Hydrodynamic Bearing Damage and Remediation of Contributing Factors in Rotating Machinery
Titre de la présentation

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Causes of bearing damage have been identified, and remediation efforts have been successful in many turbomachinery applications. However, bearings continue to suffer damage from a variety of sources, such as abrasives, static and dynamic overload, insufficient lubrication, loss of clearance, cavitation, electric discharge, misalignment and high start-up loads. Methods to diagnose the different types of bearing damage in rotating machinery are presented as well as recommended techniques to remedy these. Damage of babbitted bearings will be the primary focus of the analyses because babbitt is the most widely used tilting pad thrust and journal bearing material. However, the discussion will also address the type of damage observed where engineered polymers and ceramic form the bearing surfaces.

Les causes d'avaries dans les paliers ont étés identifiées et les efforts pour y remédier ont étés fructueux dans la plupart des applications de machines tournantes. Malgré tout, les paliers continuent à subir des avaries de toutes natures, comme les surcharges abrasives, statiques et dynamiques, le manque de lubrification, la réduction du jeu de fonctionnement, la cavitation, les passages de courant, le mésalignement et les démarrages sous forte charge. Des méthodes de diagnostic de ces différentes avaries de paliers de machines tournantes sont présentées, ainsi que les techniques recommandées afin d'y remédier. Les avaries de paliers régulés bénéficieront de l'attention la plus grande puisque les métaux blancs sont les matériaux les plus utilisés dans les paliers et les butées à patins oscillants. Toutefois, les discussions concerneront également les avaries constatées dans les paliers où les surfaces sont constituées de matériaux polymères et céramiques.

1 Introduction

Strides have been made to improve the reliability of turbomachinery through improved bearing designs and materials. Identification of bearing problems and the subsequent incorporation of problem solutions into bearing designs have contributed to the improvement in turbomachinery reliability. For example, delamination of babbitt from copper backed pad material is no longer an issue due to the identification of the cause and the subsequent fix to this problem. Unfortunately, for a variety of reasons bearing damage still occurs in turbomachinery. Common causes of damage to tilt pad thrust and journal bearings that lead to reduced machine reliability that still occur are scoring due to abrasives, overload and overheating, lack or loss of lubricant, loss of clearance, cavitation, electrical discharge, misalignment, and high loads at start-up/shut down.

Furthermore, as more applications utilize process fluids for lubrication and operate under adverse conditions, alternate materials, such as engineered polymers and ceramics, are being used for bearing surfaces. These materials can also suffer damage in ways similar to babbitted bearings. In particular, lack of lubrication, overload and loss of clearance have resulted in damaged to polymer lined bearings. For ceramic bearings, excessive load have resulted in damage to the bearing surfaces.

This paper discusses the causes of different forms of bearing damage and the actions that can be taken to avoid such occurrences in order to improve the reliability of turbomachinery by reducing the potential for bearing damage. As with any diagnostic approach, operating history of the machinery is often invaluable in diagnosing the problem.

2 Scoring due to Abrasives

Ingestion of foreign matter or 'dirt' into turbomachinery bearings is a common source of damage to both thrust and journal bearings in all types of turbomachinery. Dirt may be present at start-up if the housings, shafts, lubrication path and bearing aren't properly prepared prior to assembling and starting the machine. Also, dirt may enter the bearing through the lubrication supply that has been contaminated from outside sources through breathers and air filters or from wear particles of other components during operation. The 'tracks' from abrasive particles at start-up when the speed is slow are irregular, and the particles may appear to have rolled through the bearing surface. Figure 1 is photograph of a thrust pad that was damaged by dirt during start-up. If the particles enter the bearing during operation when speeds are higher, the damage in the bearing surface is more likely to follow consistent patterns, such as concentric tracks in a thrust pad, as shown in Figure 2. Visual inspection and metallurgical study of the particle can be used to identify the source of the contamination, such as worn shaft material for example.

Fig 1. Abrasive Damage due to Foreign Material at Start-Up.

Fig 2. Abrasive Damage due to Foreign Material During Operation.

One of the benefits of using a soft bearing material such as babbitt, also known as whitemetal, is its capability to embed material in the bearing surface. At the end of a particle track, the particle will embed itself in the babbitt, resulting in haloes or raised regions around the embedded particle, as shown in Figure 3. Polymer lined pads also have the capability to embed material. A polymer thrust bearing with metallic particles embedded into it is shown in Figure 4.

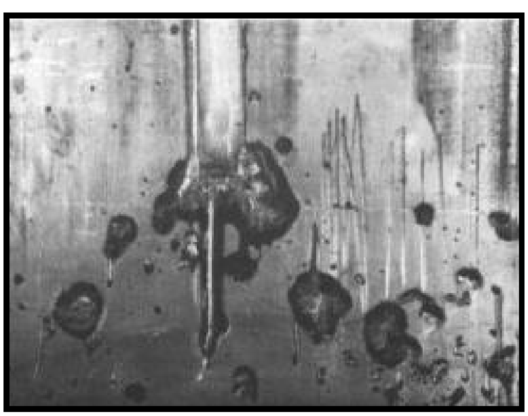

Fig 3. 'Haloes' From Embedded Particle.

