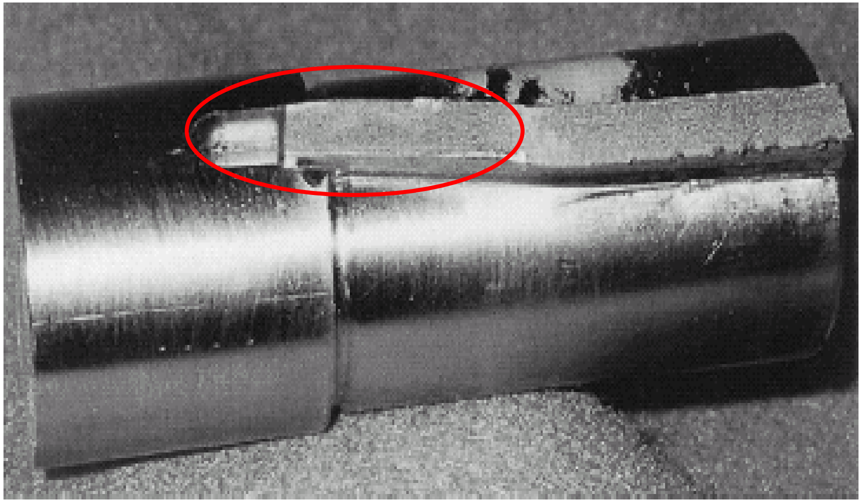




1040 carbon steel motor shafts that failed due to rotational bending fatigue. The point of failure was at the bearing journal shoulder.

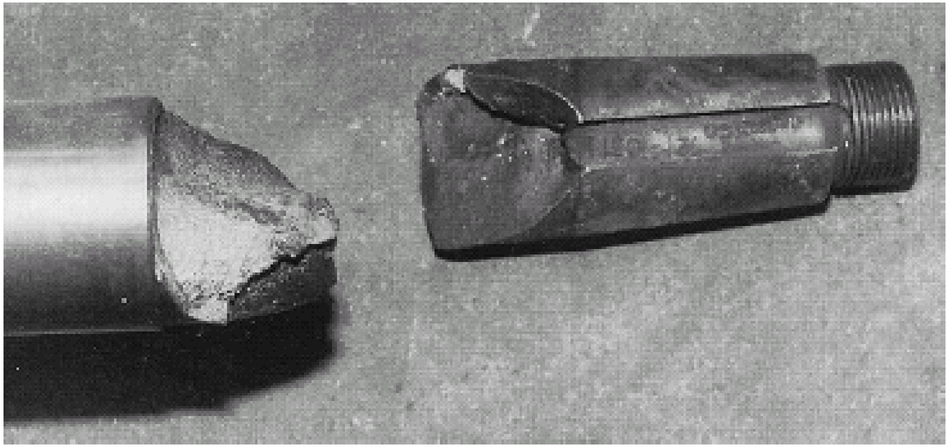
The most common shaft failures : Common shaft failures



