TWO UNUSUAL AND CATASTROPHIC BEARING FAILURES CAUSED BY ELECTRICAL ARCING IN THE OIL FILM, THEIR CAUSES, AND THE SURPRISINGLY SIMPLE SOLUTIONS THAT CURED THEM

by
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ABSTRACT

Rotating equipment engineers are frequently not prepared to deal with the catastrophic damage that often accompanies electrical arcing in the oil film of high-speed turbomachinery. Electrical engineers at the site are often of little help. This paper deals with two specific examples of unusual and catastrophic bearing failures directly attributable to arcing in the oil film. The cause of each failure is identified, and the successful solutions are discussed. Suggestions are made as to how to handle the organization of a team to effectively address this type of problem.

The first example is a 1000 hp (746 kW) motor/gearbox/centrifugal compressor train installed in a major Gulf Coast petrochemical complex. This unit successfully compressed anhydrous hydrochloric acid vapor for a period of one year after startup. It then began experiencing bearing failures due to electrical arcing. Consultants were called in, components were demagnetized, shaft grounding brushes were installed, and insulated couplings were tried, all with no success. In the end, it took changes in the lubricating oil to solve the problem.

The second example is a high-pressure turboexpander operating on a platform in the North Sea. This unit experienced arcing induced failures from the initial startup. Again, consultants were called in, and all parts were demagnetized, but to no avail. While the damage was similar to the first example, the mechanism was believed to be electrostatic in nature, and the solution was once again achieved by changing the lubricating oil characteristics.

INTRODUCTION

Bearing damage due to electrical arcing in the oil film is not a new problem. It can be somewhat intimidating to begin work on a machine with this problem. If no other equipment at the plant site has had this problem before, it can be very difficult to convince others that electrical arcing is occurring inside the bearing, leading to the failure. This is especially true if the failure is catastrophic, since much of the evidence is destroyed.

The principal author of this paper first heard about electrical arcing failures in 1980, when he came across an article called "Are Magnetic Currents Destroying Your Machinery?" (Sohre, 1979). The mechanism of failure seemed far-fetched at the time, but the terrible consequences described in the paper prompted him to start a file on the topic. That file grew for nine years before he had need to draw on its contents. The information contained in that file made the identification of the failure mechanism much easier, and also contributed greatly to convincing upper management and other engineers that the problem was "real."

DESCRIPTION OF ELECTRICAL ARCING IN THE OIL FILM

Perhaps the best analogy to help in understanding this question is to compare what is happening in the bearing to a machining process that many people are now aware of called "electrical discharge machining," or EDM. The EDM process is widely used for such routine purposes as removing broken taps, as well as producing precision cooling holes in exotic alloys used in turbine blades. The process removes metal by taking advantage of the damaging effects of electrical sparks between two conducting surfaces immersed in a dielectric fluid. A spark occurs when the applied voltage between two conducting surfaces that are separated by a dielectric medium becomes sufficiently large to bridge the gap between the surfaces. In most commercial EDM systems, the dielectric medium is a hydrocarbon oil. The resulting particle that is dislodged from the surface is typically swept away by the oil flow.

The similarities between the EDM process and what goes on inside a typical fluid film bearing are numerous. The missing link is: Where does the high voltage come from? First, you have to define high voltage. Anyone who has seen one of those "man-made lightning" displays at a science museum (using a Van de Graaff generator) generally thinks that the voltage required to form an arc must be on the order of 100,000 volts or more. However, when you consider the dielectric properties of a typical turbine oil, and the fact that the bearing film thickness is on the order of 0.001 inch (25.4 microns) or less, it turns out that the required voltage is more likely in the range of 10 to 200 volts, with a maximum of perhaps 5000 volts. These lower levels make it easier to understand that residual magnetism or static buildup caused by seemingly small sources such as high velocity steam or oil flowing through certain types of filter media can provide the voltages necessary to produce electrical arcing in fluid film bearings.

For more detailed information on this topic, see the papers by Sohre and Nippes (1978), or Vance, et al. (1987). Both papers explore the mechanisms in which electrical arcing can be generated in turbomachinery. In addition, both papers list excellent references for obtaining more information.

EXAMPLE 1— MOTOR/GEAR/COMPRESSOR TRAIN

This anhydrous hydrochloric acid vapor compression train is driven by a 1000 hp (746 kW) electric motor operating at 1800 rpm. The seven stage centrifugal compressor operates at 16,000 rpm via a speed-increasing gearbox utilizing a single set of double helical gears. The entire train utilizes a common API 614 lube oil skid for the motor, gearbox, and compressor. The pinion bearings are five pad tilt pad bearings. During the first year of operation, there was no gearbox failure of any kind. During the second year of operation, the gearbox pinion bearings suffered a failure, with a resulting high bearing temperature. The initial inspection of the failed parts had some evidence of electrical pitting, but this was not considered in the initial failure investigation. The machine was repaired and returned to service.