Fig 4. Polymer Lined Thrust Bearing with Showing Embedded Metallic Debris

Light scoring (small and infrequent scratches) does not cause a significant degradation in performance; pads should be cleaned up. If the bearing shows signs of heavy scoring, the damage may compromise performance and may damage the shaft or collar. Bearings that are heavily scored should be replaced or repaired. In either case, the lubrication system should be cleaned.

One type of abrasive wear that causes severe damage to babbitt lined bearings and to shafts is 'wire wooling'. Wire wooling occurs when a relatively large particle is embedded in the babbitt. The particle may react with the shaft material and form a hard deposit, commonly known as 'black scab' on the pad. The hard deposit then causes severe damage to the mating surface by acting like a cutting tool; this machining then self-propagates to the point that the shaft and the bearing are inoperable. Figure 5 shows a shaft with wire wooling damage from a journal bearing. A thrust pad with 'black scab' damage is shown in Figure 6. Shafts and collars containing more than 1.3% chromium are susceptible to 'wire wooling' damage. Also, certain oil additive packages have been shown to increase the chances of wire wooling. Adding a low alloy steel sleeve to the shaft or chrome plating the shaft or collar will reduce the likelihood of wire wool damage to a steel with a significant amount of chromium (such as a stainless steel).

Thoroughly cleaning the system prior to start-up and maintaining a clean lubricant supply is necessary to reduce the likelihood of damage from abrasives. If the amount of abrasive entering the bearing cannot be limited, for example in a process lubricated application, a ceramic bearing (commonly monolithic silicon carbide) can be used as a means to handle the abrasives. An example of a set of ceramic thrust and journal bearings for a water-injection pump is shown in Figure 7. The extremely hard material will 'grind' abrasives without any scoring of the bearing surfaces.

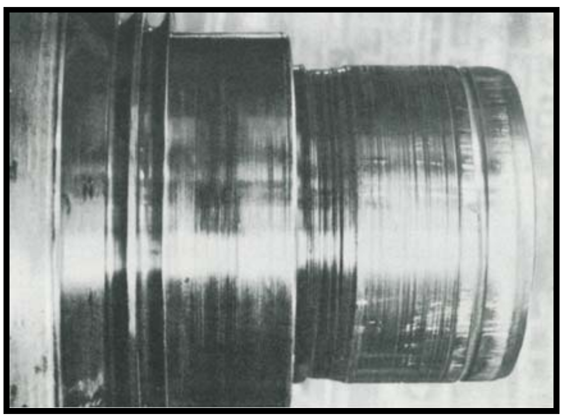

Fig 5. Wire Wooling of Shaft.

Fig 6. Black Scab on Thrust Pad.

Fig 7. Ceramic Bearings from a Seawater Injection Pump.

3 Overload

Hydrodynamic bearings rely on a thin film of lubricant to separate the rotating shaft or collar from the stationary bearing. When the load exceeds the capability of the film to support the load, the rotating and stationary components contact each either. The contact leads to an increase in the temperature of the bearing lining that can lead to smearing or even localized melting of the bearing lining. Babbitt is selected as a bearing material because it is compatible (non-galling) with many metals and it has the capability to conform to the shaft, thus the babbitt wipes instead of seizing on the shaft. Light polishing or wiping of the babbitt surface indicates that the material has performed as needed. However, severe damage to the bearing will result if the overload is not reduced. A tilt pad thrust bearing that has been wiped due to an overload is shown Figure 8. Babbitt has been displaced from one area to another in the direction of rotation. Metallurgical analysis typically reveals a change in grain structure in the damaged layer from the base material.

Polymer bearings, like babbitt lined bearings, have good bearing properties but can also be over-loaded and wear due to the contact between the bearing and the journal or collar. Figure 9 shows a thrust pad that has been lightly overloaded resulting in melting of the polymer and the characteristic formation of a fibrous ball of wiped material on the trailing edge.

Fig 8. Wiped Thrust Pad Due to an Overload.

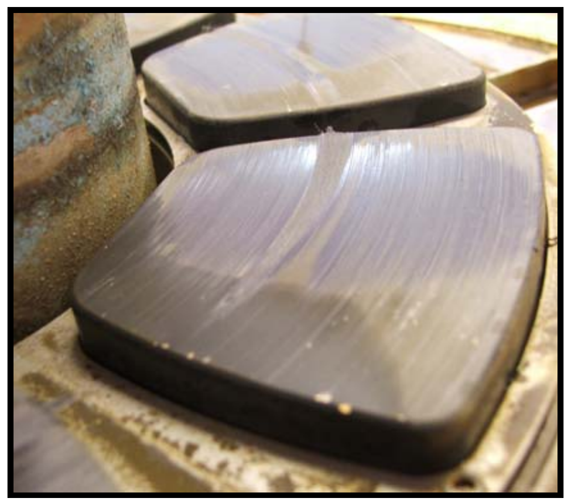

Fig 9. Worn Polymer Thrust Pad

If overload results in damage to the bearing, geometry and material changes can be incorporated into the design to increase the capacity of the bearing. The pad supporting structure (pivot, shell, links,) will also need to be evaluated and upgraded as well.