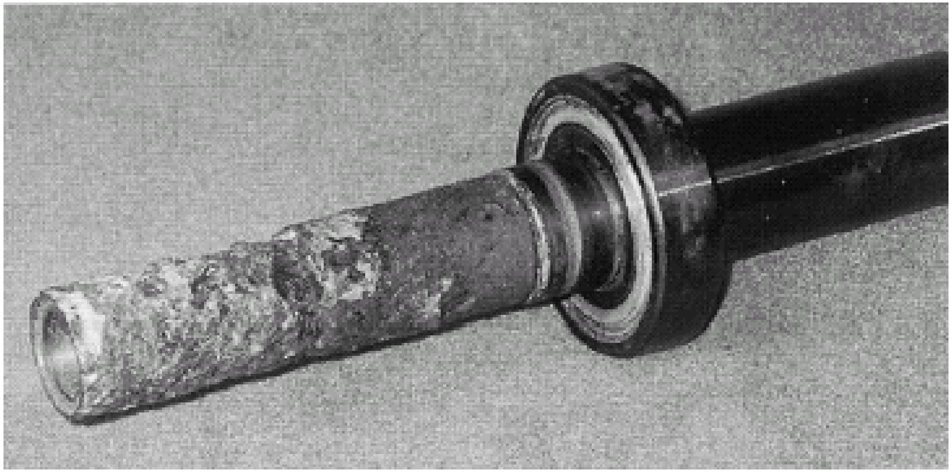


Shaft failures due to high-impact loading

The most common shaft failures : Common shaft failures

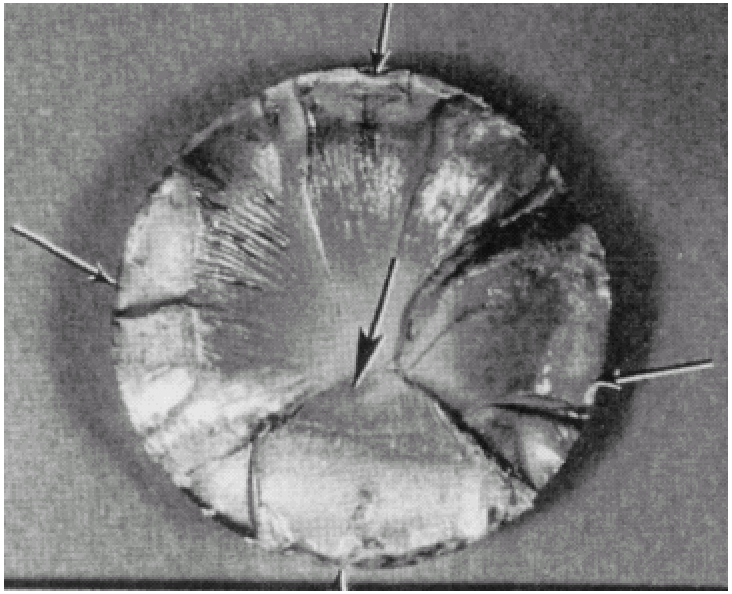


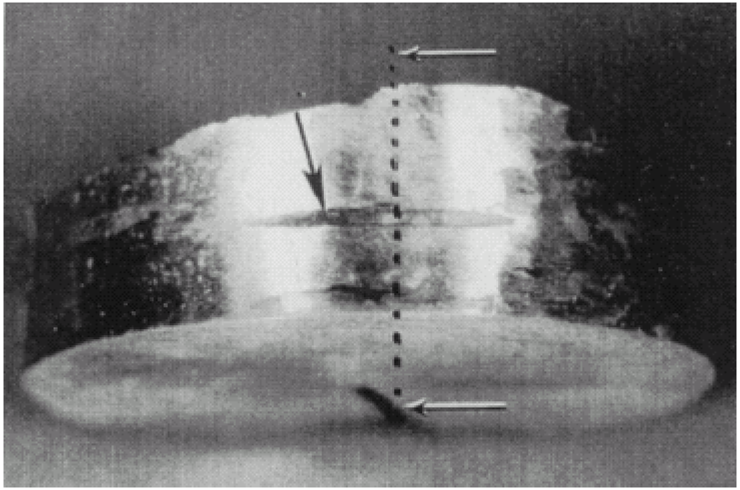
A **shaft fatigue failure** due to reversed torsional loading



Extreme **corrosion**, **wear** and **cracking** on a pump shaft

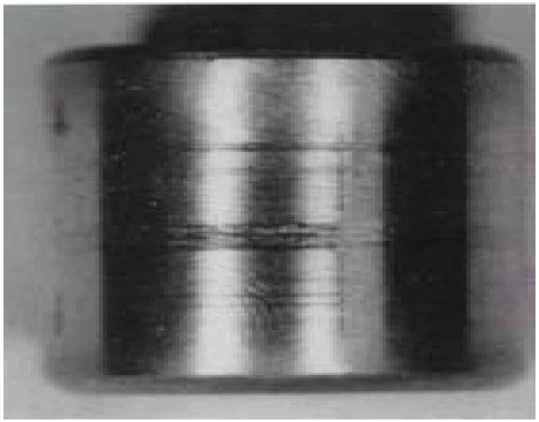
The most common shaft failures : Common shaft failures



