Proceedings of the Forty-First Turbomachinery Symposium
September 24-27, 2011, Houston, Texas

MECHANICAL SEALS FOR HIGH-SPEED BOILER FEED PUMPS IN ULTRA-PURE WATER

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ABSTRACT

Since 2007, the hot-filament Chemical Vapor Deposition (CVD) technology for crystalline diamond thin-film coatings has found its way into the mechanical seal market to combat the problems of dry running, corrosion and abrasion. This new technology has proved successful in hundreds of pumping applications in a wide range of services and duties. The reliability and lifetime of mechanical seals are improved by using diamond-coated faces.

One such application involved the sealing of large boiler feed and steam generator pumps in power plants. The duty conditions for the pump's seals can be as high as pressures up to 580 psig (40 bar), shaft RPMs up to 6,500 and temperatures up to 400˚F (200˚C). Consequently, the mechanical seal faces are highly loaded in a fluid with far less than ideal lubricating qualities. It is evident, therefore, that these applications are technologically challenging for mechanical seal manufacturers not only from a tribological perspective, but also from a corrosion viewpoint when the feed water has a low electrical conductivity or is free of impurities.

This paper discusses a new seal-face treatment using hot-filament CVD manufacturing technology tested in a lab for 16,000 hours and currently used in feed pump operations in several power stations in the USA and Europe.

INTRODUCTION

For the sealing of feed pumps in power plants, mechanical seals have proven to be a reliable and cost-effective sealing method compared to alternatives such as packing and throttle-bushing seals with an injection of cold condensate. Single, balanced, stationary spring-type mechanical seals with a silicon-carbide rotating face and carbon stationary face (Figure 1) achieve lifetimes of 40,000 hours or more in older power plants that historically use the All Volatile Water Treatment, or AVT.

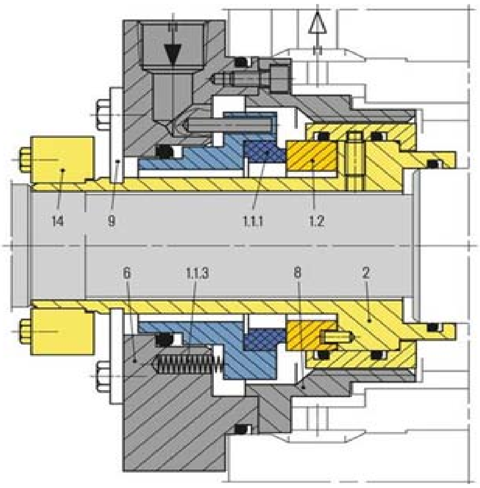

Figure 1: EagleBurgmann SHF mechanical seal for boiler feed pump services

Typically, these seals operate with a cooling system (API Plan 23) to reduce the water temperature to approximately 120 -140˚F (50 - 60˚C) in the area of the seal (Figure 2). It was not until the introduction of neutral feed water conditioning in nuclear boiling water reactor systems (1980s), and more recently, the Combined Oxygen Treatment (COT) in new fossil-fueled stations (1990s), that corrosion problems in mechanical seals started to occur.

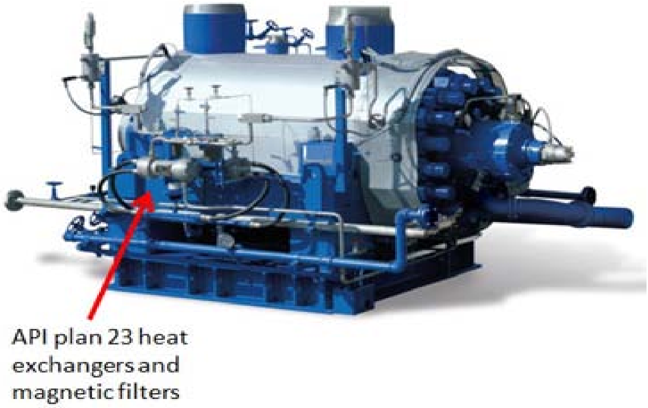

Figure 2: Barrel type boiler feed pump

In comparing the different water chemistries, the electrical conductivity of the fluid has been reduced to low levels with the newer methods, (< 2 µS/cm for COT water and <1 µS/cm for neutral water) from >25 µS/cm for AVT water. The water's electrical conductivity indicates water purity. As impurities are removed, the feed water becomes an electrical insulator rather than a conductor. The main reasons for using ultra-pure water is longer life for the boiler pipes and reduced hydraulic losses in the pumping system, considerably reducing the life cycle cost of the boiler system.