4 Overheating

As the lubricating fluid passes through the bearing clearance it undergoes shearing, which generates heat. This heat is mostly carried away by the lubricant but some is also transferred to the bearing. Operating bearings at excessive temperatures continues to be a common cause of damage to bearings. The high temperatures can be generated by different mechanisms, such as high loads, high inlet temperatures, high speed, and insufficient lubrication. Excessive temperatures are sometimes indicated by a blackened (oil coking) area on the pad, as shown in Figure 10.

Babbitt is an anisotropic material with different thermal expansion coefficients along different grain axes. Thermal cycles through large temperature ranges may lead to a mottled (faceted) appearance of the bearing surface or, if excessive, intergranular cracking of the babbitt due to the anisotropic nature of babbitt. Typically, faceting, as shown in Figure 11, is not detrimental but highlights the different grains in the babbitt structure. However, high temperature gradients can lead to intergranular cracking. Shear and normal forces act on the babbitt, potentially opening up cracks. A thrust pad with intergranular cracking is shown in Figure 12.

The yield strength of babbitt falls off rapidly with increasing temperature, which can lead to creep when the actual, local pressure exceeds the yield strength of the babbitt at the local temperature. The bearing surface has a rippled appearance, as shown in Figure 13, due to the babbitt flowing under the high pressure and temperature. Potentially, the babbitt can continue to flow past the edge of the pad, as also shown in Figure 10. Note that wiping hasn't necessarily occurred because there hasn't been bearing to shaft contact.

Fig 10. Coking on Thrust Pad Due to Excessive Temperature.

Fig 11. Faceted Thrust Bearing Pad Due to Thermal Cycling of Pad.

Fig 12. Intergranular Cracking on a Thrust Pad From Excessive Temperatures.

Fig 13. Thrust Pad with Rippled Surface From Creep.

Another source of potential damage to turbine bearings, in particular, is latent heat in the shaft or housing conducting into the tilt pads once the rotor has stopped. Often referred to as 'heat soak back', the heat from the shaft or housing may be sufficient to melt the babbitt if cooling lubrication is not maintained. Figure 14 shows journal tilt pads where the babbitt melted due to heat soaking from the machine casing into the bearing. When cooling lubrication cannot be guaranteed, the babbitt can be replaced with a material that can withstand the higher temperatures but also has good bearing characteristics. Engineered polymers can be used as alternate to babbitt to combat potential damage due to heat soak back. A polymer lined tilt pad journal bearing is shown in Figure 15.

Again, geometry and material changes can be used to lower the surface temperatures or can be used to lessen the impact on the bearing if excessive temperatures are encountered.

Fig 14. Tilt Pad Journal Bearing Damaged by Heat Soak Back.

Fig 15. Polymer Lined Tilt Pad Journal Bearing.

5 Lack or Loss of Lubrication

Hydrodynamic bearings, including tilt pad journal and tilt pad thrust bearings, rely on a film lubricant to separate the rotating and stationary components. Typically, mineral or synthetic oil is used as the lubricant in turbomachinery. Increasingly, process fluids, such as water, toluene, and refrigerant, are also being used as the bearing lubricant. In addition to providing the necessary fluid to form the film, the lubricant is also used to carry heat away from the bearing. When the lubricant is interrupted, either momentarily or for an extended period time, the hydrodynamic film does not form and is insufficient to support the load; contact between the rotating and stationary parts can occur. Even if contact doesn't occur due to inadequate lubrication, the cooling effect will be incomplete, resulting in overheating of the bearing material. A damaged thrust pad and journal bearing from inadequate lubrication is shown in Figure 16 and 17, respectively.

Fig 16. Wiping of a Tilt Pad Thrust Bearing Due to Loss of Lubrication.

Fig 17. Light Wiping of a Journal Tilt Pad Due to a Momentary Reduction in Oil Flow.

The damage to the bearing surfaces often resembles the damage that results from overload. The surfaces can be wiped and the babbitt being smeared. The bearing surfaces may have the appearance of being overheated with oil varnish appearing on the surfaces. An interesting form of wiping has been observed when the oil was momentarily interrupted due to a reduction in flow from a pump that momentarily loses pumping capacity, which may have occurred from a reduction in power to the pump. The babbitt on the pad surfaces reached a temperature sufficient to melt but quickly re-solidifies, forming a thin foil of babbitt on the pads. Figure 18 shows a tilt pad journal bearing that was damaged by a momentary interruption in oil flow to the bearing. During investigation into the damaged pads, a thin foil (shown in Figure 19) of babbitt was removed from the journal pad. The damage to this pad was attributed to an occasional decrease in the lubricant flow from the main lubrication pump due to a drop in electrical power to the pump motor.