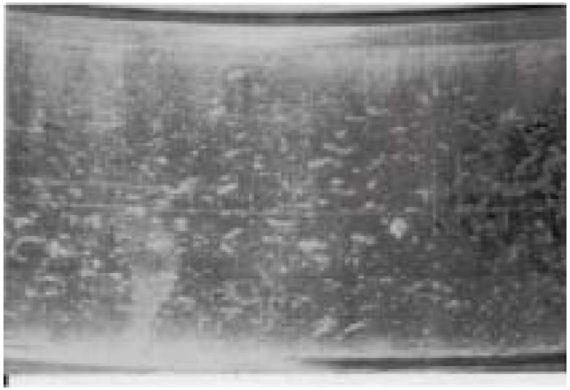


1051 carbon steel turbine shafts that failed due to **rotational bending fatigue**. There were also signs of minor torsional fatigue. Cracks initiated at the toe of a coupling weld. This material has poor weld ability characteristics. There were also signs of misalignment. Note the surface pit and grinding marks; both of these conditions can weaken the shaft.

The most common shaft failures : Common bearing failures



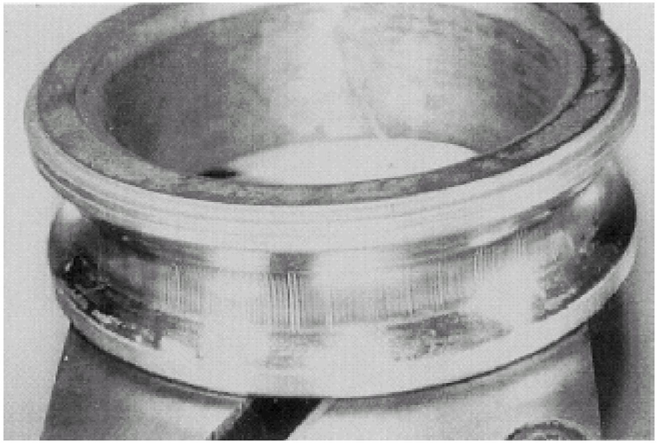
Smear marks on roller caused by debris



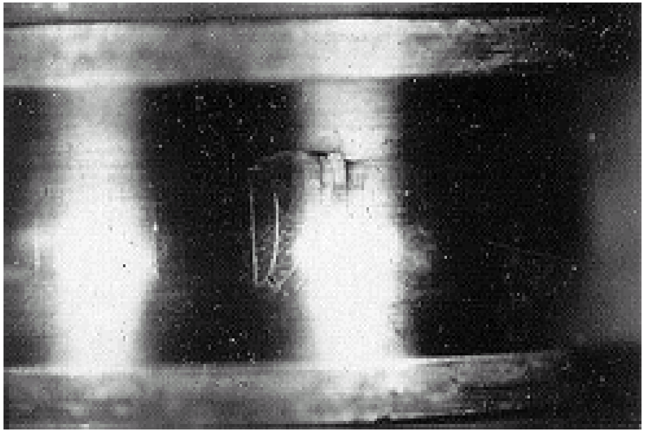
Metallic contamination in raceway

Damaged caused by **water intrusion**

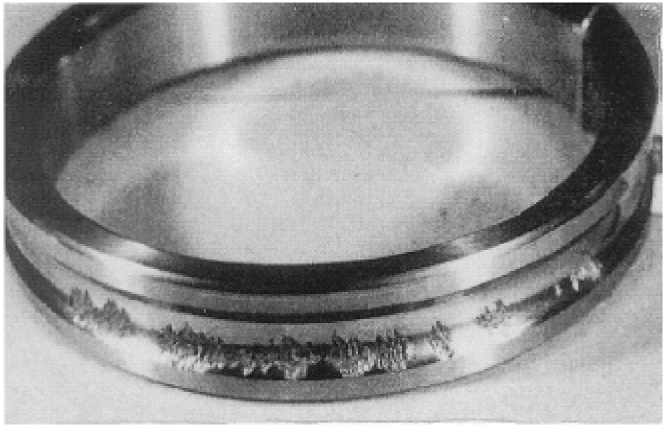
Fretting corrosion caused by loss fit and vibration