Over the course of several weeks, the pinion bearings suffered repeated failures. Again there was evidence of arcing present. The pinion bearings were determined to have the highest loading and the smallest film thickness of all bearings in the train, making them more likely to have the arcing problem, all other things being equal. It is interesting to note that the low-speed gear bearings never did fail or show any problems. A meeting was held to discuss the problem. There was no uniform agreement that electrical arcing was the problem. Still, using the published information gathered over the previous nine years on this type of failure, we were able to agree to call in consultants who specialized in this type of problem. Due to the repeated failures, the spare parts inventory had been depleted, and all failed parts were being refurbished on an emergency basis. This meant that the consultants, when they arrived, had to rely on verbal descriptions and inadequate photographs of the failed parts to form their initial opinions.

One of the items that was observed during the later failures was that the oil pH seemed to be low at the time of failure. It was believed that this was due to hydrochloric acid (HCL) from the compressor, though the leak path was not identified (remember that the gearbox and compressor shared a common lube oil system). Oil pH was not routinely measured on this machine, so after changing the oil it was decided to monitor the pH after the next startup. Some people thought that the low pH was etching the babbitt, rather than electrical arcing. However, because the "etching" was located only in the areas of minimum film thickness, it was determined that the damage was not due to etching (etching would occur in a more uniform manner on the exposed surfaces, not simply near the trailing edge of the pads). There was also a suspicion that the dielectric properties of the oil would change due to the low pH.

Demagnetization Process

Proper demagnetization (degaussing) of rotating equipment is difficult. In fact, simply measuring the amount of residual magnetism in some parts is difficult. One of the first things the consultants wanted to do was demagnetize the equipment. Of course, conducting the magnetic survey to determine the amount and polarity of the magnetism had to be done first, so that these areas could be demagnetized. This proved frustrating, and a brief story is probably the best way to describe this.

With the top half or "cap" of the gearbox removed and sitting away from the deck on a wooden pallet, an elevated gauss reading was observed, ranging from about 2 gauss to 25 gauss. The top half was loaded on a large flatbed truck with a wooden bed and taken to the nondestructive testing (NDT) facility for degaussing. When it was returned to site, a quick check before installation showed that it was the same as before. An angry call to the NDT technician indicated that he had not performed the degauss procedure, or even taken the cap off the truck, since everything was below 3 gauss, and he did not want to make it worse. This time we brought the same gaussmeter to the NDT shop with the cap, to prove that there was in fact residual magnetism. To our surprise, the entire cap was below 2 gauss when tested at the NDT shop, with the same meter used in the field! It was decided not to degauss, but to take the top half back to the site. At site, it again had elevated magnetism levels! It was discovered that by simply placing the top half of the gearbox on five wooden pallets stacked together, the residual magnetism would drop considerably. In fact, when it was supported by a crane, a steady increase in magnetism could be detected as the cap was lowered toward the concrete. The conclusion was made that there must be some interaction going on with the rebar in the concrete, and the readings would be checked as the cap was set on the lower half of the gearbox.

As the cap was lowered into position, the residual magnetism levels first increased, then decreased as the two halves made contact. It was decided to degauss the two halves in a position when they were nearly touching. This resulted in lower levels overall regardless of the position of the top half.

Another problem with degaussing is that the alternating current (AC) degaussing machines normally associated with magnetic particle testing are subject to a "skin effect," in which the demagnetization is ineffective on thick cross-sections of metal. For this reason, a procedure using direct current (DC) was used by lowering the level down in discrete steps, reversing the polarity each time the level of current was reduced, which is referred to as "down-cycling."

Insulated Coupling

Whenever there is an electric motor or generator in the train, one of the first places to look for the source of stray electrical currents is from this component. Discussions with the plant electrical personnel and the consultants concluded that it was worth converting the motor-to-pinion coupling to an electrically insulated coupling so that any stray currents from the motor could not enter the pinion shaft. It was the consultants' opinion that the motor was the most likely source of the problem, and that an insulated coupling had a high probability of fixing it. A late night of redesign engineering and some calls around sunrise to local machine shops produced an insulated coupling in time for the startup (Figure 1, the original sketch from 1989). The design was marginal, in that the resin impregnated material used to insulate the shoulder of the bolts was not of sufficient strength to withstand the full bolt torque, according to the calculations. A quick test in the shop confirmed this. Calculations were then made for reduced torque, and it was decided that the coupling would be safe enough for a trial run, but that if it were successful, stronger materials would have to be installed. When the unit was eventually restarted with this coupling, all unnecessary personnel were removed from the area, and safe zones were established for those that were required to be in the area. The calculations proved correct, and the coupling worked flawlessly during the trial running.

