4

Shaft Failures

Section Outline

Page

INTRODUCTION TO SHAFT FAILURES

The majority of shaft failures are caused by a combination of various stresses that act upon the rotor assembly. As long as the stresses are kept within the intended design and application limits, shaft failures should not occur during the expected life of the motor. These stresses can be broken down into the following groups:

Dynamic/Mechanical

- Overloads including sudden shock loads
- Cyclic loads.
- Overhung load and bending.
- Torsional load.
- Axial load.

Environmental

- Corrosion.
- Moisture.
- Erosion.
- Wear.
- Cavitation.

Thermal

- Temperature gradients.
- Rotor bowing.

Residual

- Manufacturing processes.
- Repair processes.

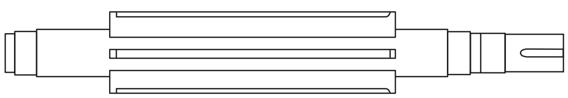
Electromagnetic

- Side loading.
- Out-of-phase reclosing.

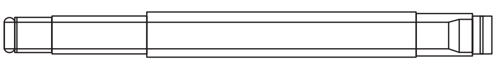
It is assumed that the reader has a fundamental knowledge of physics and mechanics and is already familiar with the basic terms, nomenclature and theory associated with motor shafting.

Figure 1 shows a variety of rotor shafts used in electric motors.

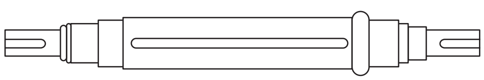
FIGURE 1: TYPICAL MOTOR SHAFT CONFIGURATIONS



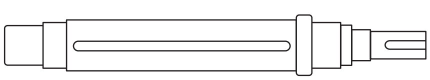
Large motor spider shaft



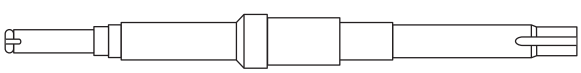
Vertical motor hollow shaft for pumps



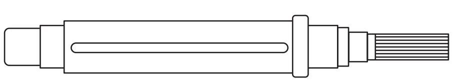
Totally-enclosed, fan-cooled shaft



Open dripproof shaft



Close-coupled shaft for pumps



Splined or geared take-off shaft

MOTOR SHAFT MATERIALS

For most motor applications, hot-rolled carbon steel is a good choice. When higher loads are present, an alloyed steel such as chromium-molybenum (Cr-Mo) is frequently used. For applications with extreme corrosion or a hostile environment, a stainless steel material is required. Table 1 shows some of the most common steels and their characteristics.

With the stainless steel, you give up yield and tensile strength in favor of resistance to corrosion.

TABLE 1: COMMON SHAFT MATERIALS

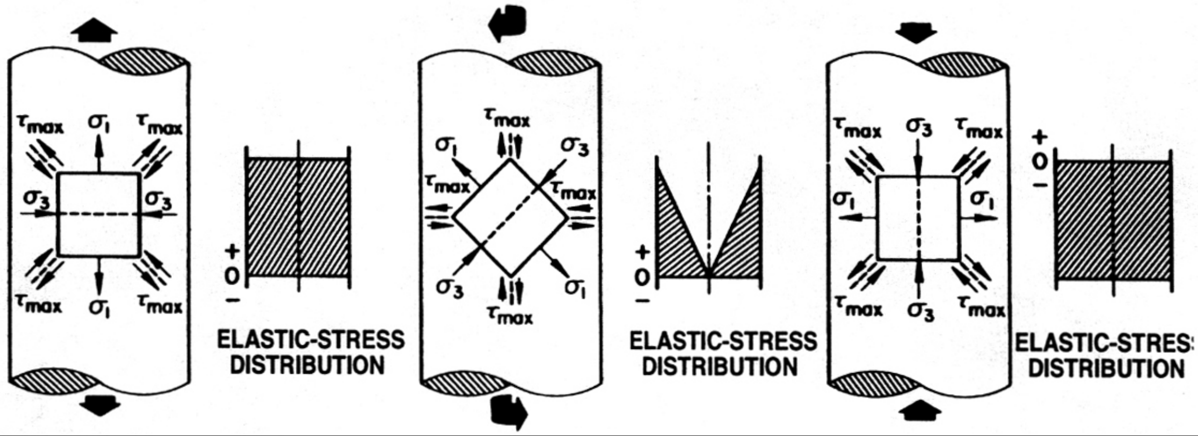
AISI	Material	Application	Tensil	Yield
1045	Hot-rolled carbon	General purpose	82,000 psi	45,000 psi
4142	Cr-Mo	High stress	100,000 psi	75,000 psi
416	Stainless	Corrosive environment	70,000 psi	40,000 psi
1144	Cold-drawn carbon	General-purpose small motors	108,000 psi	90,000 psi

STRESS SYSTEMS ACTING ON SHAFTS

Before the causes of shaft failures can accurately be determined, it is necessary to clearly understand the loading and stresses acting on the shaft. These stresses can best be illustrated by the use of simple free body diagrams. The

PHOTOGRAPHS OF SHAFT FAILURES

FIGURE 2: STRESSES ACTING ON SHAFTS



σ_1 = Tensile stress σ_3 = Compressive stress τ_{max} = Maximum shear stress

These diagrams show the orientation of normal stresses and shear stresses acting on a shaft under simple tension, torsion and compressive loading.

Metals Handbook, Volume 10

free body diagram is simply a sketch showing the types and directions of forces acting on a shaft under tensile, compressive and shear stress.

Figure 2 is reproduced from the Metals Handbook, Volume 10 and illustrates how tension, compression, and torsion act on the shaft for both ductile and brittle materials. In the case of motor shafts, the most common materials can be classified as ductile. However, in the presence of a stress riser, a normally ductile material can act as a brittle material and fail rapidly. Failures caused by bending can be treated as a combination of tension and compression where the convex side is in tension and the concave side is in compression.

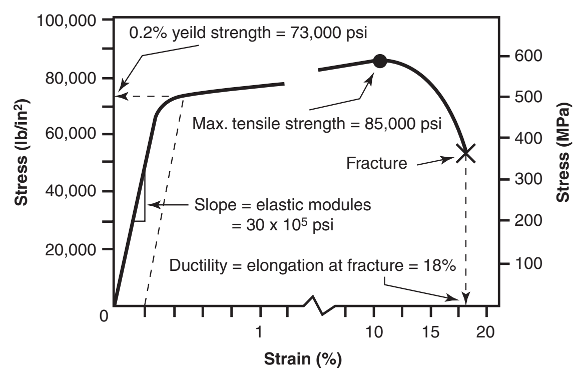
STRESS/STRAIN CURVES

To understand the failure mechanisms of a steel motor shaft, it is important to know the relationship between stress and strain for a particular shaft material along with other characteristics associated with a specific material. Figure 3 is a typical stress/strain curve for motor applications.

This stress-strain diagram for cold-rolled 0.18% carbon steel, showing how the 0.2 percent yield strength and other tensile mechanical properties are determined. When a tensile stress is added to a material, the material will begin to deform at a certain level of stress. This deformation is elastic until the stress reaches the yield strength point of steel (at 73,000 psi in Figure 3). Elastic deformation simply means that the material will return to its original shape when the force is removed. Strain is measured by the percent of deformation, and the yield strength is where the strain is at 0.2%. After the applied stress is greater than the yield strength, the deformation is plastic and the steel will not return to its original shape. At this point, the bond between the molecules of steel has been altered, or the molecules have been "torn apart" and cannot go back. The maximum tensile strength is the point at which it is just about to fracture.

FIGURE 3: TYPICAL STRESS/STRAIN CURVE FOR MOTOR SHAFTS

(Cold-rolled 0.18% carbon steel)



Information from C.R. Brooks and A. Choudry, *"Metallurgical Failure Analysis,"* McGraw-Hill, 1993.

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. The most common tools available to do this can be categorized as follows:

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

It is assumed that it may be necessary to employ the services of a skilled metallurgical laboratory to obtain some of the required information. However, a significant number of failures can be diagnosed with a fundamental knowledge of motor shaft failure causes and visual inspection. This may then lead to confirmation through a metallurgical laboratory. The material presented in this article will help lead to an accurate assessment of the root cause of failure.

FAILURE ANALYSIS SEQUENCE

There is no absolute specific sequence for determining the cause of failure. The sequence steps may depend on the type of failure. However, the following steps may be useful to determine the cause of a shaft failure:

- Describe failure situation.
- Visual examination.
- Stress analysis.
- Chemical analysis.
- Metallurgical examination–to determine the composition of the shaft material.
- Material properties—to determine if the right material is used for the application.
- Failure simulation.

METHODOLOGY FOR ANALYSIS

To be consistent with the previous material on stator, rotor and bearing failures and in combination with the above sequence, it is proposed that the analysis of shaft failures contain at least the following elements:

- Failure mode.
- Failure pattern.
- Appearance.
- Application.
- Maintenance history.

FAILURE MODE

For motor shafts, 90% of all failures can be grouped into the modes shown in Table 2. If the shaft is not designed, built, applied or used properly, a premature failure may occur in any of the failure modes.

TABLE 2: FAILURE MODES AND THEIR CAUSES

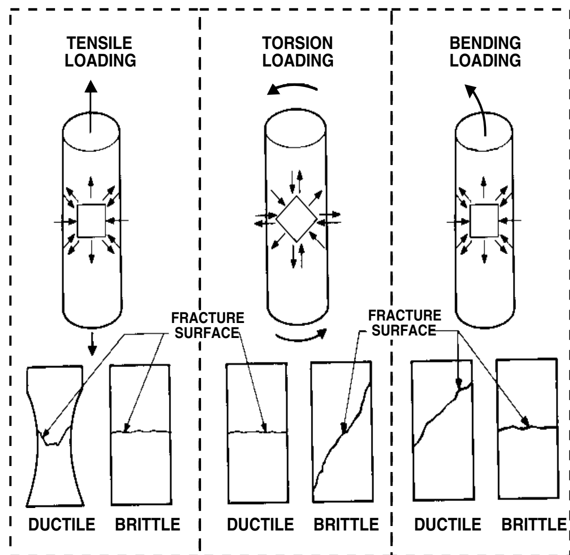
Failure mode	Cause
Overload	High-impact loading (quick stop or jam)
Fatigue (mechanical or dynamic)	Excessive rotary bending, such as an overhung load, high torsional load or damage causing stress raisers
Corrosion (environmental)	Wear pitting, fretting, and/or cavitation can result in a fatigue failure if sever enough
Thermal	Temperature gradients, rotor bowing or loss of running fits
Residual	Surface finish, surface coating, welding, etc.
Electromagnetic	Side loading, out-of-phase reclosing

FAILURE PATTERN

Failure patterns can be associated with the appearance of the shaft after failure. Shaft fractures can be classified as ductile or brittle.