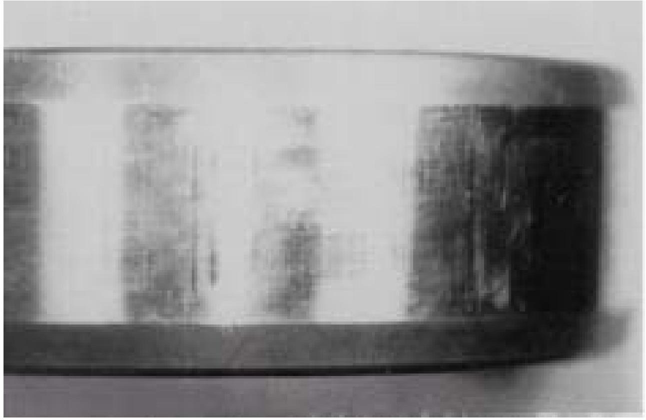
Pitting caused by electrical currents



Fluting caused by internally generated current

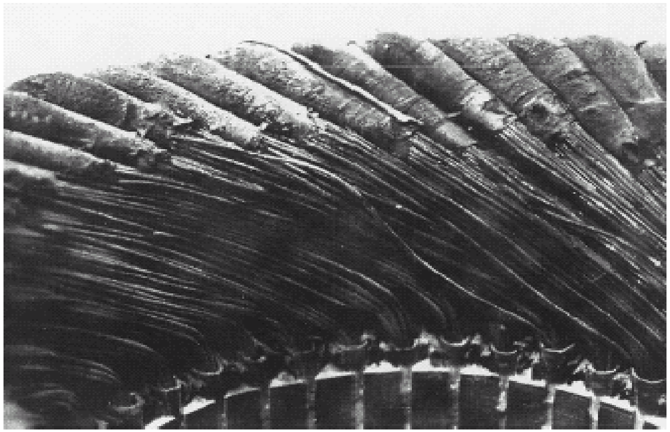


Advanced stages of **spalling**

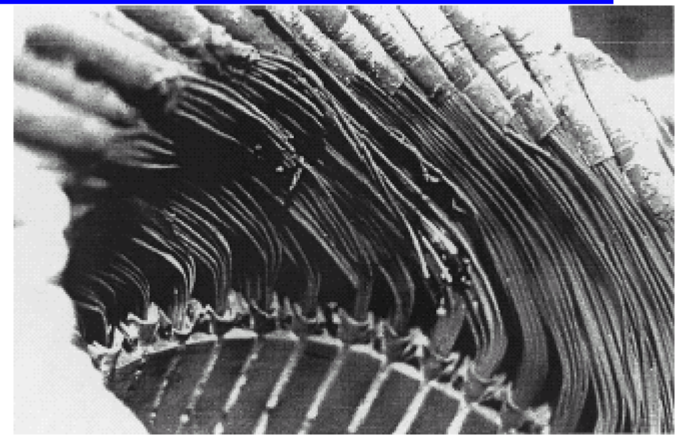


False brinelling and **fretting** caused by vibration in a nonoperating condition

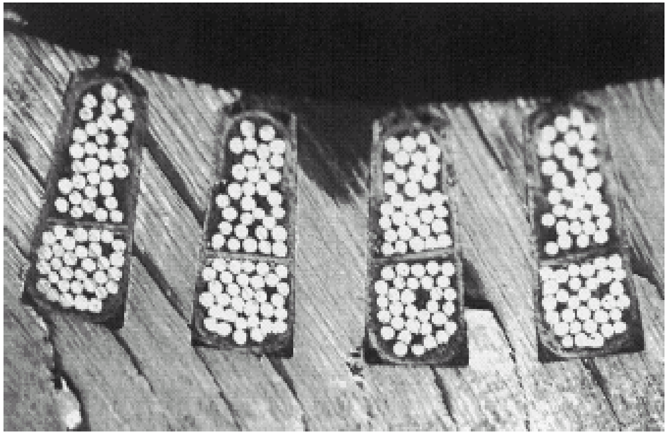
The most common shaft failures : Common stator failures