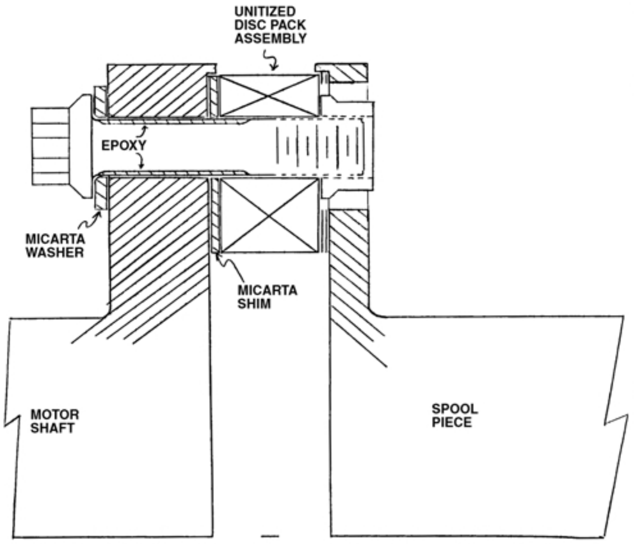

Figure 1. Original Coupling Modification Sketch to Form Electrical Insulating Barrier.

Shaft Riding Brushes

Prior to the consultants' arrival on site, a ground brush was installed on the high-speed pinion shaft. This did not seem to help, since the machine failed again, even with this brush installed. The consultants recommended that shaft voltage and current readings should be taken at all available access points while the machine was in operation. A plan was developed whereby the electric motor would be run alone, then the gearbox would be coupled (using the insulated coupling), and finally the entire train would be run. Shaft voltage and current were measured at each step. Figure 2 shows the locations of these temporary brushes.

A sample of the data taken is included as Figure 3. The things learned from this effort:

• Shaft voltages and currents of meaningful levels were measured, and "spikes" were observed.

• There were no accessible points at which grounding was effective at stopping the damage. The conclusion from this was that the path of the electrical circuit that was causing the arcing was such that none of the locations available to install a grounding brush was effective at disrupting the electrical circuit. It is possible that some sort of internal grounding brush configuration could have been effective, but this was not attempted.

• The insulating coupling did not help at all, even though it functioned as designed. The conclusion from this was that the motor was not the source of the problem.

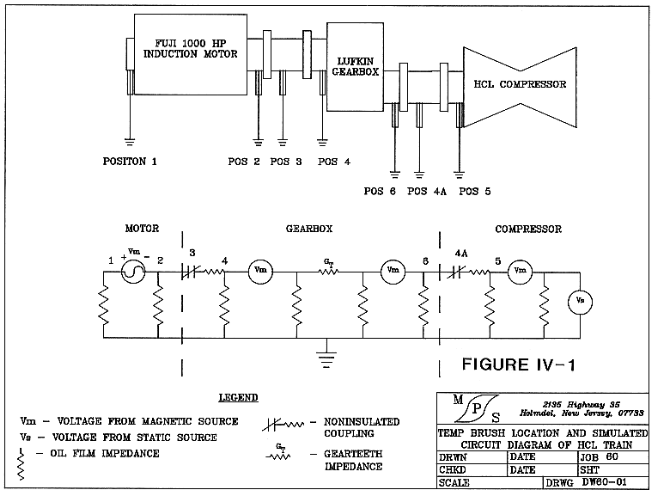

Figure 2. Temporary Grounding Brush Locations.

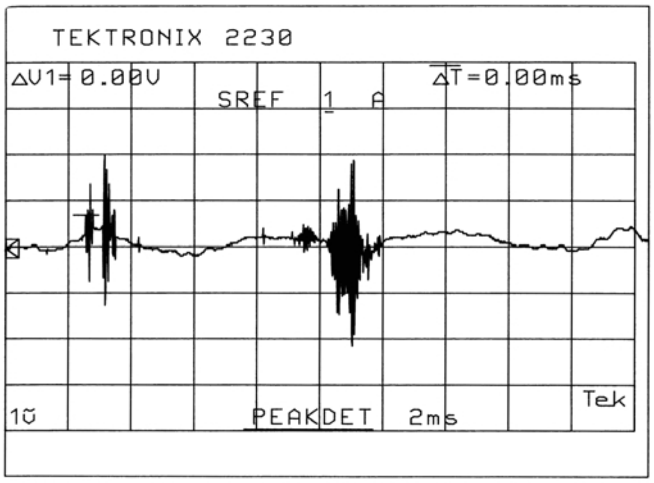

Figure 3. Electrical Discharge Spikes from Grounding Brush.

Lubricating Oil pH

The restart of the unit occurred with fresh VG-32 turbine oil. In a relatively short period of time, it was determined that the oil pH was dropping. When the oil pH dropped to about five, we began to notice that the bearing temperatures for the gearbox pinion bearing started to increase. A sample of the lube oil was taken to the lab to experiment with how much oil would have to be drained from the reservoir and replaced with fresh oil to raise the pH high enough to see if the bearing temperatures would stop rising. The results indicated it could be done without risking the machine, so the pH was raised and the bearing temperatures stabilized! Note that the bearing temperatures did *not* return to normal, they simply stopped rising. It was later determined by shutting down the train *before* it failed completely that the electrical arcing at the trailing edge of the pads was slowly changing the pad curvature from a positive preload to a negative preload, thus causing the temperatures to rise over time in relation to the amount of material removed from the trailing edge of the bearing (Figures 4, 5, and 6).