Plastic deformation is associated with ductile fractures since only part of the energy is absorbed as the shaft is deformed. In brittle fractures, most of the energy goes into the fracture and most of the broken pieces fit together quite well. Ductile failures have smooth surfaces and brittle failures have rough surfaces as shown in Figure 4, which is an expansion of Figure 2, where the stresses acting on shafts are shown.

FIGURE 4: DUCTILE VS. BRITTLE FAILURES



APPEARANCE CONSIDERATIONS

When coupled with the class and pattern of failure, the general motor appearance usually gives a clue as to the possible cause of failure. The following check list will be useful in evaluating assembly conditions that may have contributed to the shaft failure:

- Is there evidence of foreign material in the motor?
- Are there any signs of blocked ventilation passages?
- Are there signs of overheating exhibited on the surface of the shaft, insulation, lamination, bars, bearings, lubricant, painted surfaces, etc.?
- Have the rotor laminations or the shaft rubbed? Record all locations of contact.
- Are the motor cooling passages clear of debris?
- What is the physical location of the shaft failure? Which end is it on? Did the failure occur at the keyway, bearing shoulder, or elsewhere along the shaft?
- Are the bearings free to rotate and are they operating as intended?

- Are there any signs of moisture on the stator or rotating assembly or contamination of the bearing lubricant or corrosion on the shaft?
- Are there any signs of movement between rotor and shaft or bars and laminations?
- Is the lubrication system as intended or has there been lubricant leakage or deterioration?
- Are there any signs of a stall or locked rotor?
- Was the rotor turning at the time of 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?
- What is the condition of the coupling device, driven equipment, mounting base, and other related equipment? What is the condition of the pulley? Is it worn?
- 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 shaft loaded axially or radially?
- Do the stress risers show signs of weakness or cracking (the driven end shaft keyway is a weak link)?
- Was there a proper radius on each shoulder along the shaft?
- Was the keyway sledded or milled? Are there stress risers on the sides and back of the keyway?
- What material is the shaft made from? Is it stainless steel? If so, it is magnetic or non-magnetic?
- What is the shaft runout and geometry along all surfaces?
- Is the shaft bent or is there any twisting?

When analyzing shaft failures, it is helpful to draw a sketch of the shaft and indicate the point where the failure occurred as well as the relationship of the failures to both the rotating and stationary parts such as shaft keyway, etc.

APPLICATION CONSIDERATIONS

It is usually difficult to reconstruct conditions at the time of failure. However, a knowledge of the general operating conditions will be helpful. The following items should be considered:

- What are the load characteristics of the driven equipment and what was the load at the 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? Does the motor use power factor correction capacitors that could cause the shaft to break if the power factor is overcorrected?
- How long does it take for the unit to accelerate to full 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 during operation?
- How often is the unit started and is it manual or automatic? Does it use part winding, wye-delta, ASD, or across-the-line starting?
- What type of protection is provided?
- What tripped the unit off-line?
- Where is the unit located and what are the normal environmental conditions? Are there potentially corrosive materials in the environment?
- What was the ambient temperature around the motor at the time of failure? Was there any recirculation?
- What were the environmental conditions at the time of failure?
- Does the mounting base properly support the motor?
- Was power supplied by a variable frequency drive? How far away is the drive from the motor?
- How would you describe the driven load method of coupling and mounting and exchange of cooling air?
- Is the load belted? If so, how many belts are there and were they too tight? Does the motor use individual or poly belts?

MAINTENANCE HISTORY

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

- How long has the motor been in service?
- Has this motor, or more specifically the shaft, failed in the past and what was the nature of the failure? If so, where was the failure, and what was the cause?
- 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, etc.) were observed prior to failure?
- What comments were received from the equipment operator regarding the failure or past failures?
- 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?
- Has the shaft been repaired previously? If so, what method was used to restore the original geometry; stubbing, welding, plating, metalizing, etc.? Was the shaft stress relieved at the time of repair?

CAUSES OF FAILURE

Studies have been conducted to try to quantify the causes of shaft failures. One industry study provided the following results for rotating machinery as shown in Table 3.

TABLE 3: CAUSES OF SHAFT FAILURES

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

Adapted from C.R. Brooks and A. Choudry, *"Metallurgical Failure Analysis,"* McGraw-Hill, 1993.

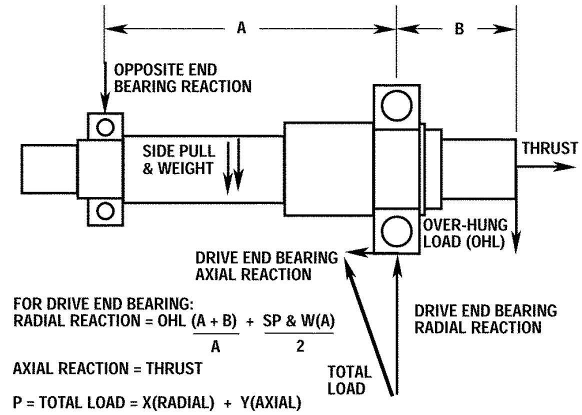
There are other informal studies that suggest that the majority of all motor shaft failures are fatigue related, in the 80 to 90% range. For motor applications, it is at least the majority of all shaft failures. The number climbs into the 90% range when the result of corrosion and new stress risers are added. Hence, the main focus of this section will be failures associated with fatigue.

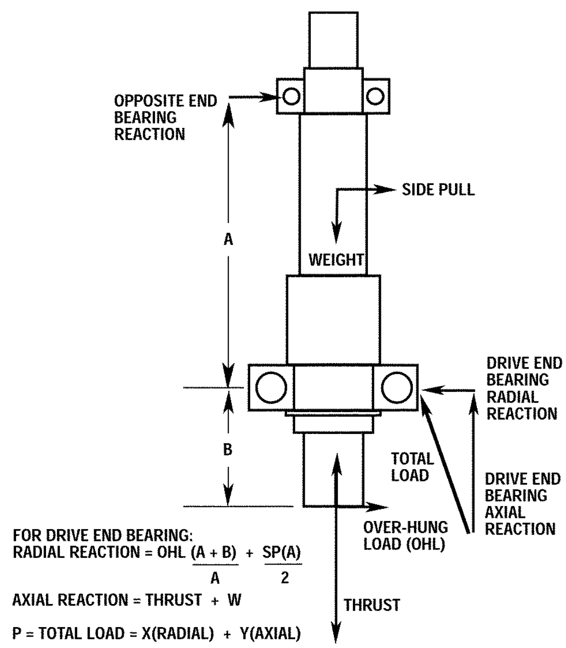
Figure 5 illustrates the typical loading on the shaft and bearings for both horizontal and vertical motors. These free-body diagrams show the distribution of forces in each direction of loading.

The examples in Figure 6 provide the types of motor shaft loading conditions that can lead to fatigue-type failures.

FIGURE 5: SHAFT LOADING CONSIDERATIONS

It is important to understand the shaft loading and the critical stress areas in order to conduct a thorough shaft inspection. This illustration shows the various loading conditions that can exist.





A = Distance between bearing centers

B = Distance between the center of the bearing to the center of the load (if unknown, to the end of the shaft)

DEFINING THE FATIGUE PROCESS

Fatigue fractures or damage occurs in repeated cyclic stresses, each of which can be below the yield strength of the shaft material. Usually, as the fatigue cracks progress, they create what is known as beach marks, since they look like the marks that waves leave on the beach.

The failure process consists of the following: first, the fatigue leads to an initial crack on the surface of the part; second, the crack or cracks propagate until the remaining shaft cross-section is too weak to carry the load. Finally, a sudden fracture of the remaining area occurs.

Fatigue-type failures usually follow the weakest link theory. That is, the cracks form at the point of maximum stress or minimum strength. This is usually at a shaft discontinuity somewhere between the end of the rotor keyway and the shaft coupling.

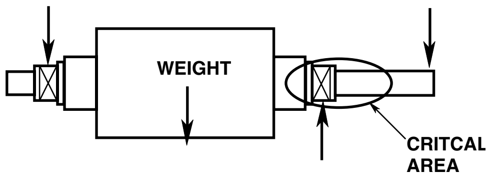
There are many variables that affect the fatigue life of a shaft; these include temperature, environment, residual stresses, and the appearance of fretting on the surface, just to name a few.

STRESS CYCLE (S-N) DIAGRAMS

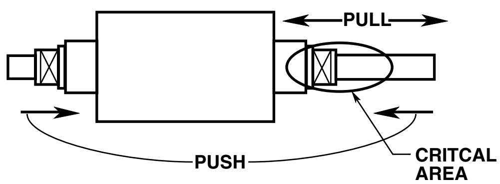
Since most shaft failures are related to fatigue, which is failure under repeated cyclic load, it is important to understand fatigue strength and endurance limits. One way to establish

FIGURE 6: FATIGUE FAILURES

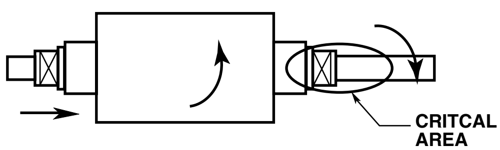
These three examples illustrate the most common types of motor shaft loading that can lead to fatigue failures.