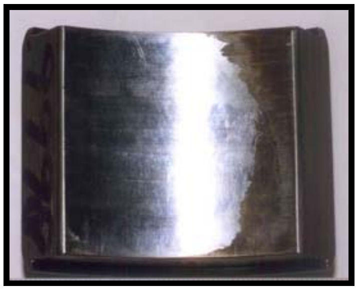

Fig 18. Light Wiping of a Journal Tilt Pad Due to a Momentary Reduction in Oil Flow.

Fig 19. Thin 'Foil' of Babbitt Removed from Pad in Figure 17.

Materials with solid particle lubrication can be used to combat inadequate lubrication. Polymer bearings have the ability to operate with reduced lubrication that occur during a brown out or coast-down under load, but will have excessive wear if allowed to operate continuously without lubrication under typical turbomachinery conditions. Figure 20 shows the damage to polymer tilt pad thrust bearing when the lubrication was interrupted. Obviously, the best prevention is a system that maintains adequate lubrication to the bearing at all times.

Fig 20. Damaged Polymer Thrust Bearing Due to Insufficient Lubrication.

6 Loss of Clearance at Start-up

The clearance between the bearing bore and shaft in tilt pad journal bearings is often designed to be 'tight' in order to achieve specific bearing performance. During quick starts on cold machines, such as gas compressors driven by motors, a 'tight' bearing clearance may be lost as the shaft and pads thermally expand quickly while the bearing housing and machine casing do not. The shearing of the lubricant in the film is the heat source for the thermal growth. But, the housing and casing don't expand as fast as the pads and shaft because of their relatively large thermal mass and the poor conduction of heat from the pads to the housing. With the shaft expanding due to the heat and the pads growing inward from the thermal growth but being restricted by the housing, the clearance between the pads and the shaft is reduced, causing a transient loss in clearance. With the clearance reduced, all of the pads contact the shaft, resulting in wiping of all the pads around the bearing. If the loss of clearance is severe enough, the rotor may seize. A set of journal tilt pads are shown in Figure 21 with all of the pads wiped over the pivots. This type of damage occurs during start up and isn't necessarily accompanied by dynamic vibrations. The machine's operational data should be reviewed to confirm that the damage didn't originate from high dynamic loads and orbits, as shown in Figure 22.

To reduce the chances of transient loss of clearance from occurring, the operating conditions should be reviewed and bearing clearance selected with regard to all conditions, including the type of start-up. Most bearing manufacturers have suggested minimum bearing clearance for journal bearings (see Figure 23) or equations, such as $(N^{0.25})/6000$, where N is speed. These recommendations are guidelines, and for specific reasons, such as dynamic characteristics, the clearance may fall below these limits. An understanding of the machine operation and experience with the application should be reviewed before designing a bearing with clearance below this level.

Special consideration must be given when using polymer lined tilt pad journal bearings because the polymer layer is insulating and a loss of clearance may occur with a polymer lined tilt pad journal bearing that has the same clearance as a babbitt lined tilt pad journal bearing that hasn't experienced loss of clearance damage.

As part of determining the correct operating bearing clearance, the fit between the bearing and the machine housing needs to be considered. If the fit is an interference one, the bore of the bearing will be smaller than the 'free' bearing. An excessive crush can be a contributing factor to damage due to a loss of clearance.

Fig 21. Wiping of All Journal Tilt Pads Due to Loss of Clearance at Start-up.

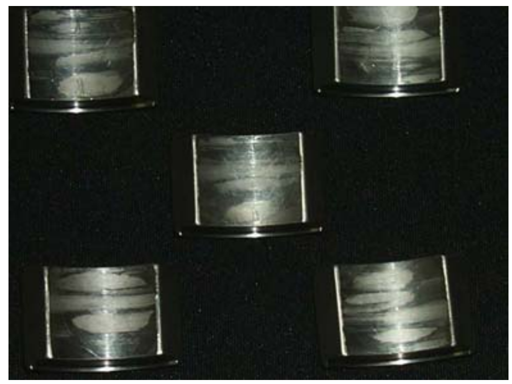

Fig 22. High Dynamic Load Damage to All Tilt Journal Tilt Pads.