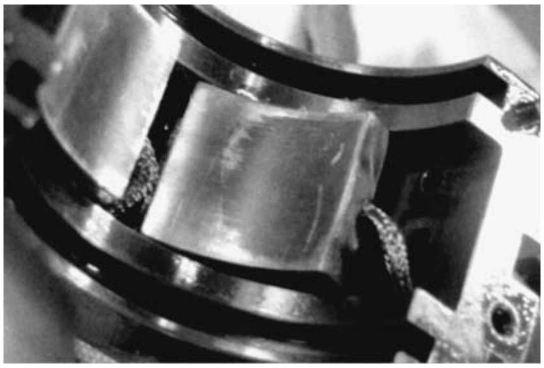

Figure 4. Arcing Damage to Loaded Pad Prior to Total Failure.

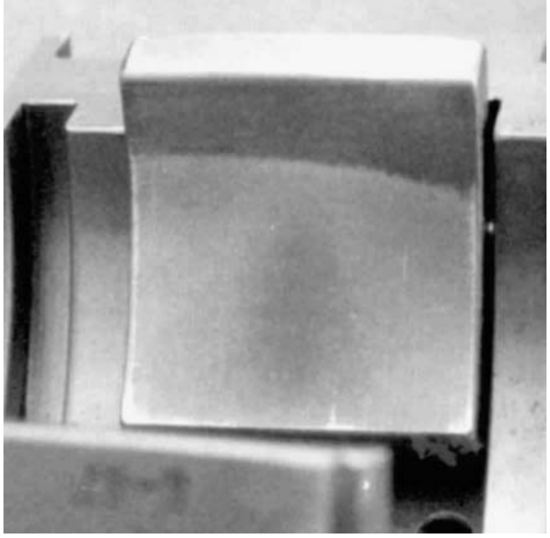

Figure 5. Arcing Damage to Partially Loaded Pad Prior to Total Failure.

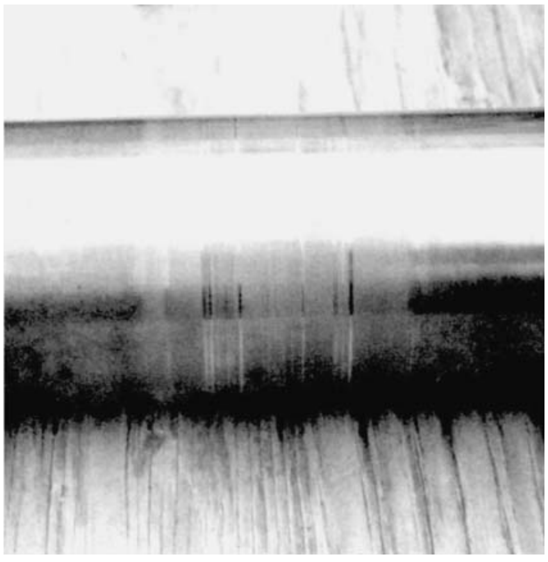

Figure 6. Pinion Shaft Prior to Total Failure, Showing Spark Tracks in the Bearing Journal Location.

As the unit continued to run, we continued to monitor the oil pH. Again, when it got to about five, the pinion bearing temperatures started to rise! The focus of the effort began to shift rapidly. The oil manufacturer communicated that turbine oil is considered "low ash" oil, as opposed to something like an engine oil, which has a higher ash content to absorb the acid formed during combustion. Ash is one of the items in oil that helps it to absorb acid. It acts somewhat like a buffer, allowing acids to be absorbed into the oil with minimal adverse effects. Higher ash oil was rushed to the site, allowing the unit to continue operation.

The source of the HCL contamination was traced to the static O-ring under the dry gas seal sleeve on the compressor. The design of the sleeve was such that gas leaking between the shaft and the sleeve could get into the bearing housing, even with the air gap between the seal housing and the bearing housing. At the next shutdown, this was corrected.

The shaft grounding brush was removed, since it proved ineffective at stopping the arcing. Prior to removal, however, it was used to verify that the arcing was eliminated when the oil pH was maintained above five.

The insulated coupling, which had proven ineffective at preventing the arcing, was left in operation, with the agreement that it was to be removed at the next shutdown. Due to the multiple outages in such a short time period, the plant management was not willing to shutdown to take the coupling out as long as it was working in an acceptable manner. Years later it was discovered that the insulated coupling continued to be installed following each overhaul because nobody wanted to change anything in the system once the problem was solved! This is a lesson that is unfortunately relearned all too often: "temporary fixes" and "test connections" will be left in place by plant personnel until they cause a problem! Whenever possible, these items should be removed before finishing the project.