Damage to the mechanical seal parts in these applications was quite unusual in that the silicon carbide rings showed severe chipping of the outer edges and the carbon rings showed signs of material loss and softening in certain areas of the rubbing surfaces (Figure 3). In the early 1990s, mechanical seal vendors and independent organizations developed numerous theories for this damage.

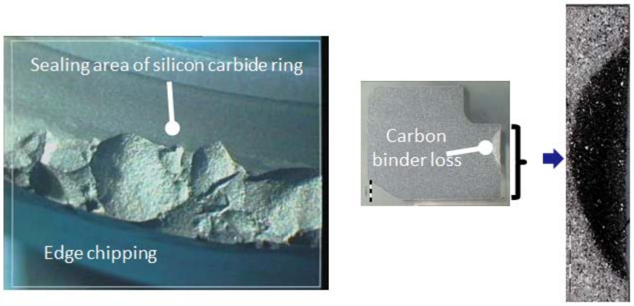

Figure 3: Selective corrosion of carbon face and silicon carbide ring

One theory explained the damage as a special form of cavitation, i.e., erosion cavitation, due to the use of more oxygen in the new treatment methods (Schoepplein, W., Zeus and Dr. Ing. Zeus, 1990). Extensive material investigations conducted by or in cooperation with material suppliers produced no conclusive results. Seal designs were evaluated for stiffness and deflection characteristics. The cooling circuitry and pumping device of the seal was studied intensively. None of these efforts yielded any resolution to the problem.

Field data also indicated that the problem was statistically random in nature, since seals on the same pump and unit with the same feed water had significantly different life times. In the mid-1990s, a different approach was taken; it became evident that something in the water, pump or process had to be at the root of the seal troubles. A specially designed, high-speed test rig was constructed featuring a water treatment system that allowed simulating the actual water and sealing environment of a power plant's feed pump (Figure 4). Soon, it was possible to create different damage patterns on the test stand, which broadened the search for the effects of electrochemical attack on the seal-face materials.

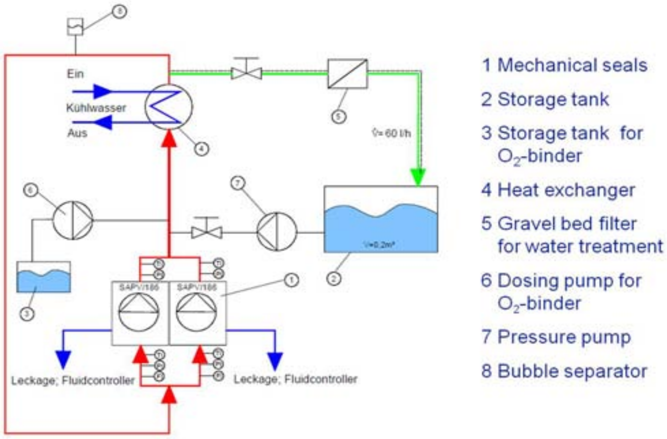

Figure 4: Test set-up to simulate field conditions

SEALS AND ELECTRIC CURRENTS

High velocity differentials can cause electrical potential differences, which in turn can be the source for inducing an electric current. Such high differentials are present between the stationary and rotating parts of the seals, as well as in the fluid film surrounding the seal faces. The same effect can happen through the velocity difference between the rotating and stationary pump parts, as those parts are effectively isolated by the bearings and feed water. In both cases, this could lead to an effect similar to the principle of galvanic corrosion.

Electro-static charging occurs as soon as two seal faces separate from each other, where at least one of the seal faces is highly insulated (Figure 5).

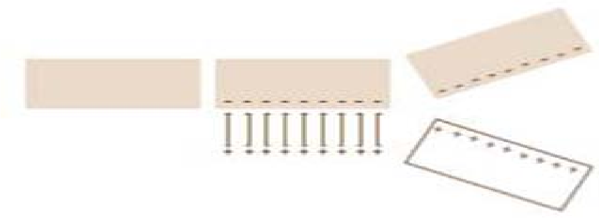

Figure 5: Electro-static charging of two separating surfaces

When the two seal surfaces come into contact, a re-organization of charge carriers (ions) takes place. If the final process of separation is fast enough, compared to the moveability of the load carriers after separation, the re-organized loads will have an opposite load on the surface. At friction, this process (tribocharging) happens simultaneously at different locations. The balance between charging by load separation and the de-charging by the load dissipation rate defines the level of the load.

SEAL MATERIAL TESTING

A simple test in low conductivity water proved that after inducing an electric voltage not only was the free silicon eroded, but also the silicon carbide due to anodic effects (Figure 6) (Nosowicz, Dr. J, 1999). The resulting silicon oxide is a relatively soft material that is easily removed by the high-flow velocity, and thus allows the chemical attack to proceed until deep chips and craters progress in the wear track of the seal faces.