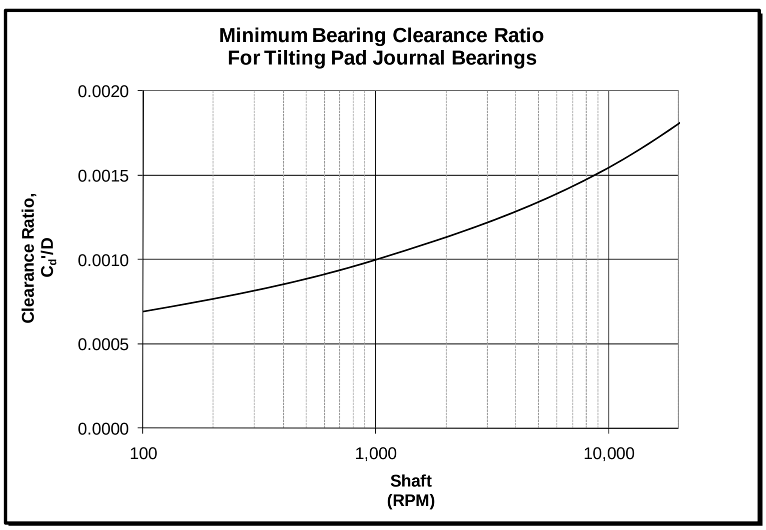

Fig 23. Minimum Bearing Clearance as a Function of Speed

7 Cavitation

In addition to a viscous fluid and relative motion, hydrodynamic bearings require a converging geometry to generate pressure to counter the load. Downstream of the minimum film thickness, the gap between the bearing and the shaft increases; the change in geometry can be gradual or sudden. If the expansion is rapid, vapor bubbles may form in the lubricant and collapse, causing cavitation erosion damage in the babbitt. The implosions create pits and crevices in the babbitt, and, in some cases, the corrosion extends back underneath the surface.

Figure 24 shows cavitation damage at the edge of the outside diameter of a thrust tilt pad. A portion of the damage is shown at higher magnification in Figure 25. Typically, the cavitation damage is over a small area of the tilt pad. Note that cavitaiton damage may cover a significant portion of the bearing surface of fixed geometry journal bearings.

Including gradual changes in bearing geometry the design can reduce the occurrence of the cavitation. Also, minimizing sharp edges and other sudden changes in the collar annulus will reduce the formation of vapor bubbles. Likewise, ensuring that rotating surfaces are free of defects will also reduce the chances of cavitation erosion from occurring.

The harder the bearing material the less likely cavitation erosion will occur. Polymers and ceramics are less susceptible to cavitation damage and no reported cases of cavitation erosion in polymers or ceramics have been reported.

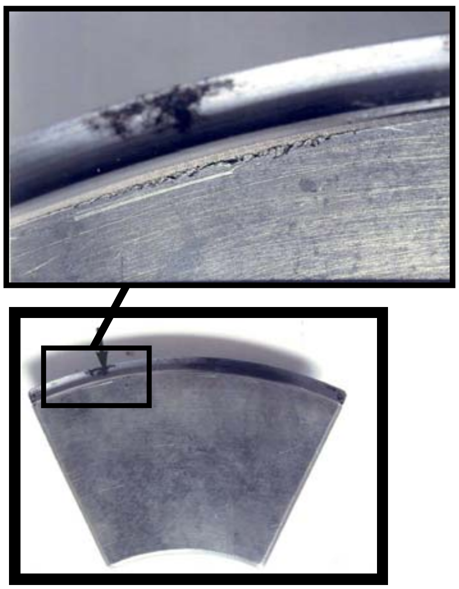

Fig 24. Cavitation Damage on a Thrust Tilt Pad.

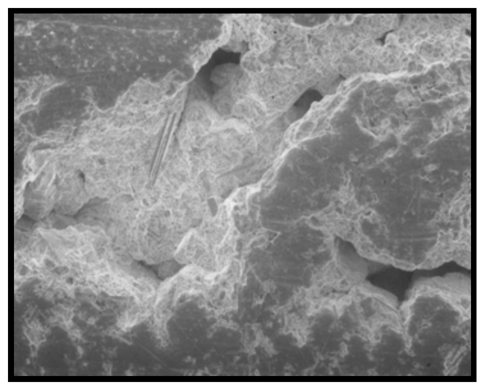

Fig 25. Scanning Electron Micrograph of Cavitation Damage on the Edge of the Thrust Pad Shown in Figure 23.

8 Electrical Discharge

During operation, electrical charge may build up on the shaft. Sources of this 'charge' can be from residual magnetic fields on the shaft, varying electrical-mechanical fields, stray shafts currents or static electricity build up from 'wet' stages on a steam turbine. When the electrical potential is sufficient, the charge will arc to ground through the path of least electrical resistance. Because fluid film bearings operate on very thin films of lubricant, the arc often passes from the shaft to ground through the bearing if the bearing is unprotected. When the charge does jump the gap between the stationary bearing and the rotor, the babbitt material is 'spark' eroded by the arc. The resulting pits are typically hemispherical and shiny, giving a frosted appearance to the damaged area. There are typically no high spots around the pits, as may occur with embedded particles (haloes). Often the damage starts at an area of minimum film and then increases in size as material is removed, resulting in a clear boundary between the area of the pad with the damage and the area without. If the electrical arcing continues, the majority of the pad can be spark eroded and the backing material can be exposed. Typically, the rotating part also has similar pitting. Figures 26 and 27 show thrust pads that have been damaged by electrical discharge. Note the distinct transition 'line' from undamaged to frosted area on the thrust pad. A portion of the damage area of the pad in Figure 26 is shown at a higher magnification in Figure 28. Figure 29 is a microphotograph of one of the electric discharge pits. Damaged pads should be repaired or replaced. The shaft or collar should also be repaired to remove any defects.