The bearings have now operated for more than 10 years with no recurrence of the problem.

EXAMPLE 2— TURBOEXPANDER ON AN OFFSHORE PLATFORM

This unit is located on an offshore platform in the North Sea, as shown in Figures 7 and 8. The turboexpander is designed to produce about 3000 hp (2240 kW) at a speed of about 12,500 rpm. Very soon after startup, it was noticed that the bearings were experiencing rapid failures. Initial operating life ranged from a few weeks to a few months. All bearing failures exhibited signs of electrical arcing in the oil film. Magnified views of this arcing are shown in Figures 9, 10, and 11.

Turboexpander Description

A turboexpander, in its most common form, looks quite a lot like an automotive turbocharger. On one end of a common shaft is located a radial inflow turbine, and on the other end is a centrifugal compressor. In between, the shaft diameter is increased to form a very rigid shaft, supported by fluid film bearings. Typically, the bearings and shaft run in a pressurized bearing housing that is hermetically sealed from the atmosphere outside the bearing housing. The rotating assembly for this machine is shown in Figure 12.

The purpose of the turboexpander is usually refrigeration. The gas passing through the expander has work extracted from it, causing the gas to get colder. If the gas is far from its saturation point, then most of this refrigeration is observable as a decrease in the outlet gas temperature (sensible heat). However, as is frequently the case for turboexpanders, if the gas is at or near its saturation point, much of the refrigeration will be observable as condensation of the heavier components in the gas stream (latent heat). The approximate range of condensed liquids, expressed as a weight percentage of the inlet flow, is from zero to 50 percent, depending on the process conditions and the design of the turboexpander. At 50 percent, this means that one-half the total inlet stream, on a weight percent basis, is converted to liquid simply by expanding it through the turboexpander! Turboexpanders normally have an isentropic efficiency between 80 and 90 percent.

Figure 7. Offshore Platform Where Turboexpander Is Installed.

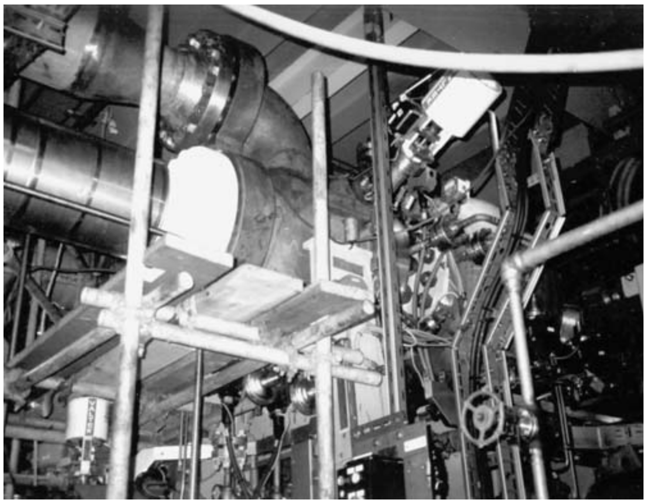

Figure 8. Turboexpander Installation Showing Tight Working Space Available on Offshore Platform.

Initial Plan of Attack

To help in the resolution of the problem, a consultant who specialized in this type of damage was hired. It was believed that the most likely cause of the problem was magnetized components due to the fact that there had been substantial welding in the area prior to the initial startup. The consultant knew what to look for, had the equipment to measure the magnetism levels, and had both the equipment and knowledge to reduce the residual magnetism to acceptable levels. Expectations were high that this problem would be quickly resolved.

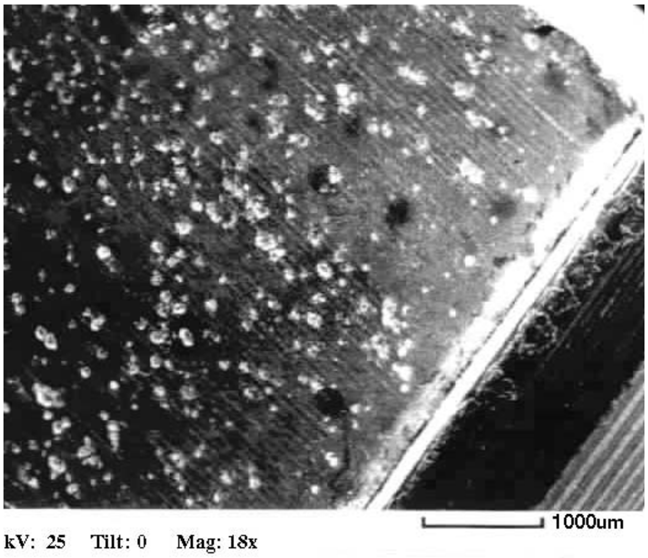

Figure 9. Pits on Babbitt Surface.