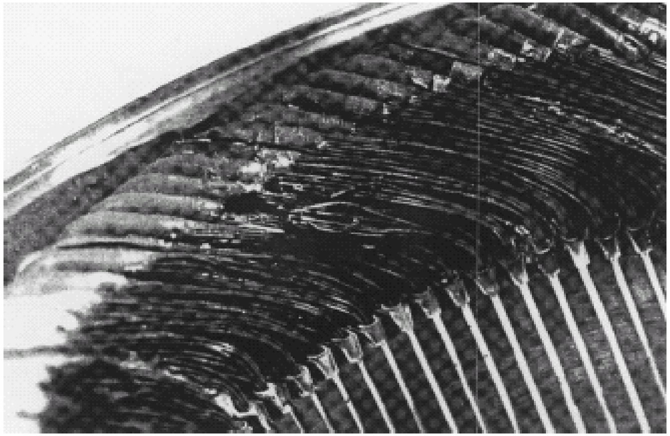
Turn-to-turn shorting



Single-phase turn-to-turn shorting

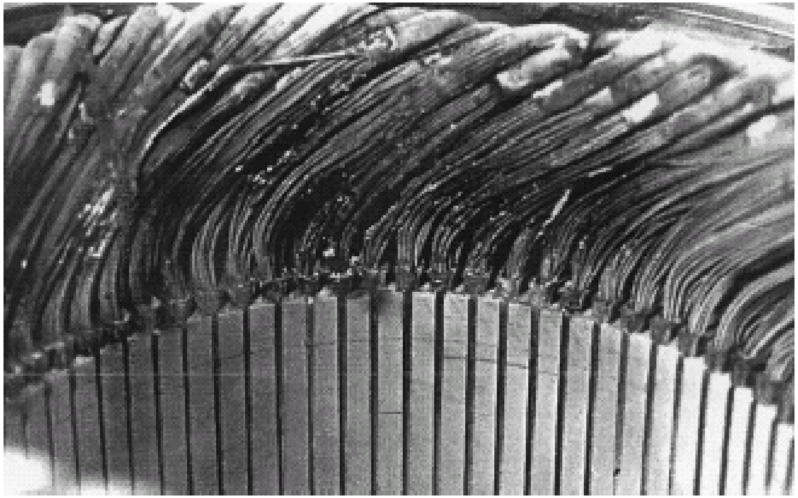


Stator cross section where shorting can occur

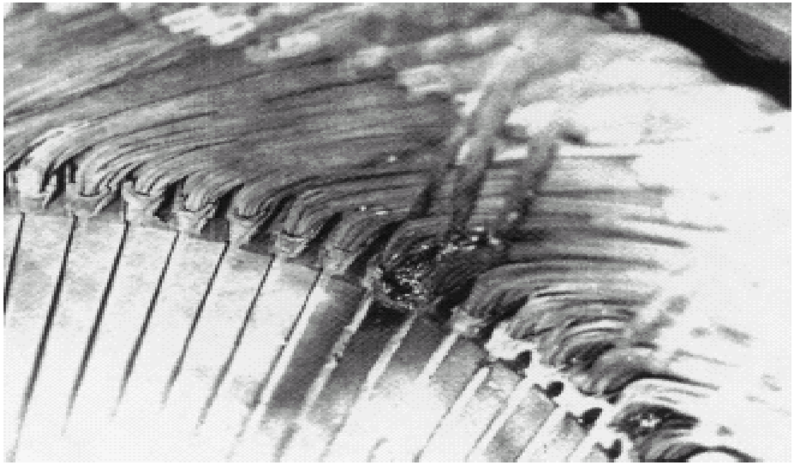


Nonsymmetrical shorting without grounding

The most common shaft failures : Common stator failures



Nonsymmetrical shorting with grounding

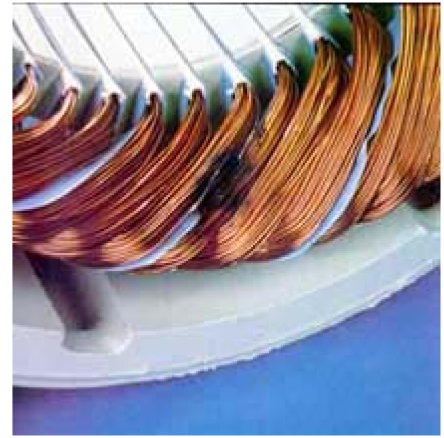


Same stator as above figure at point of grounding

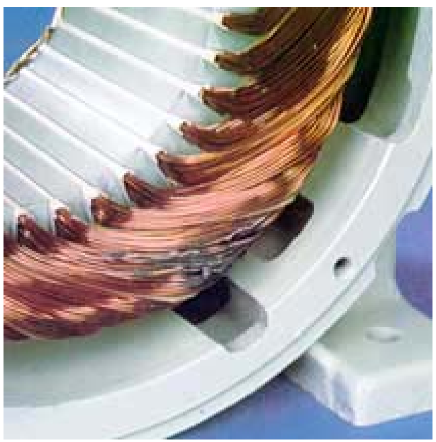
The most common shaft failures : Common stator failures