Insulating the bearings is the typical method to protect bearings from spark erosion. In addition to or in lieu of insulating the bearings, polymer lined pads can be used to prevent the bearings from being the path to ground for the charge. In some cases, the insulation moves the path of least resistance to another bearing or other component on the rotor. Insulating the bearings is common in generators and motors. However, if all paths to ground are not properly insulated, stray currents can still pass through the bearing to ground. The electrical discharge damage in Figure 26 is attributed to improperly insulated hydrostatic lift connections and temperature sensors; the bearing and its housing were properly insulated.

In addition to protecting bearings with insulation, there are additional methods for mitigating potentially damaging shaft currents that can be incorporated into the machine so that electrical charges do not arc through the bearing. Bearings in motors, particularly those equipped with Variable Frequency Drives (VFD's), may be protected by brushes or shaft current diverting devices such as Inpro/Seal's patented Current Diverter Ring (CDR) technology. A CDR, as shown in Figure 30, uses conductive carbon filaments that safely divert stray shaft currents away from the bearings to ground.

Fig 26. Thrust Tilt Pad with Electrical Discharge Damage.

Fig 27. Thrust Tilt Pad with Electrical Discharge Damage.

Fig 28. Magnified Section of Thrust Pad in Figure 26.

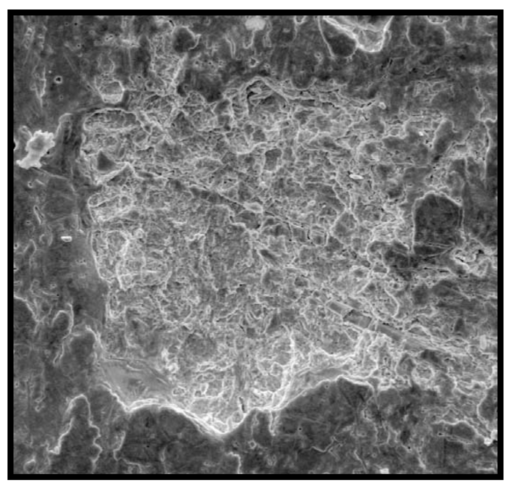

Fig 29. Microphotograph of 'Pit' From Electrical Discharge; Smooth Features at Higher Magnification.

Fig 30. Current Diverter Ring Installed on a With VFD Motor (Photo courtesy of Inpro/Seal, a Dover Company).

9 Misalignment

With both tilt pad thrust and journal bearings, misalignment between the shaft and the bearing can cause localized, excessive loads over a small area, resulting in damage due to high pressures and temperatures. The damage appears as discoloration, wiping or cracking of the bearing surfaces, depending on the localized pressure and temperature. Again, the damage has the appearance of other types of damage modes, such as overloading, but the wear pattern due to misalignment is usually uneven. With journal bearings, the damage occurs towards the axial end of one or two pads. With tilt-pad thrust bearings, a group of pads on one side of the thrust bearing typically show damage. Figure 31 shows tilt thrust pads that have been damaged due to localized excessive temperatures and pressures that resulted from misalignment. The misalignment may have originated from poor control of machining of the bearing seats in the casing, improper installation, or dirt between the bearing and the housing.

In addition to the damage of the bearing surface, misalignment may result in damage to the supporting structure where the pivot contacts the bearing housing or the bearing contacts the machine casing. As with the damage to the babbitt surface, the wear pattern in the bearing components is uneven.

If precision machining of the machine casing is insufficient or impractical to insure alignment, design features can be incorporated into the bearing to minimize the impact of the misalignment on the bearing. For thrust bearings, the most common method is to support the thrust tilt pads on a series of levers to help equalize the load from one pad to another, see Figure 32. In journal bearings, different schemes are used to help minimize the impact of misalignment. The bearing housing can be machined with a spherical OD to mate with the same geometry in the casing bore. Although more common with fixed profile journal bearings, spherical seats have been used with tilt pad journal bearings. But, tilt pad journal bearings typically incorporate a feature between the tilt pad and the bearing housing to increase the ability of the bearing to handle misalignment. Undercutting the support behind the journal pad allows the pad to deflect in order to handle minor amounts of misalignment. Adding a contour in the axial direction into the bore of the bearing housing will also allow the pads to tilt axially in order to handle the misalignment. Increasingly, a spherical seat and pivot (ball and socket) is used to support each pad to handle misalignment and provide sufficient tilt of the journal pad to form a hydrodynamic film. A large ball and socket journal pad support is shown in Figure 33. Regardless of the type of pivot, it is critical that proper engineering practices are employed to insure that the design is safe with respect to pivot stresses and the ability to tilt freely.