Overhung load — Failure mode: Bending fatigue and shaft rub



Axial load — Failure mode: Bearing failure

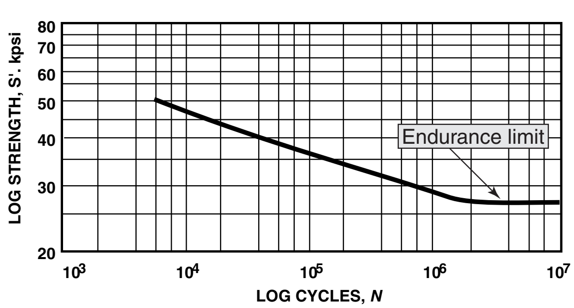


Torsional load — Failure mode: Torsional failure

the strength and limits is to develop a stress cycle or S-N diagram as shown in Figure 7 for a typical 1040 steel. The plot of the maximum stress vs. the number of cycles before failure is called the stress-cycle diagram, or commonly the S-N diagram.

To develop the curve, a steel specimen is subjected to alternating tension and compressive stress by rotating it with a bending load. The stress level is plotted against the number of cycles before the specimen fails. Subsequent tests are done with the same type of specimen at lower and lower stress levels. Each point is plotted to develop the S-N curve for the type of steel.

FIGURE 7: S-N DIAGRAM FOR 1040 STEEL



For steel, these plots become horizontal after a certain number of cycles. At a certain stress level, the piece will not fail, no matter how many cycles at which the stress is applied. This stress level, represented as the horizontal line in Figure 7 is known as the fatigue or endurance limit.

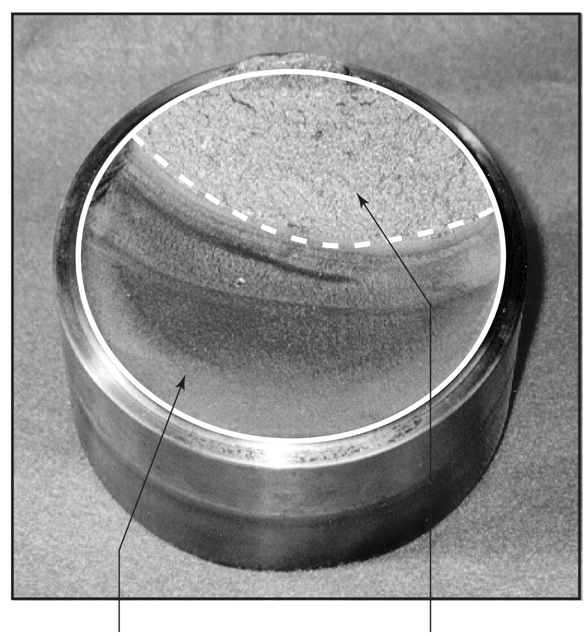
APPEARANCE OF FATIGUE FRACTURES

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 tip and a whole host of other topologies. (See Figure 13.) Some of the most common ones associated with motor shafts that have failed are due to rotational bending fatigue. The surface of a fatigue fracture will usually display two distinct regions as shown in Figure 8.

Region A includes the point of origin of the failure and evolves at a relative slow rate depending on the running and starting cycle, and of course, the load. Region B is the instantaneous or rapid growth area and exhibits very little plastic deformation. If the conchoidal marks were eccentric, that would indicate a cyclical load.

In Figure 8, both the slow growth region and instantaneous regions can be seen. This shaft fractured at the snap ring groove, which is a stress riser. Note the presence of ratchet marks on the periphery of the shaft. These point to the origin of the cracks. Ratchet marks are the boundaries of each fracture plane. The individual cracks will grow inward and eventually join together on a single plane.

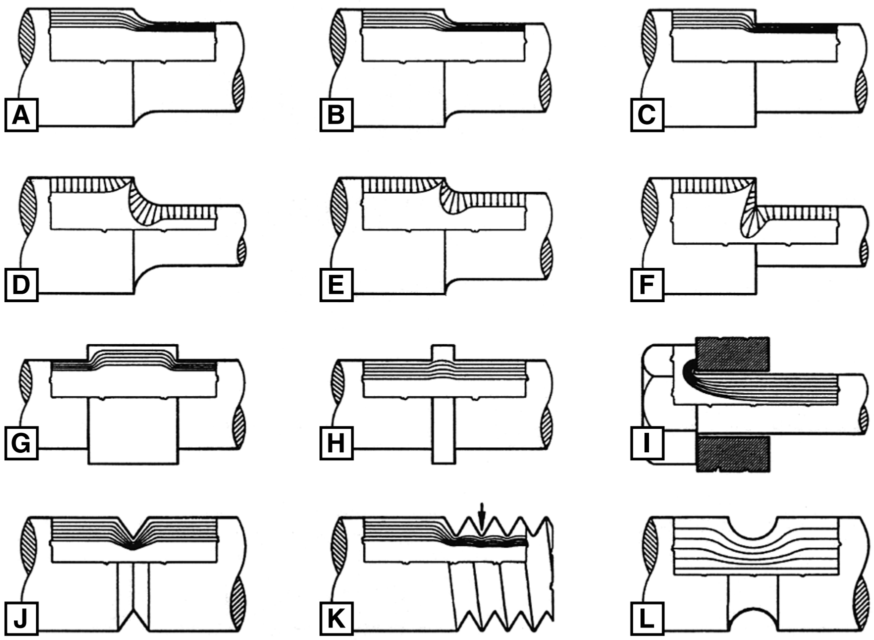
FIGURE 8: REGIONS OF A SHAFT FAILURE



Region A
Slow growth area of fracture. Note changes in color which represent change in rate of growth.

Region B
Instantaneous area of fracture with little plastic deformation.

FIGURE 9: STRESS RISERS IN SHAFTS



Stress is represented by a series of parallel lines. The closer the lines, the higher the stress.
Metals Handbook, Volume 10, Page 105

THE IMPACT OF STRESS CONCENRATIONS ON FATIGUE STRENGTH

The origin of cracks caused by fatigue is usually the result of the presence of some surface discontinuities which are commonly referred to as stress risers. A stress riser is a physical or metallurgical discontinuity that increases the stress on a material by some factor. Examples of stress risers on motor shafts are keyways, steps, shoulders, collars, threads, splines, holes, or shaft damage or flaws. Lack of a radius on the shaft will increase the stress at that point dramatically. A larger radius better distributes the stress at the shoulder; in fact, it will be about 60% stronger than the shaft with no radius.

Figure 9 illustrates the distribution of stress as a result of various types of risers. The stress is represented by a series of parallel lines where the stress is inversely proportional to the distance between the lines: the closer the lines, the higher the stress.

It is evident in Figure 9 that the sharper the corner, the higher the level of stress at that point. Along the top row it is shown that a generous radius decreases the stress associated with a sharp inside corner on the keyway. This is one of the reasons why it may be a good idea to taper or sled the keyway because it can reduce some of the shaft failures that occur on the keyway.

Going back to the stress-strain relationships, steel is consistent for a ductile material. For a brittle material, the maximum tensile strength is the same as the yield strength. There is no period of plastic deformation; it simply fractures brittly when it reaches the yield strength. When a ductile material has a notch, which acts as a stress riser, it tends to act like a brittle material and will fail at the yield strength point before it reaches its maximum tensile strength. So the presence of a stress riser will actually reduce the true strength of the shaft.

Whatever the type of load, the critical areas of highest stress are all in the same area for the three types of load. Most shaft fatigue failures are either behind the bearing journal or at the keyway because these are the points where the stress is the highest.

Quoting from the handbook:

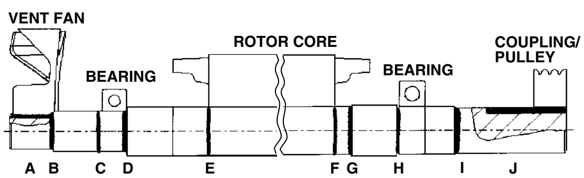
"Progressive increases in stress with decreasing fillet radii are shown in Figure 9A, 9B and 9C and the relative magnitude and distribution of stress resulting from uniform loading of these parts is indicated in Figure 9D, 9E and 9F.

Stress caused by the presence of an integral collar of considerable width is shown in Figure 9G; Figure 9H shows the decrease in stress concentration that accompanies a decrease in collar width. Stress conditions are very similar when collars or similar parts are pressed or shrunk into position. The stress flow at the junction of a bolt head and a shank is as represented in Figure 9I.

A single notch introduces a considerably greater stress concentration effect than does a continuous thread: the reason for this is clear when the stress flow is considered. The stress concentration effect of a single sharp notch is as shown in Figure 9J. The stress concentration at the right of the arrow in Figure 9K is very similar to that in the narrow collar in Figure 9H because of the mutual relief afforded by adjacent threads. To the left of the arrow, however, the last thread is relieved from one side only and in consequence there is a considerable stress concentration, similar to than of the single notch in Figure 9J. This is why bolts so frequently fracture through the last thread.

The effects of a groove or gouge on stress concentrations is less severe than a sharp notch. A series of grooves will have an effect similar to that shown in Figure 9L."

FIGURE 10: AREAS OF HIGHEST CONCENTRATION



All of the highlighted areas create stress risers. Planes F, H, I and J are the most vulnerable because of torque. Shafts do not normally fracture at points A, B, C, D or E.

AREAS OF HIGHEST CONCENTRATION

Figure 10 illustrates areas on a normal motor shaft where design stress concentrations (risers) will exist. Wherever there is a surface discontinuity such as a bearing shoulder, snap ring groove, keyway, shaft threads or a hole, a stress riser will exist. Shaft damage or corrosion can also create stress risers. Fatigue cracks and failure will usually occur in these regions. For motors, the two most common places are at the shoulder on the bearing journal (Point H) or in the coupling keyway region (Point J). Although in most cases an axial load will first result in a bearing failure, there are numerous examples where the shaft is damaged before shutdown is achieved.