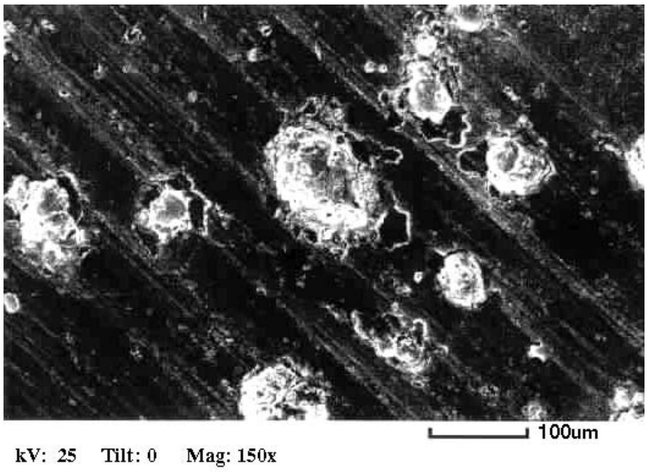

Figure 10. Enlarged Picture of Pits on Babbitt Surface.

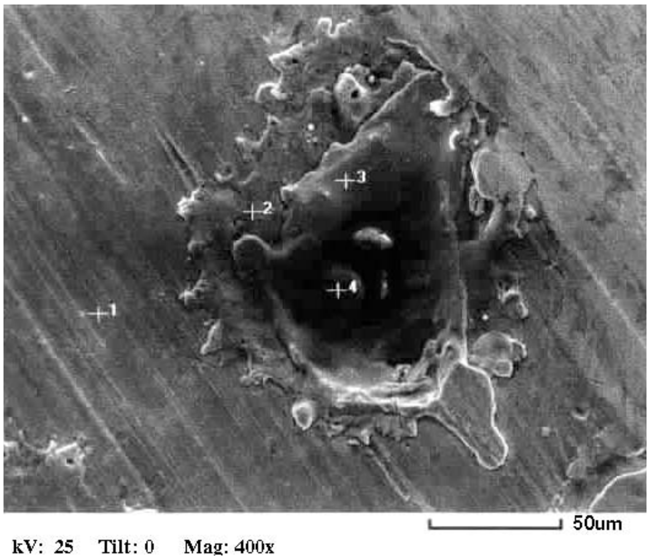

Figure 11. Enlarged Picture of Single Pit Showing Melted Surface of Pit.

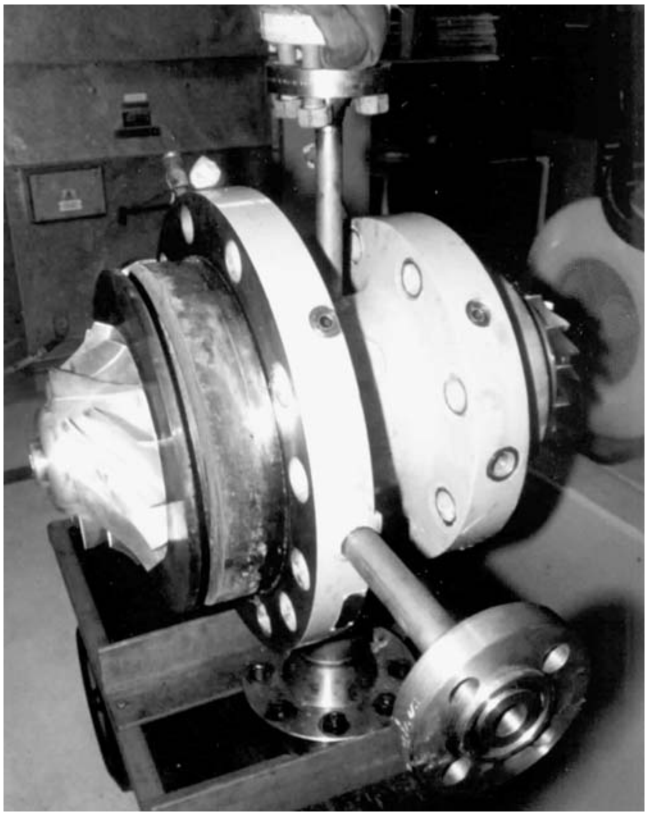

Figure 12. Turboexpander Rotating Assembly.

Unfortunately, the consultant found very little that could explain the failures being observed in this application. All components were checked, and any areas that seemed suspicious were degaussed to bring them to acceptable levels of magnetism. Figure 13 shows the shaft being degaussed, and Figure 14 shows the bearing housing being degaussed. The machine was put back together and restarted. Within a short time, the bearings failed again due to arcing in the oil film (Figures 15, 16, and 17).

Subsequent conversations with the consultant indicated that two areas were worth pursuing. First, the magnetic speed probe seemed to leave residual magnetism in the shaft directly under the speed probe location. It was recommended that the type of speed probe be changed to an eddy current probe, thus eliminating this potential cause of the problem. The second recommendation was that a shaft grounding brush be installed to drain off any voltage potential from the shaft.