In addition to embeddibility (the capability to 'absorb' hard particles) and compatibility (non-galling with steel), babbitt also has the capability to conform to misalignment, provided it is not too severe. Polymer bearings have a similar ability to handle misalignment in that they will wear if the misalignment is large. Ceramics, on the other hand, don't have the ability to handle misalignment very well. A method to ensure proper alignment of the journal bearings from end to end and an ability to provide load equalizing in thrust bearings will help prevent bearing damage in ceramic bearings, as well as babbitted bearings.

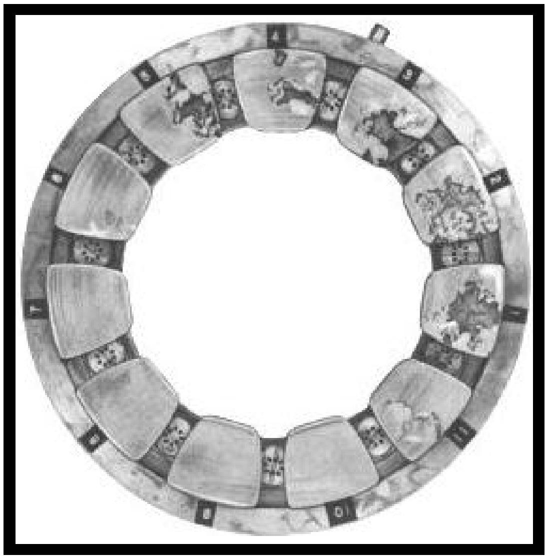

Fig 31. Tilt Pad Thrust Bearing Damage Due to Misalignment.

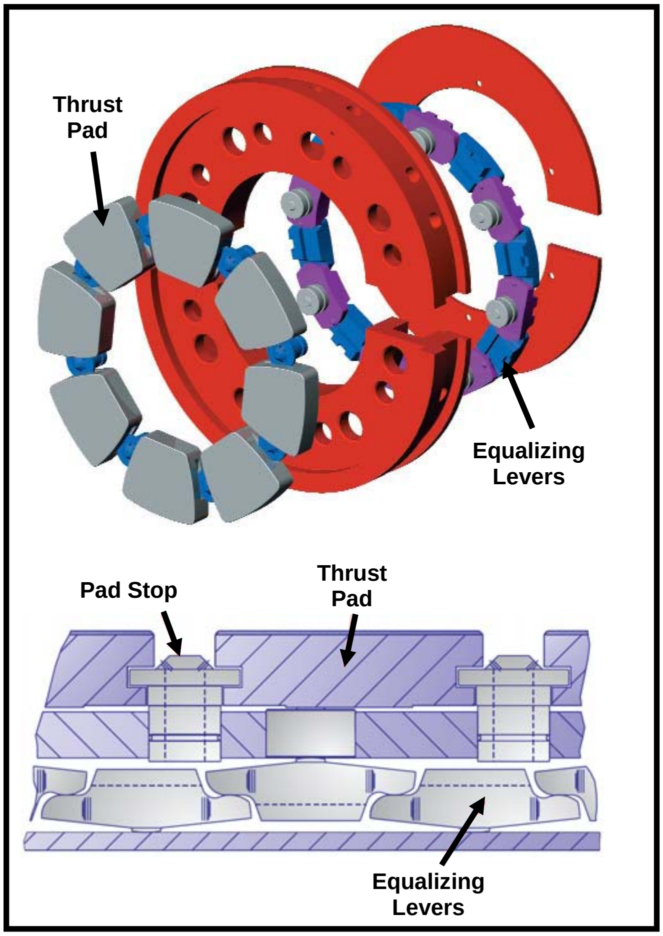

Fig 32. CQ Leveling Mechanism for Tilt Pad Thrust Bearing.

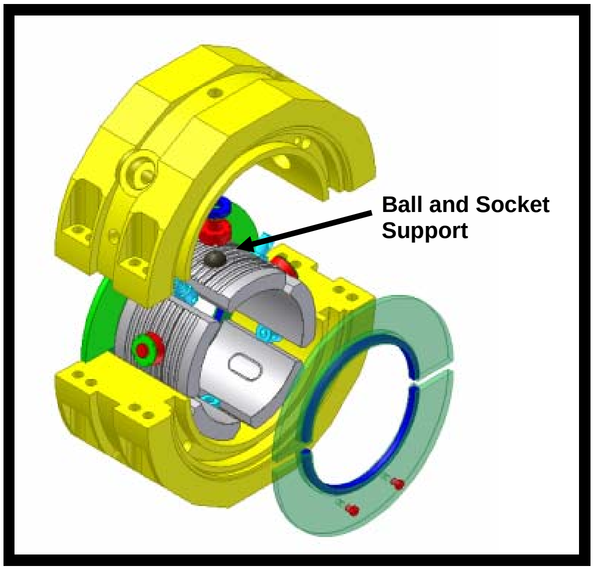

Fig 33. Ball and Socket Support for Tilt Pad Journal Bearings.