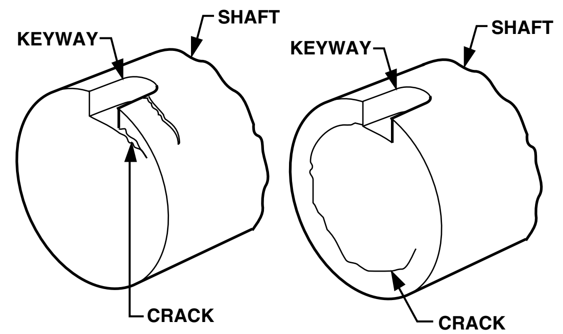
SHAFT KEYWAYS

Keyways are used commonly to secure fans, rotor cores and couplings to the shaft. All of these cause stress risers. However, the keyway on the take-off end or drive end of the shaft is the one of most concern because it is located in the region of highest shaft loading. When this loading has a high torsional component, fatigue cracks may start in the fillets or roots of the keyway.

Keyways that end with a sharp step have a higher level of stress concentration than those that use a "sled-runner" type of keyway. In the case of heavy shaft loading, cracks frequently emanate at this sharp step. It is important to have an adequate radius on the inside corners of the keyway. Loosely-fitted keys can cause fretting that may accelerate shaft failures. (See Figure 11.)

Figure 12 shows a cracked journal on the rotor core keyway that carries the rotor laminations. This particular problem was detected by vibration analysis. A visual inspection would only have revealed this condition if the shaft was removed from the rotor core. The crack originated in the high stress area of the keyway. If the crack had not been detected, the failure of the shaft would have been catastrophic.

FIGURE 11: COMMON KEYWAY FAILURES



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

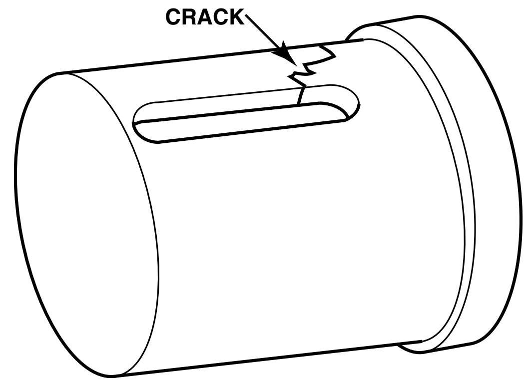
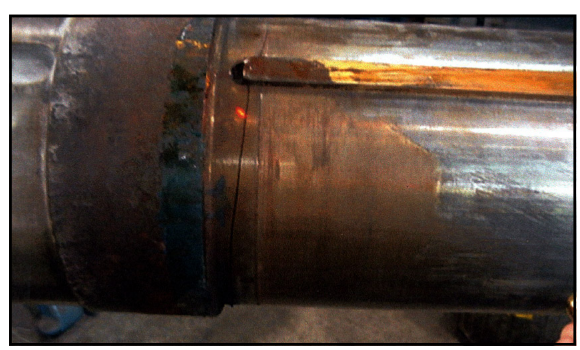


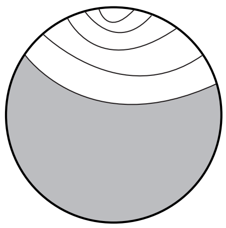
FIGURE 12: CRACKED ROTOR CORE KEYWAY



This cracked journal carries the rotor lamination and was detected through vibration analysis. A different type of keyway with a reduced stress riser may have prevented this failure from happening.

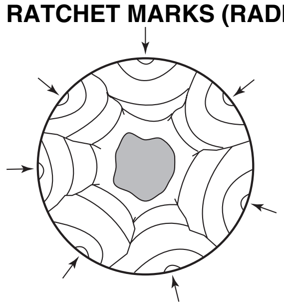
FIGURE 13: APPEARANCE OF THE MOST COMMON SHAFT FAILURES

BEACH MARKS (CLAMSHELL, CONCHOIDAL)



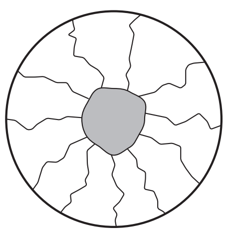
Beach marks indicate successive positions of the advancing crack front. The marks are usually smooth textured near the origin and become rougher as the crack grows.

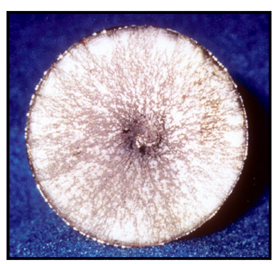
RATCHET MARKS (RADIAL STEPS)



Ratchet marks are the telltale sign of several individual cracks that ultimately merge to form a single crack. Ratchet marks are present between the crack origins.

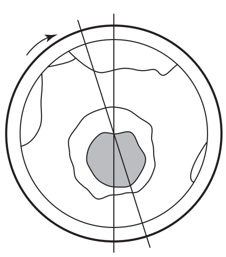
CHEVRON MARKS

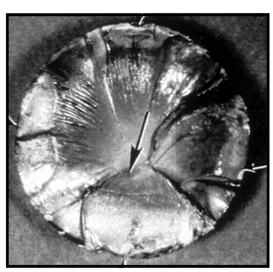




Chevrons, or arrows, point to the origin of the crack. Some failures (like the one shown below under torsional) will have more pronounced chevrons. The more brittle the fracture, the smaller the end point of failure.

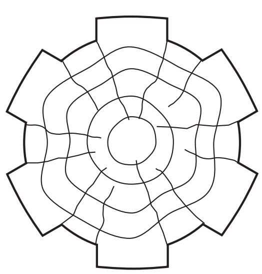
ROTATIONAL BENDING

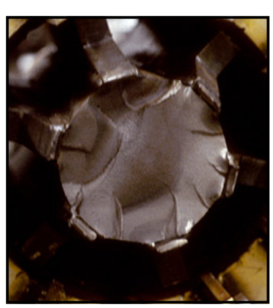




Rotational bending fatigue failures occur when each part of the shaft is subject to alternating compression and tension under load. A crack can start at any point on the surface where there is a stress riser, and may grow unevenly because of the rotation. This particular shaft has several points of initiation as indicated by the ratchet marks on the perimeter.

TORSIONAL





Torsional failures are identified by the "twisted" appearance on the shaft However, depending on the amount of torsional loading and whether the material is ductile or brittle, the failure may appear differently. This particular shaft shows some amount of twisting before failure. The stress risers on the shaft were at the points the spiders were welded. If the shaft material is ductile, it will show more twisting before failure; if the shaft is more brittle, or subject to extreme torsion, the fracture will have a rougher appearance.

DYNAMIC AND MECHANICAL STRESSES

Dynamic or mechanical stresses have to do with movement. Since the shaft is one of the moving parts of the motor, it is more susceptible to damage or failure when subject to dynamic and mechanical stresses. These stresses include:

- Overloads, including sudden shock loads.
- Cyclic loads.
- Overhung loads and rotational bending.
- Torsional loads.
- Axial loads.

Dynamic and mechanical stresses are normally caused by forces that are external to the motor itself, specifically the load. Shafts can bend or break if the load causes a stress that exceeds the yield strength of the shaft material.

OVERLOADS

All materials have a limit to the amount of load they can carry. When a shaft fails due to a single application of a load that is greater than the maximum strength of the material, it is considered an overload failure. This will usually happen almost immediately.

This type of failure can be ductile or brittle. Brittle fractures look like they could be glued back together. There are also "chevron marks" on the face of a brittle fracture that show the progression of the failure across the piece. The chevron "arrows" always point to the place where the crack started.

A severe shock load, even on ductile material, can cause it to break like a brittle material. The appearance of a failure, whether ductile or brittle, depends on a number of different factors including the shaft material, the type and magnitude of the load, and the temperature of the shaft when it failed.

CYCLIC LOADS

Fatigue cycle life is affected by the type of load on the motor. The fatigue cycle can be described as one cycle of the load. Therefore, if it is a variable torque load, each start will represent one fatigue cycle. A reciprocal or cyclical load will fatigue cycle every time the load changes. When the shaft is subject to rotational bending, the fatigue cycle will be once every revolution.

With the presence of a stress riser, a cyclic load will only speed up the failure process when the shaft is subjected to heavy loads. In the case of a shock load, or sudden overload, the shaft may snap and appear as a brittle failure. (See Table 4.)

OVERHUNG LOAD AND ROTATIONAL BENDING

Bending fatigue, due to overhung loads or heavy radial loads (such as a large pulley), can cause the shaft to bend or rub. Most "bending" failures are considered rotational, since the shaft is subject to alternating tensile and compressive stress at every point around its diameter every time it makes a revolution. Each rotation is a fatigue cycle, so shaft speed will be a factor in the fatigue cycle life. If the shaft is exposed first to tension and then compression, a crack can start anywhere on the surface, and more than one crack can form. As the crack progresses across the face, it will grow unevenly.

FIGURE 14: SPALLING ON A BEARING RACEWAY

The condition of the bearing can be a clue to the type and direction of loading on the shaft. This illustrates how excessive load can cause spalling on the bearing raceway. Spalling will normally occur as the bearing fails; however, the time to failure can be accelerated with an increase in load.