Neither of these suggestions was met with enthusiasm by the OEM. First, the magnetic speed probe was a standard design, used in hundreds of machines worldwide, and there seemed to be no rational reason why it should be the source of the problem. Second, the bearing housing operates at approximately 935 psi (65 bar), and the maximum shaft speed is approximately 15,000 rpm, thus making a grounding brush very difficult to design, even if a location to install it in the bearing housing could be found.

Brainstorming Session

A meeting was scheduled at the OEMs facility, with representatives from the end user's facility attending. A thorough review of the data indicated that there seemed to be no "mechanical" reason for the bearing failures. In fact, the end user operated another platform in the North Sea with turboexpanders using exactly the same shaft and bearings. This second platform had been operating for a longer period of time, and had not had any problems. Parts from the "good" and "bad" machines were interchanged, and the problem stayed with the location, not the parts. This indicated it was something "site specific."

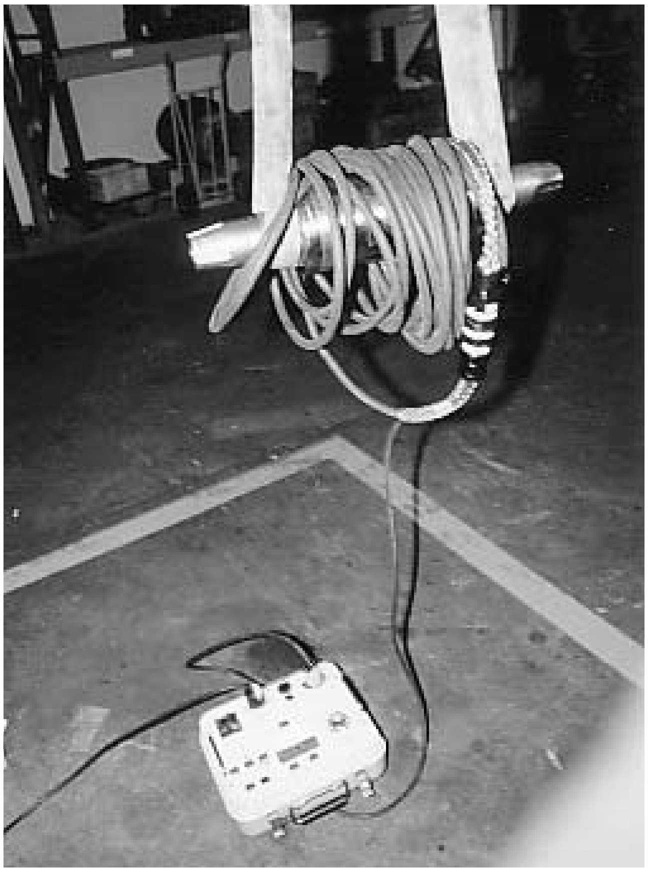

Figure 13. Turboexpander Shaft Degaussing Setup.

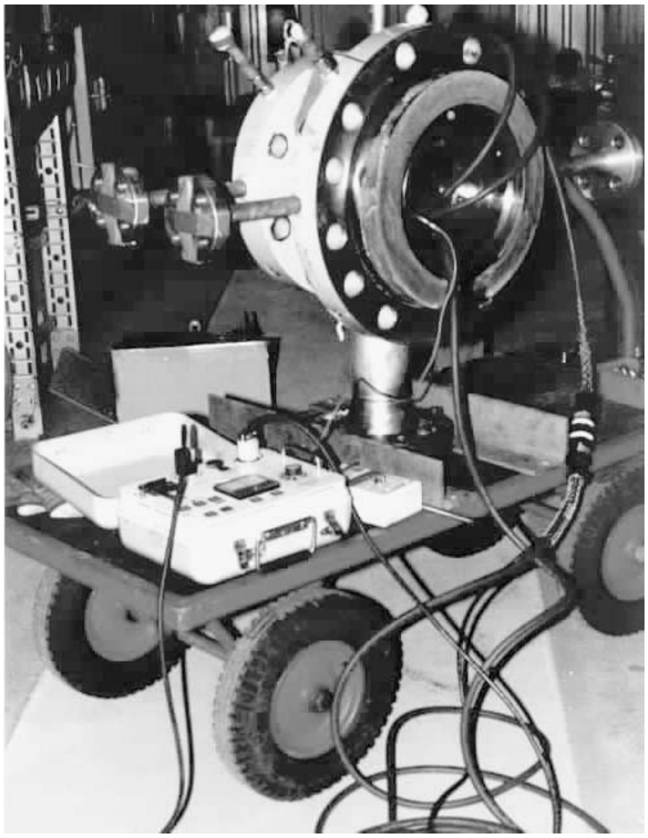

Figure 14. Turboexpander Bearing Housing Degaussing Setup.

Figure 15. Bearing Surface Showing Bearing Damage Due to Pitting.

Figure 16. Bearing Surface Showing Pitting Damage.