1. Winding Single-Phase (Y - Connected)

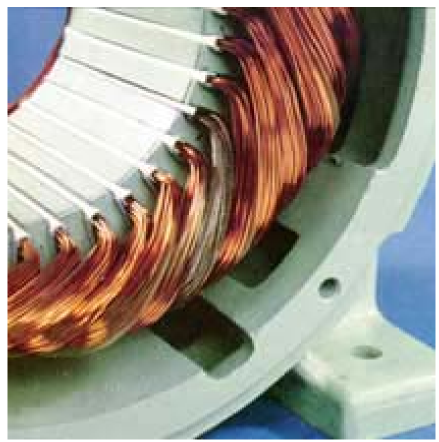
2. Winding Single-Phase (Δ - connected)



3. Winding Shorted Phase-to-Phase



4. Winding Shorted Turn-to-Turn

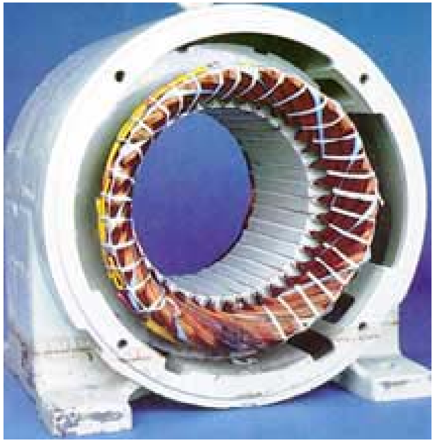


5. Winding with Shorted Coils

6. Winding Grounded at Edge of Slot

The most common shaft failures : Common stator failures

7. Winding Grounded in Slot



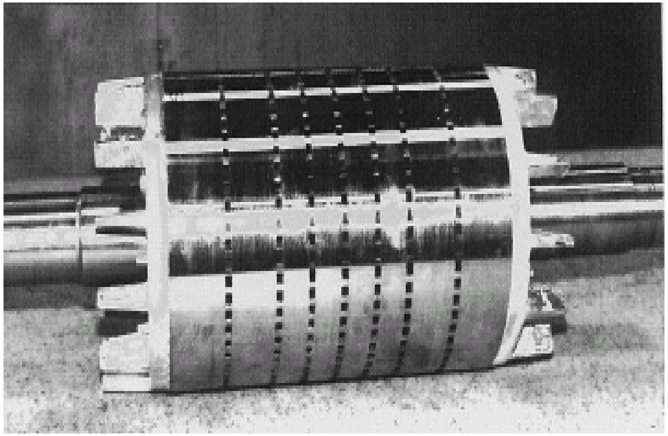
8. Shorted Connection

9. Phase Damage Due to Unbalance Voltage

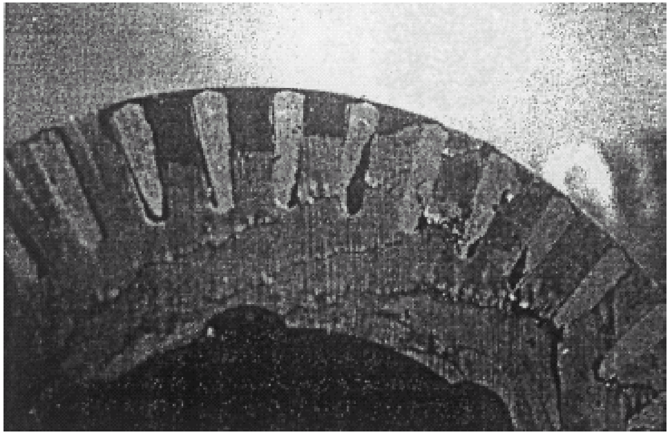
10. Winding Damage Due to Overload

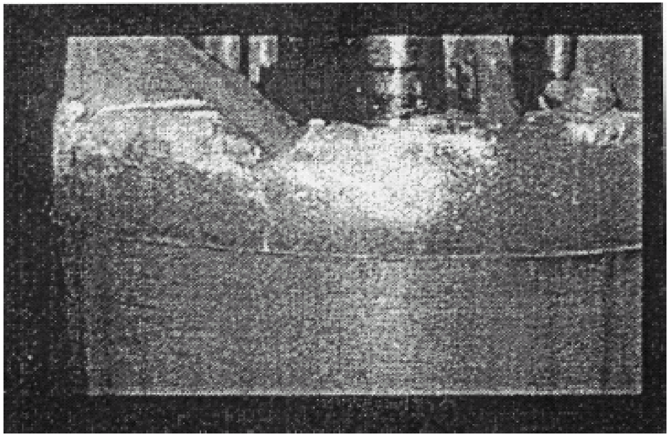