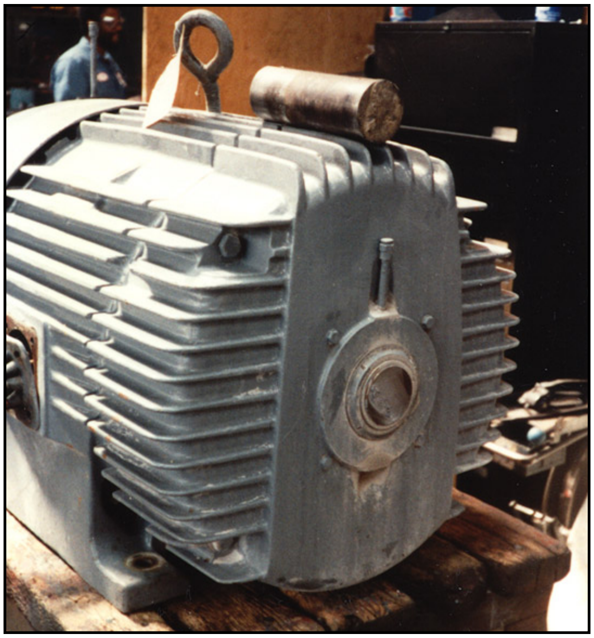
AXIAL LOAD

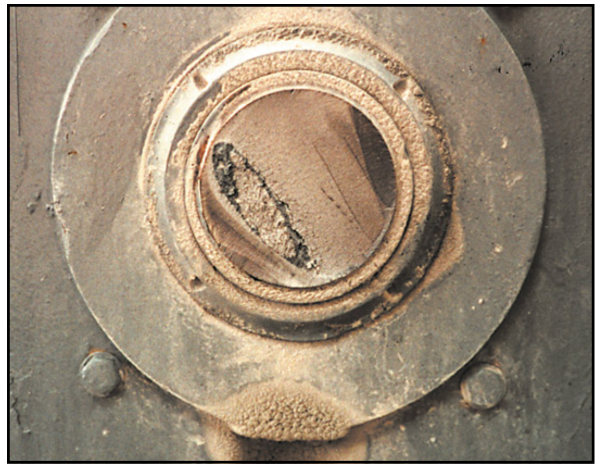
Axial fatigue is commonly associated with vertical shaft mounting, but also may describe a substantial thrust load. Typically, the bearing carrying the axial load will fatigue before the shaft. This is usually evidenced by spalling of the bearing raceways (Figure 14).

TORSIONAL LOAD

Torsional fatigue is associated with the amount of shaft torque present and transmitted load. Torsional loads describe the "twisting" load of a shaft transmitting torque. The more cyclical the load, the sooner this will lead to failure.

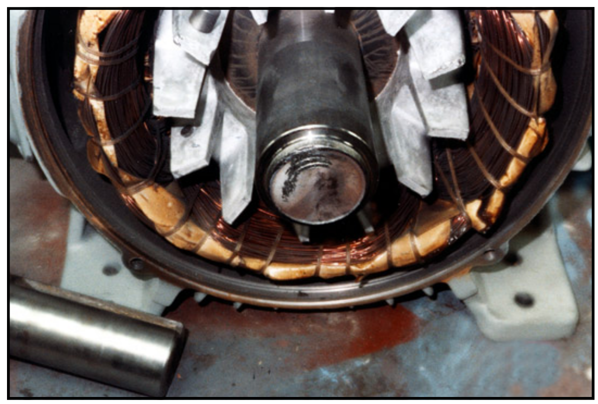
DYNAMIC AND MECHANICAL STRESSES

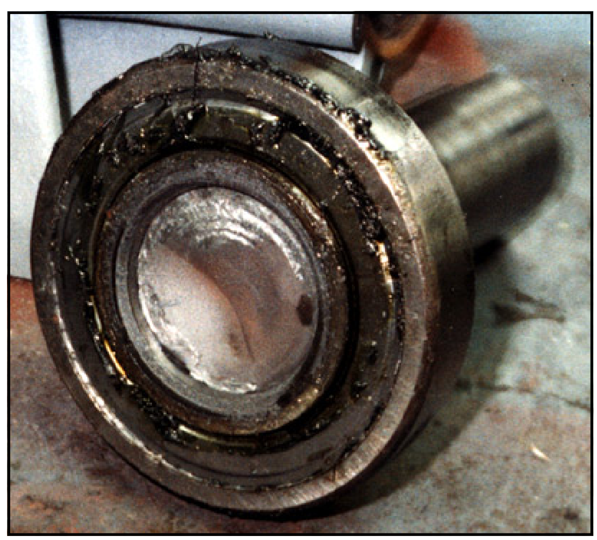




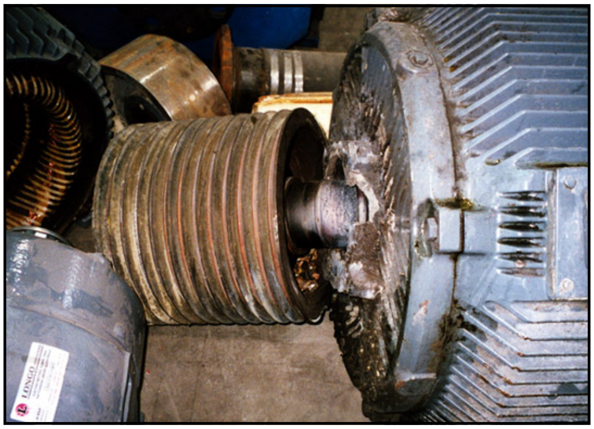
These are all examples of rotational bending. Each example clearly shows one or more points of origination, along with a region of growth before the ultimate failure of the shaft. Each failure occurred at a change in geometry of the shaft, which is a significant stress riser.

Note the ratchet marks (below) and the successive changes in shaft diameter (above).

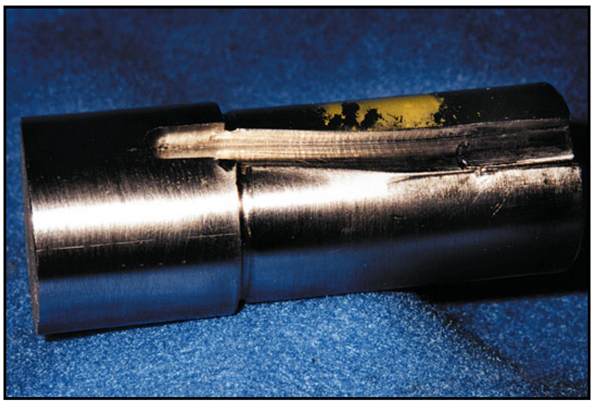




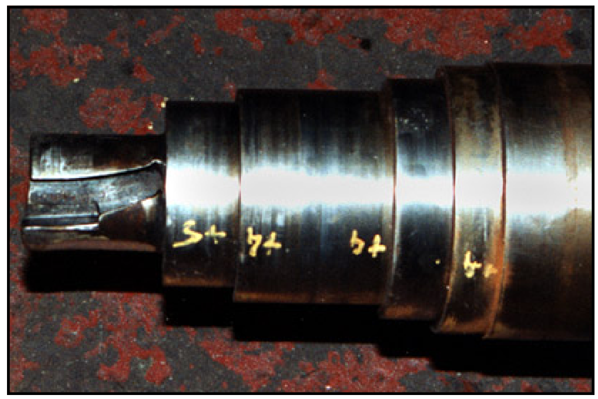
DYNAMIC AND MECHANICAL STRESSES



This failure was caused by a loss of running clearance between the shaft and bracket. There are a number of possible root causes to this failure including heavy overhung load, improper lubrication practices, excessive vibration, misalignment, or excessive thermal stress.



The keyway on this shaft extends too far back, past the step. Note the torsional bending.



This shaft failed due to torsional bending. The “heads-up” service center marked the shaft as they checked for runout along each step, since there could be twisting further along the shaft.

This fatigue crack began at the high stress riser at the keyway.

ENVIRONMENTAL STRESS

Environmental stress results from materials in the environment, whether chemical or moisture. These substances can attack the surface of the shaft to cause corrosion, abrasion and wear. Each pit or eroded area becomes a stress riser. The additional stress risers can speed up the fatigue process.

Environmental stress includes:

- Moisture.
- Erosion.
- Wear.
- Corrosion.
- Cavitation.

There are certain shaft materials that can resist the effects of chemicals, but their use requires careful consideration, since the strength of the shaft may be reduced.

The appearance of a shaft damaged by environmental factors is easy to identify. The presence of moisture might appear as rust. Abrasion, corrosion and wear will remove material from the shaft surfaces.

CORROSION FAILURES

In corrosion failures, the stress is the environment and the reaction it has on the shaft material. Corrosion occurs when the surface of the shaft comes into contact with chemicals or moisture in the environment. It usually appears as oxidation or pitting of the shaft surface.

At the core of this problem is an electrochemical reaction that weakens the shaft. Pitting is one of the most common types of corrosion, which is usually confined to a number of small cavities on the shaft surface. Corrosion will cause a loss of material on the shaft. Even a small amount of material loss can result in perforation, with a resulting failure in a relatively short period of time without any advanced warning. On occasion, the pitting has caused stress risers that result in fatigue cracks.

When a motor is in an environment where corrosion is possibile, the use of a stainless steel shaft can prevent damage. However, stainless steel has a lower yield strength and fatigue cycle life than a typical carbon steel. As a note, if a stainless steel shaft is replaced, confirm whether the shaft is magnetic or non-magnetic stainless steel, since in rare cases the shaft material contributes to the rotor flux. If it is not properly replaced, failures can occur.

Corrosion can reduce the fatigue life of a shaft and can cause failure at lighter loads than expected. This is referred to as corrosion-induced fatigue.

CAVITATION

In pumping applications where the flow of liquid over the shaft is turbulent, a phenomena known as cavitation can occur. Cavities, bubbles or voids are created in the fluid for short durations. As they collapse, they produce shock waves that erode the shaft surface. The shaft can be weakened and fail prematurely. A common approach to minimizing this condition is to use a stainless steel shaft, which has a much enhanced abrasion resistance and wear quality. There are also some elastomeric coatings that increase resistance to erosion.

SHAFT FRETTING

Shaft fretting can cause serious damage to the shaft and a mating part. The cause of this condition is movement between two mating parts and the presence of oxygen in air.

Fretting occurs where two surfaces are in loose contact with each other. Typical locations are points on the shaft where a “press” or “slip” fit should exist. Keyed hubs, bearings, couplings, shaft sleeves and splines are examples.

These parts normally have an interference fit and are suseptible to very slight vibration which can cause some movement between the parts. When this happens, microscopic particles wear away from the points of contact. The particles are so small that they oxidize in air immediately. The presence of ferric oxide (rust), which is reddish-brown in color, between the mating surfaces is strong confirmation that fretting did occur. The oxide particles act as an abrasive, accelerating the rate of wear on the shaft surface.