10 High Start-up Loads

Prior to reaching a speed that is sufficient to develop a hydrodynamic film, the stationary and rotating components of the bearing are in metal-to-metal contact, initially without any lubrication between the surfaces in contact (boundary lubrication) and then with marginal lubrication between the surfaces (mixed lubrication). The contact between the surfaces causes polishing of the bearing material and eventually may result in the wearing of the bearing material. With the removal of the material the bearing no longer performs as designed. Many types of turbomachinary can have high loads at start-up. Tilt pad journal bearings on large gas and steam turbines are often subjected to high loads (the weight of the rotor) at start-up. Thrust bearings in vertical pumps and hydroturbines often have to support the weight of the shaft, motor and impellers. Another example of a machine with high start-up load is an overhung gas compressor, where pipeline pressure may place a high load at start-up on the normally unloaded thrust bearing. Figures 34 and 35 show thrust and journal tilt pads that have been damaged due to excessive load at start-up and during shut down. Note the thin layers of babbitt that build up on the edge of the pads due to successive starts and stops under excessive load.

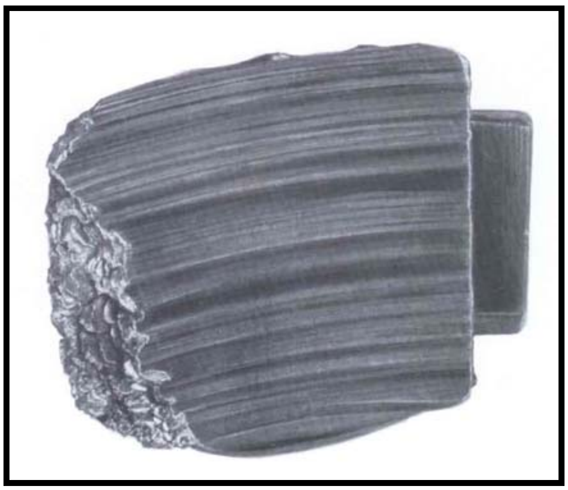

Fig 34. Wiping of a Thrust Tilt Pad Due to High Loads at Start-up.

Fig 35. Wiping of a Journal Tilt Pad Due to High Loads at Start-up.

To eliminate the chances of damaging the bearing at start-up or during operation at low speeds and high loads, hydrostatic lift (jacking oil) systems are employed. High pressure oil that is supplied by an external pump is injected into a pocket in the pad that is specifically designed to lift (jack) the shaft away from the bearing. In addition to protecting the bearing at start-up from damage, hydrostatic lift pressure also reduces the start-up torque to allow for the rotor to turn over easily. A low start-up torque is often necessary for motor driven machinery to start. Also, a large gas turbine can be turned by a short lever and hand with a lift system. Not only does the system need to operate at start-up but also at shut down if the high load is present as the machine comes to a stop. A damage thrust pad is shown in Figure 36. The vertical motor was brought down without the hydrostatic lift pressure being supplied. Bearings made with advanced materials also can be damaged during start-up and shut down while under load. 'Scuffed' ceramic thrust pad surfaces from a pump are shown in Figure 36. During start-up and shutdown the ceramic bearing acted as a disc brake in the pump.

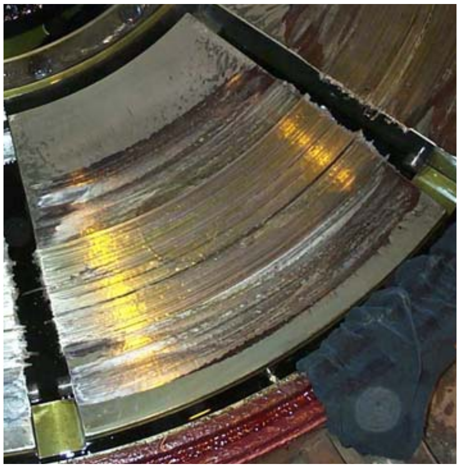

Fig 36. Damaged Thrust Tilt Pad with a Hydrostatic Lift Pocket; Hydrostatic System Failed.

Figure 37 Scuffing of Ceramic Thrust Pad Surfaces During Start-up and Shutdown.

11 Conclusion

Although efforts have been made to decrease the frequency of bearing damages, bearing damage still happens. A variety of damage to tilt pad thrust and journal bearings have been presented. In addition to traditional bearing material, damage modes for alternate materials, in particular polymer, were presented. Operational data is often important to differentiating between different causes of bearing damage and should be obtained whenever possible.

12 Acknowledgements

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