11. Damage Caused by Locked Rotor

12. Winding Damaged by Voltage Surge



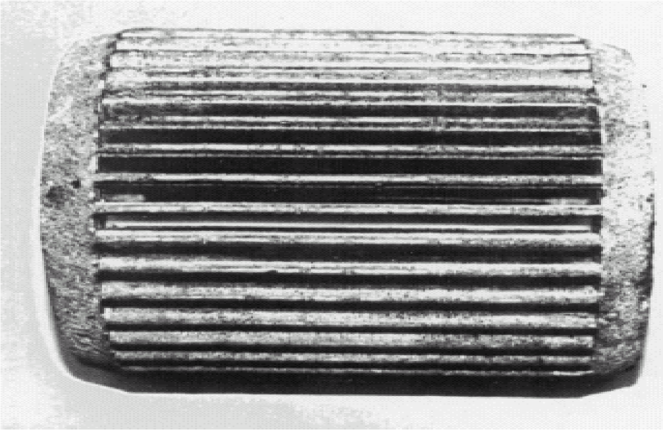
Typical cast air-ducted rotor; any damage to the fans, end rings, or air ducts can cause overheating and damage to the cage.



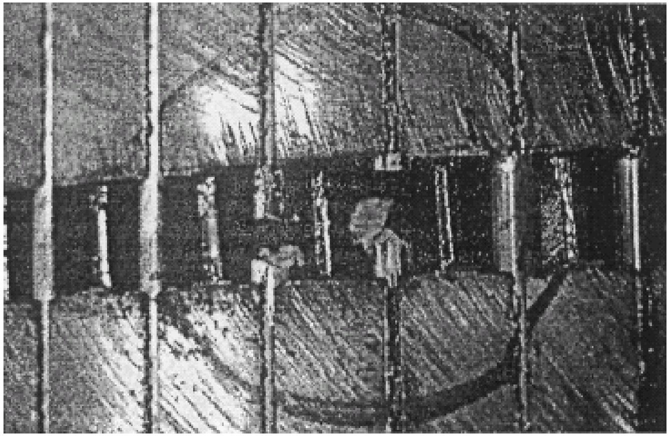


Overheated aluminum cast rotor end ring

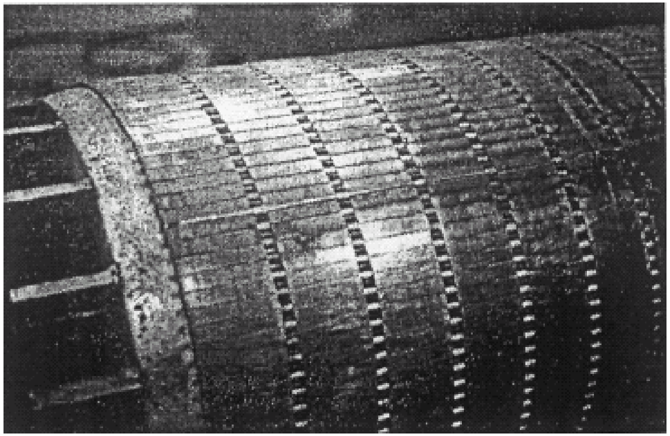
Incomplete rotor bars on aluminum cast rotor



Typical aluminum squirrel cage without the lamination. Any damage to the cage will affect the motor performance.



Broken and loose aluminum fabricated rotor bar.



Overheated aluminum fabricated rotor bars