Figure 17. Shaft Journal Surface Showing Both Pitting and Deposition of Babbitt from Bearing to Shaft.

The participants in the meeting spent considerable time isolating what could be different between the two sites. It became clear that an important difference between the two units was that the machine experiencing the problem had an inlet has stream that was saturated with water. A theory was developed that the condensed water in the turbine generated a static charge on the rotor that was being dissipated by arcing through the oil film in the bearings.

A plan was developed in which the following two items would be investigated:

- A literature review would be performed to investigate the plausibility of the theory.
- An insulated bearing design would be developed that would prevent the bearing from reaching the bearing housing's ground potential, thus "opening the circuit" and preventing the arcing.

The results of the literature review indicated that the theory was plausible. The design of the insulated bearing, however, proved to be more complex. The bearing could be converted to an insulated bearing fairly easily. The question was: what design parameters should be used? If one assumes that the voltage potential in the original design was arcing at 100 volts, and the insulation is designed for 1000 volts, would the rotor potential simply build up to 1000 volts and create an arc that is even more damaging? How much insulation would be enough? Without extensive field testing, there appeared to be no certain answers to these questions.

Lubricating Oil Additive

With no clear answers to the questions above, it was decided to pursue another option that had been discussed in the meeting. If the oil could be made sufficiently "conducting" to dissipate the voltage, then it would never build up enough to form an arc. A supplier was located with a product that is intended to render aviation fuel more "conductive" so that sparks are not formed during handling that could cause fires or explosions. The manufacturer agreed to perform testing of oil samples with various amounts of additive.

Initial tests were encouraging, and a field trial was started. Plant personnel routinely performed conductivity checks of the oil in the reservoir. These results were also very encouraging. Months have turned into years, and enough time has elapsed to declare the solution a success. Additional additive is periodically required to maintain the correct conductivity, however the additive is relatively inexpensive and does not seem to cause any other harm in the turboexpander or filter system. The turboexpander has been free of electrical arcing in the bearings since the addition of the conducting additive several years ago. Details of the type and quantity of additive can be found in the APPENDIX.

CONCLUSION

Electrical arcing in the bearing oil film can lead to catastrophic bearing failures that many rotating equipment engineers are ill-prepared to deal with. Two specific examples of electrical arc related bearing failures have been discussed.

Recommendations based on the above experiences:

- If you do not already have one, start gathering data in a file *now* on this subject. It may be years before you will need it, but it will be very helpful when the time comes.
- Plant managers and other engineers may not take you seriously if you do not have supporting data to confirm your diagnosis. The file mentioned above will help in this regard also.
- Bring in a consultant who specializes in electrical arcing failures if you are not experienced in this area. In both examples presented, special consultants were brought in and in both cases, their direct recommendations failed to solve the problem. However, their knowledge and experience provided an invaluable contribution as part of each team set up to solve these problems.
- An effective team should include:
  - A rotating equipment engineer,
  - Someone experienced in this type of failure, if the rotating equipment engineer does not have this experience (possibly an outside consultant),
  - An electrical engineer if there is a motor or generator in the system,
  - A process engineer familiar with the plant, and
  - A lead operator from the plant.

All members of the team should feel free to express their thoughts openly, without fear of ridicule. The rotating equipment engineer should assume the position of team leader.

One interesting way to view the lessons learned from Example 1 is that there was *always* sufficient electrical potential in the machine to cause bearing failure, yet this potential for failure was masked whenever the oil was near its "normal" pH. Simply dropping the pH from about seven to a little under five allowed arcing to take place that led to complete bearing failure. What does this say about the "safety factor" regarding the potential to have electrical arcing in the bearings? How many of your machines are in a similar situation? How would you know?

FINAL THOUGHTS

It is clear that there is much research to be done in the future regarding this topic. However, the authors have great confidence that engineers such as the ones reading this paper will be able to provide answers to the questions posed above. The authors believe that engineering in its purest form is sharing that which is known, and probing that which is not. This paper and the work it represents were meant to be a little of both!

APPENDIX

The oil additive used to solve the electrical arcing problem in Example 2 is called Stadis™ 450. It is a product of Octel America in Newark, Delaware. The initial charge of fresh oil is treated with 1000 ppm (parts per million) of Stadis™ 450 (i.e., one part additive to 1000 parts oil). Conductivity tests are then performed using the EMCEE Model 1152 digital conductivity meter to ensure that the oil is at least 2000 pS/m (picoSiemens per meter) at the operating temperature of the oil. Additional Stadis™ 450 is added as needed during the operation of the equipment.

Notes

- The conductivity increases with increasing oil temperature.
- 1 pS/m = 1 picoSiemens per meter = 1 picomho per meter
- 1 mho = 1/ohm
- For more information on measurement, generation, and dissipation of static electricity in petroleum fluids, refer to ASTM D4865-98 (ASTM, 1998) and ASTM D2624-01 (ASTM, 2001).

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