Damage to the shaft can also occur when pulleys and couplings are not properly fitted.

ENVIRONMENTAL STRESS

This close-coupled pump shaft shows considerable damage from corrosion. The formation of rust will reduce the fatigue life.

ENVIRONMENTAL STRESS

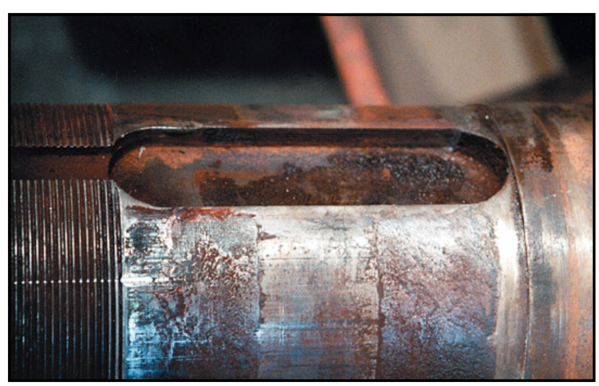
Contamination from moisture or chemicals trapped in the coupling arrangement eroded the surface of the shaft.

Severe rust has formed on the inside surfaces of this motor.

This pump shaft has been damaged by severe cavitation.

This is an example of severe corrosion on the shaft, due to seal failure. This allowed water to enter into the motor.

This is a pump shaft with considerable rust damage.



Corrosion has damaged the keyway of this shaft. The keyway is already a stress riser. If the key is at all loose, from material being worn away, the key may grind away at the surface causing more damage.

THERMAL STRESSES

When a motor is in service, it is usually under thermal stress. Thermal stress can bend and/or discolor the shaft.

Increases in temperature cause the shaft to expand. Large variations in temperature cause the rotor and shaft to alternately grow and contract. In extreme cases of overheating, the rotor can bow causing the rotor or shaft to strike the stator winding or bore.

There may be other situations can cause the shaft temperature to heat to a point where either it bends or changes the internal structure of the steel, thus altering its strength.

Situations that can contribute to thermal stress on the shaft can include:

- Ventilation failure.
- Overload.
- Bearing failure.
- Loss of clearance.
- Stall.

In the cases listed above, the shaft may not be the weak link. However, it may be weakened or bent. If the shaft is not straightened or stress relieved, more failures could occur. If not done properly, some processes, such as welding, can thermally stress a shaft as well.

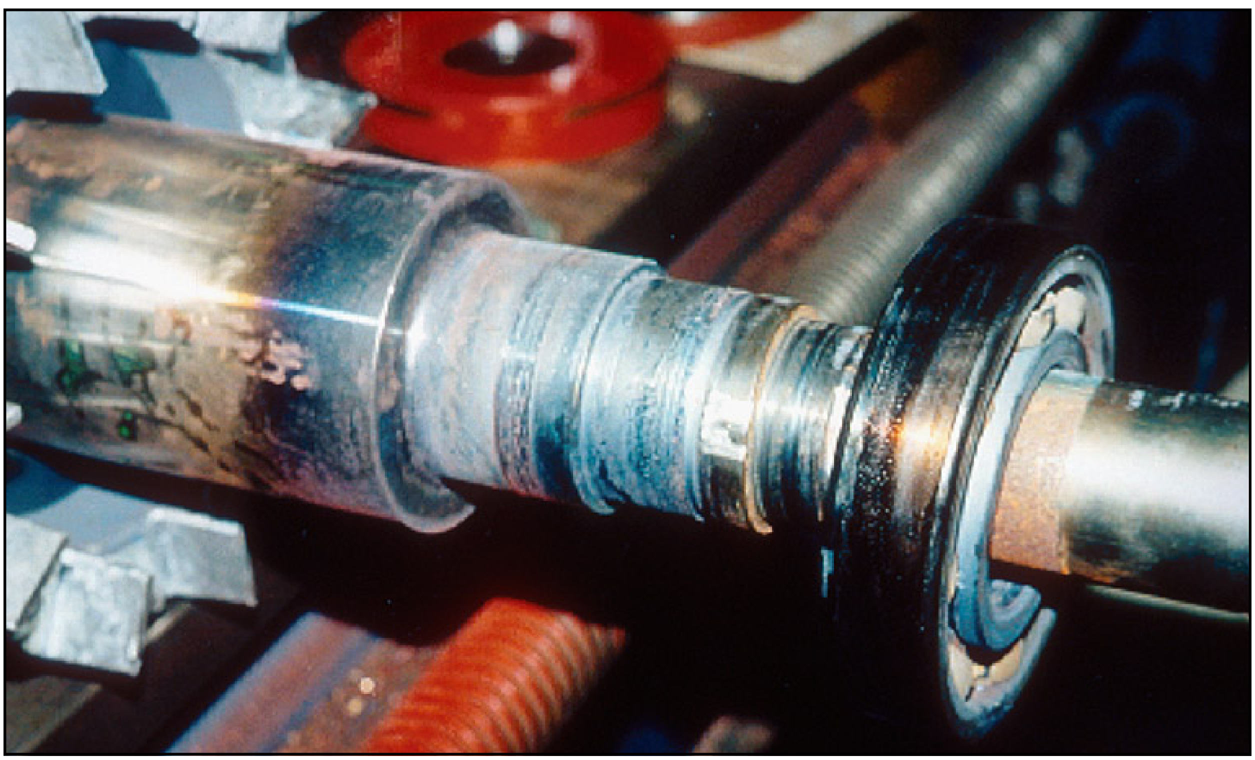
Loss of running fits between the shaft and other parts such as end brackets, shaft seals or bearing caps, can cause the temperature of the shaft to increase. This type of shaft failure is often catastrophic and can result in severe damage to the bearing, rotor and stator. The driven equipment may also be severely damaged.

If the motor continues to operate after this occurs, a tremendous amount of heat is generated at the point of contact.

Note that the motor shaft actually bends before the shaft temperature reaches the melting point.

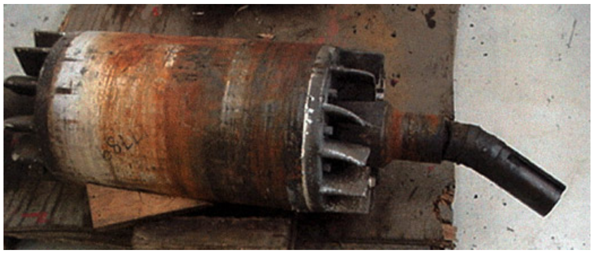
The motor over-current protection may not sense this condition. This is because the controls are usually set to trip at 125% current overload. Unfortunately, many motors operate at less than full load, but the overload protection may be sized assuming it runs fully loaded. If the bearings or shaft are heating up and failing, the current will not rise to the point where it would be taken off line, and a catastrophic failure may occur. The friction that causes the shaft to bend causes a loss of clearance. The loss of clearance will increase the load, which will in turn increase the current. If the motor is not fully loaded, then the increase in current may not trip the over-current protection. However, vibration sensors or bearing temperature detectors (if present!) will usually shut down the motor before a catastrophic failure occurs. These catastrophic failures simply illustrate the importance of a simple bearing resistance temperature detector (RTD).

THERMAL STRESS

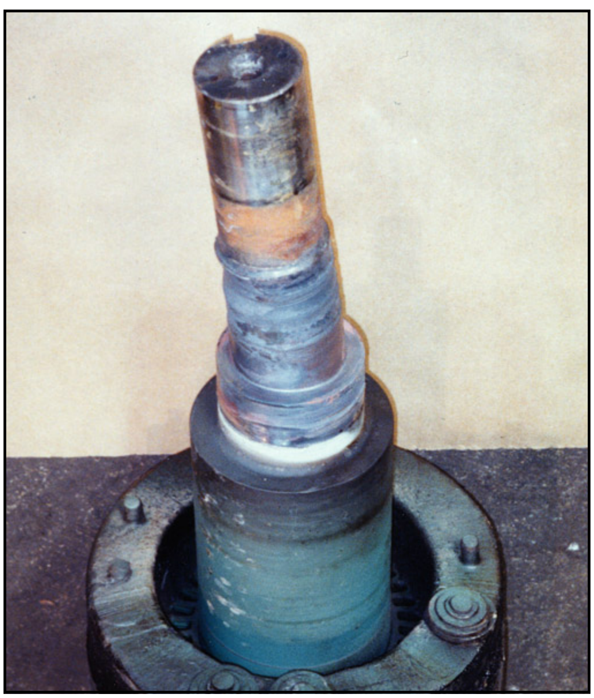


There was an enormous amount of heat generated between the bearing inner race and the shaft due to a loss of fit. The evidence that the heat originated on the shaft is that as the heat progressed inward, it was hit with cooling air from the rotor fan. The area of the shaft that was cooled by the air does not have as much damage from the heat.

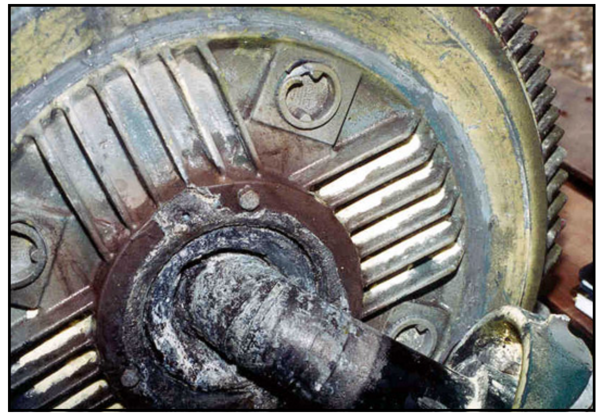
THERMAL STRESS



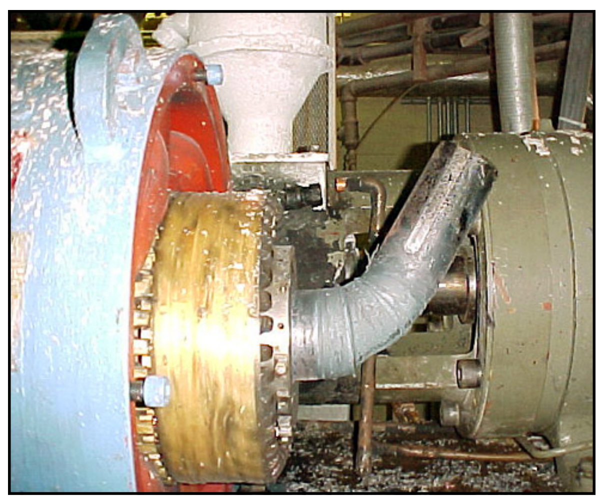
Either misalignment or vibration caused the bearing to fail which led to a loss of fit between the bearing inner race and the shaft. This generated an enormous amount of heat, bending the shaft.



Diligence and protection mean the difference between minor damage and this type of failure.



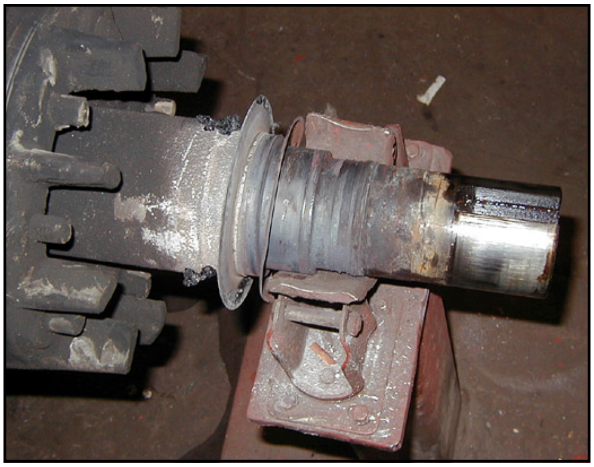
This shaft failure began when the bearing failed and led to a loss of fit on the shaft. The resulting friction caused the shaft to heat up very rapidly and bend almost 90°.

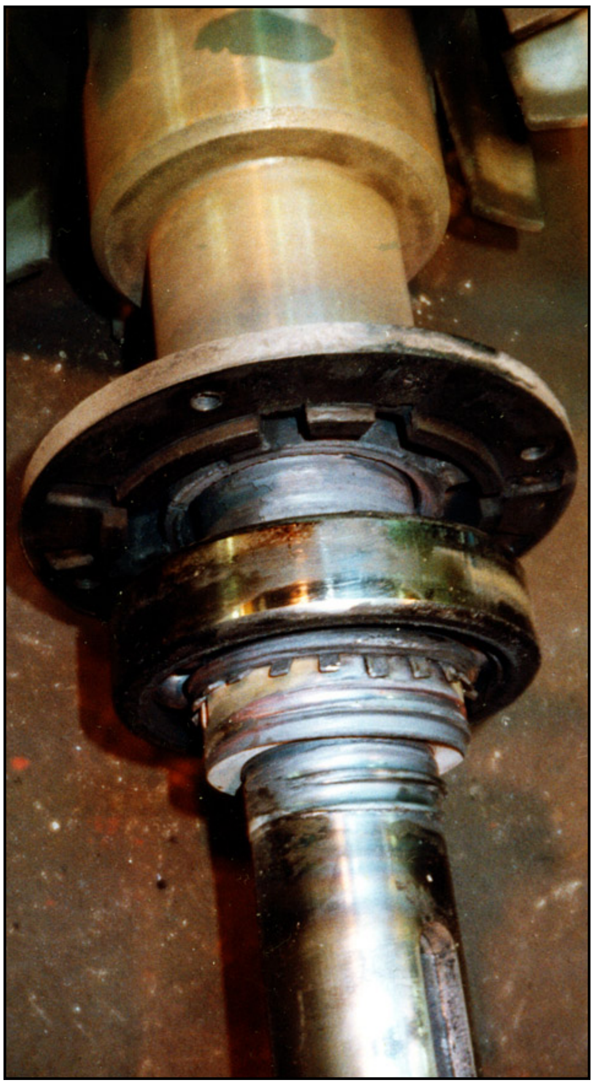


In this example, the bearing failed and disintegrated. This generated a tremendous amount of heat in the shaft, bearings, and end bracket. Due to the catastrophic nature of these types of failures, it can be difficult to determine the actual root cause of failure.

THERMAL STRESS

In all of these examples, extreme heat was generated between the stationary and moving parts of the shaft assembly. In each case, the shaft had extreme runout.





This shaft failed due to loss of clearance. The severe gouging/scoring on the shaft generated a tremendous amount of heat from the contact between the stationary and rotating parts.

RESIDUAL STRESS

Residual stress is independent of the external loading on the shaft. There are many manufacturing and repair procedures that can create residual stress in the shaft which may accelerate failure. These procedures can be mechanical or thermal. Mechanical procedures include:

- Drawing.
- Bending.
- Straightening.
- Machining.
- Surface rolling.
- Shot blasting or peening.
- Undercutting.
- Metallizing.

All of these operations can produce residual stresses. In addition to the above mechanical processes, thermal processes that introduce residual stress include:

- Hot rolling.
- Welding.
- Torch cutting.
- Heat treating.

Not all residual stress is detrimental to the shaft. If the stress is parallel to the load stress and in an opposite direction, it may actually be beneficial. Stress relieving will reduce the residual stresses.

SURFACE FINISH EFFECTS

In most applications, the maximum shaft stress occurs on the surface. Hence, the surface finish can have a significant impact on fatigue life. During the manufacturing process, handling and repairs, it is important not to perform operations that would result in a rougher shaft finish. The impact of surface finish on fatigue cycle life can be seen in Table 4.

SURFACE COATING

Shafts repaired by welding are beyond the scope of this paper. However, caution must be used in this process. The selection of the proper weld material, method of application, stress relieving, surface finish and diameter transitions are all critical to a successful repair. Not all shaft materials are good candidates for welding-type repairs as shown in Table 5.

The Metals Handbook Volume 10 provides additional information on this subject.

TABLE 4: IMPACT OF SURFACE FINISHES

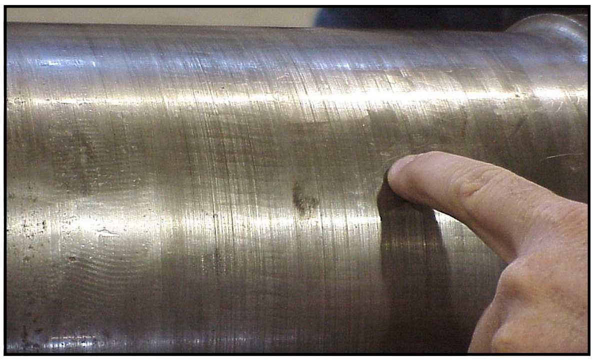
Finishing operation	Surface finish (μ in.)	Fatigue life (cycles)
Lathe	105	24,000
Partly hand polished	6	91,000
Hand polished	5	137,000
Ground	7	217,000
Ground and polished	2	234,000

Colangelo, V.J. and Heiser, F.A. *"Analysis of Metallurgical Failures*." John Wiley & Sons, 1974.

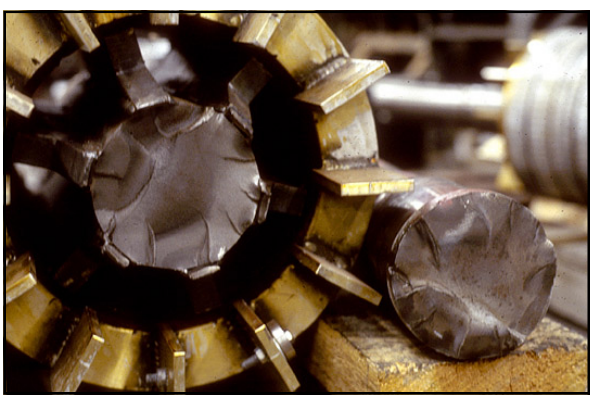
TABLE 5: COMMON SHAFT MATERIALS

Grade	Material	Comments
C10xx	Plain carbon steel (e.g., 1018, 1045, etc.)	Standard motors with normal torque up to 500 hp. Can be welded successfully (e.g., shafts with spiders).
C41xx	Chrome molybdenum steel (e.g., 4140, 4150)	High strength. Used for crusher-duty applications; propeller shafts; transmission shafts. Do not weld this material.
C1144	Resulfurized steel	Higher strength than C4150. Can be welded successfully.
C4340	Nickel chrome molybdenum	Annealed; higher strength than C1144; heavy duty. Do not weld this material.
17-4PH	Magnetic stainless (e.g., 400 series)	Use this material for explosion-proof motors that require magnetic shaft properties.

RESIDUAL STRESS



The shaft journals above were both welded. The shaft at bottom has also been machined. Axial passes with a stick welder are more likely to bend the shaft. Varying hardness is also more likely, resulting in a bearing journal that is not perfectly round. Irregularities will increase friction and cause difficulty when fitting the bearing. Machining processes will release some of the residual stresses caused by welding. For example, milling a keyway will usually result in a bent shaft, unless the shaft is properly stress relieved after welding and before machining.



This is a fabricated rotor with a spider shaft. The points where the spider was welded to the shaft introduced stress risers in the same plane, eventually causing the rotational bending failure.

The photograph at top shows a crack that occured at the keyway. In the photograph below, a crack repaired by welding. The welding process can introduce residual stresses into the shaft, thereby making the repair futile.

The crack on this shaft was detected with a dye penetrant.

ELECTROMAGNETIC STRESS

Although not specifically a shaft issue, there are nonetheless electromagnetic forces that act on the shaft. When the air gap is not symmetrical, electromagnetic force acts on the rotor to pull it closer to the stator. The smaller the gap becomes, the stronger the force. Eventually, the rotor may come into contact with the stator.

The distinction should be made between rotor pullover and electromagnetic forces of an eccentric air gap, and a rotor strike or rub due to a heavy radial load (belted, chained, etc.) that causes the shaft to deflect.

Electromagnetic stress acting on the shaft will not likely cause permanent deformation, since the force of the pullover won't be greater than the yield strength of the shaft. The shaft is typically designed with sufficient stiffness to resist bending under normal conditions. However, if a rotor strike occurs, it is often difficult to find a problem with the shaft.

Since the deformation of the shaft is not permanent, the original geometry is restored after the rub. Since rotor pullover is technically a rotor issue, it is not covered in great detail here. Rather, refer to Section 5 for additional information. Table 6 is provided as a reference to determine possible causes of a rotor strike based on the appearance of the rotor and stator laminations. Some of the causes are shaft related, while others are rotor or bearing related.

There are a few other situations that can introduce electromagnetic stresses on the shaft. These include ex-

TABLE 6: COMMON CAUSES OF ROTOR STRIKES BASED ON POINTS OF CONTACT

		Stator		
	Contact area	**One point**	**Random**	**360°**
Rotor	**360°**	• Excessive radial load on the shaft. • Failed bearing plus radial load. • Eccentric air gap. • Bearing housing machined off center.		• Failed bearing with direct-coupled load. • Broken shaft. • Severely-worn bearing fit (shaft or housing).
	Random	2	Strictly rotor pullover during starting. The shaft stiffness is not enough to resist magnetic forces during starting. 1, 3, 4	
	One point	Eccentric rotor and the shaft rotational axis is not concentric to the stator bore. 2	2	• Eccentric rotor. • Bent shaft. • Bearing journal is not concentric to the rotor.

1 Although not common, inspect for a loose stator core.

2 If anything in the motor history indicates that the problem started suddenly, look for either high line voltage or a cracked shaft within the rotor core.

3 If the motor is a 2 pole, it could be operating at excessive voltage. Check for recent transformer tap changes, etc.

4 Prolonged operation of a motor with random stator-to-rotor contact could eventually result in an appearance of 360° contact on both parts.

Note: Severe bearing failure could result in any of the above combinations.

Vertical machines with thrust bearings: Momentary upthrust can result in random 360° contact of the rotor and stator on the thrust bearing end only.

Detection methods
- Noise at starting (rotor slap).
- Vibration during starting, at multiple random frequencies.
- Check for flexing shaft using a vibration analyzer with a strobe light.

cessive radial loading and out-of-phase reclosing. Another situation that can cause a shaft to fail, although uncommon, would be overcorrection of power factor. Overcorrection can cause transient torques that can break shafts.

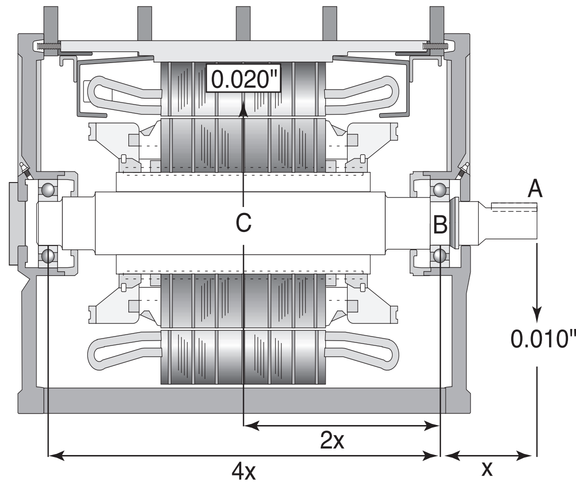
EXCESSIVE RADIAL LOAD

If there is a very heavy radial load on a shaft, it can cause a change in the air gap geometry that can lead to a rotor rub and/or a bent shaft. This is especially true if the radial load is heavy and the shaft extension is very long. This is illustrated in Figure 15. If the length of the shaft extension is x, and the distance between bearings is 4x, then if we apply a force at the end of the shaft, A, the drive end bearing at B is the fulcrum, causing maximum deflection of the shaft at C, the center point between the bearings.

OUT-OF-PHASE RECLOSING

A reclosure is most simply stated as a high voltage transient. Although the stator winding is most likely to fail, the voltage transient can create a tremendous amount of torque on the shaft. It is important to realize that the current is related to the square of the voltage. Therefore, the higher the voltage associated with the reclosure, the higher the current, and the higher the torque that is generated. If the force is great enough, the shaft can snap due to the torsional stress.

FIGURE 15: RADIAL LOADING



If the radial load on the shaft at Point A causes the shaft to bend by 0.010", then Point B acts as the fulcrum, and the defelction at Point C is 0.020".

ELECTROMAGNETIC STRESS

When a motor is subjected to a transient voltage, a very high amount of torque is generated. Shaft failures such as these shown can occur in cases such as a rapid bus transfers, lightning strikes, or out-of-phase reclosures. The torsional stress on the shaft can cause it to snap. The failure will be almost immediate, and the fracture will appear very brittle.

OTHER SHAFT PROBLEMS

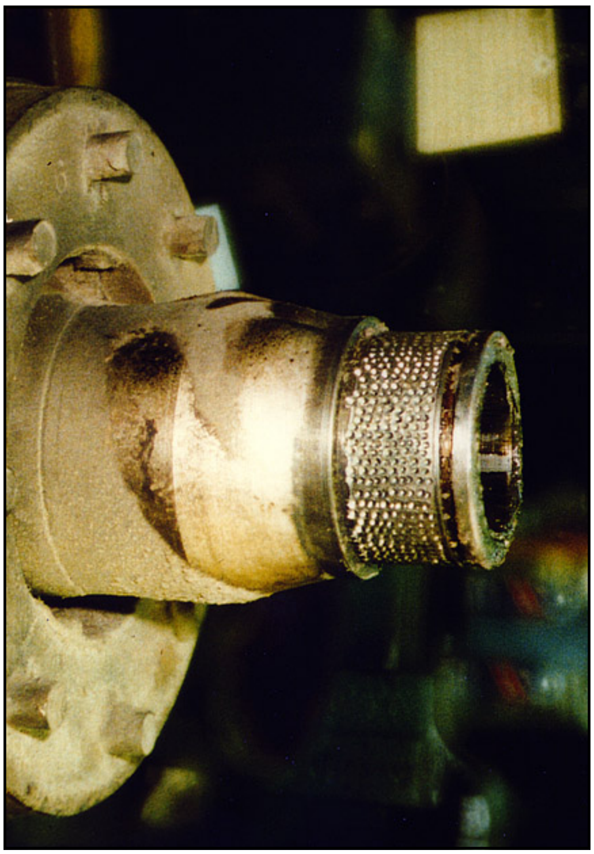
There is a broad category of shaft failures or motor failures that do not result in the shaft breaking. The following is a list of the more common causes. Stress failures caught in the early stages would also fit into this category.

Most of these anomalies are the result of incorrect manufacturing or poor workmanship. These include:

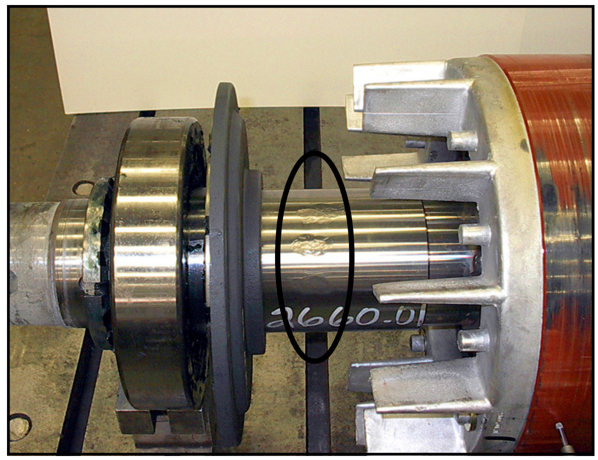
- Bending or deflection causing interference with stationary parts.
- Improper machining causing interference, runout or incorrect fits. This would also include a shaft that has too long a bearing shoulder-to-bearing shoulder distance, not allowing room for thermal growth and preloading the bearings.
- Material problems which would include inclusions or the wrong strength of material for the applicaiton.
- Excessive vibration caused by electrical or mechanical imbalance.
- Bent shaft.
- Magnetic vs. non-magnetic shaft materials. A magnetic shaft will contribute to the flux. If the shaft is improperly replaced with non-magnetic steel, the magnetizing current will increase.

Catastrophic bearing failures may cause serious shaft damage, even if the result is not fracture.

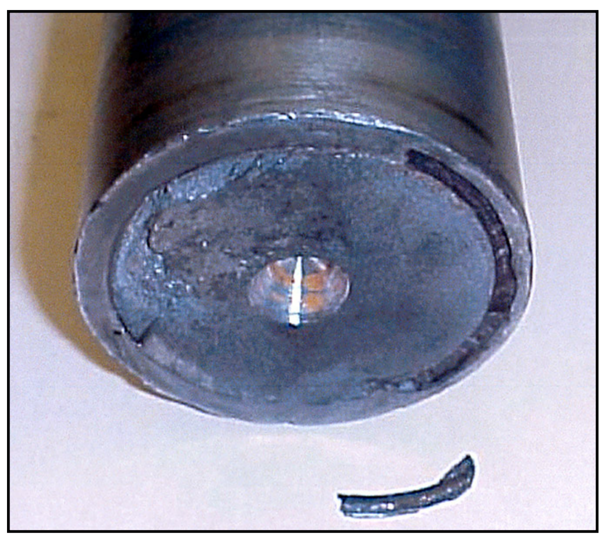
OTHER SHAFT PROBLEMS



This was a desperate attempt to temporarily restore a bearing fit on a vertical hollow shaft pump motor by prick punching. Each point represents a stress riser; however, the real danger is that the bearing will not have full contact with the shaft journal. When it was put back into service, the bearing lost its fit resulting in high vibration and temperature.



This shaft was peened in an attempt to correct a bend. However, during operation it returned to its original shape.



The snap ring groove was cut too deep and developed an unacceptable stress riser.