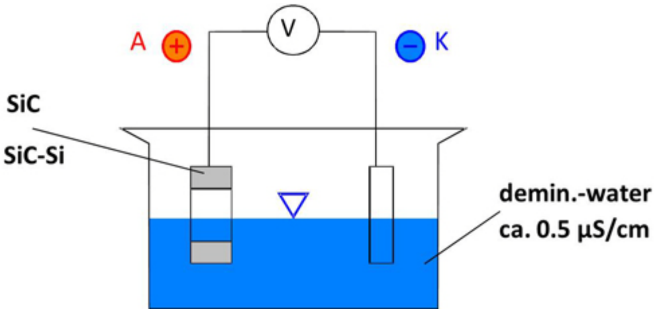

Figure 6: Simple corrosion test of silicon carbide

The testing indicated that damage starts on the OD of the silicon carbide ring without affecting the normal leakage and friction behavior of the seal. This damage increases over time as more material is removed. Once the damage reaches the contact area between the rotating and stationary faces, the seal exhibits an increase in leak rate. This pattern is typical and can progress relatively fast, i.e., within weeks or months, until the leakage becomes intolerable and shutdown of the pump is necessary. In addition to the increased leakage, the water temperature in the cooling loop rises incrementally since hotter feed water is drawn into the cooling loop to compensate for the water lost to the atmosphere.

These test results and the existing field experience showed that the rotating silicon carbide seat elements used in the seals were continually acting as anodes. Further research proved that increased electrical potential differences generate only if the rotating seat is made out of a semi-conductive material, such as silicon carbide.

IMPROVED SEAL TYPE

The logical consequence of this research was to exchange the face materials of the rotating and stationary seal face. Because of the high electrical conductivity of carbon, the generation of potential high electrical differentials would be avoided. Tests confirmed that the stationary silicon carbide face showed no signs of chemical attack. Following these results, in the late 1990s, a new, improved seal type was introduced. The new design featured a rotating carbon seat and a silicon-carbide stationary face to combat the corrosion problems in high-speed boiler feed pumps.

During the early testing period, an alternate solution was developed involving control of the water chemistry in the seal's cooling circuit (Fichte, W., 1996). The solution added a dosing system to the cooling system to increase the electrical conductivity of the water in the loop. Although a proven solution in several installations, the additional dosing system was not acceptable to many users because of increased maintenance and monitoring, as well as the potential for a system malfunction, which could alter the water chemistry in the entire boiler or reactor system.

SEAL LIFE SPAN OF THE IMPROVED SEAL TYPE

During the last 10 years, field studies of the improved seal type installed in water with low electrical conductivity without dosing have shown increased seal life by a factor of two to three. In some cases, improvement factors of five to six were achieved depending on the conductivity level of the water. The improved seal's failures were the result of attack and wear of the carbon structure, whereas the silicon carbide had minimal or no damage. By 2005, it became clear that the improved seal type was more resistant to the electrochemical effects but did not eliminate the damage, and therefore more resources and new ideas would be necessary to solve the problem.

Throughout the many field investigations, other possible contributing voltage sources were identified to explain the wide spread in the life expectancies of the seals. Several German users measured the voltage of pump shafts during operation up to 400 mV. Although this may seem like a low value, the suspicion is that the resulting electrical stray currents could be the reason for the difference in the life span of the seals. Sources for stray currents are numerous in boiler feed pump trains. Grounding of the shaft was applied at some stations with mixed results. The bottom line to all of the field investigations was that these stray currents are unpredictable and unique to each pump and seal.

SOLVING THE CORROSION PROBLEM

Beginning in 2007, the company began a new, extensive R&D program to find a permanent solution for the corrosion problem. The program consisted of the following elements:

- Laboratory tests to determine the driving forces for the corrosion process.
- Tests with boiler feed pump seals under plant-like operation conditions.
- Execution of experimental tests and their scientific validation.

UNDERSTANDING THE FAILURE MECHANISM THROUGH EXPERIMENTAL TESTING

Two experimental laboratory tests were carried out in collaboration with the Fraunhofer Institutes of surface engineering/thin films and material mechanics.

The first test set up (Figure 7) consisted of a silicon carbide pin and a flat silicon carbide probe, separated with a predefined gap and immersed in ultra-pure water. At voltages of approximately one volt, the silicon carbide probe, which acts as the anode, was damaged and an analysis clearly indicated that SiOx was present. The pin, acting as the cathode, showed the formation of hydrogen gas bubbles as a result of the disintegration of the water.

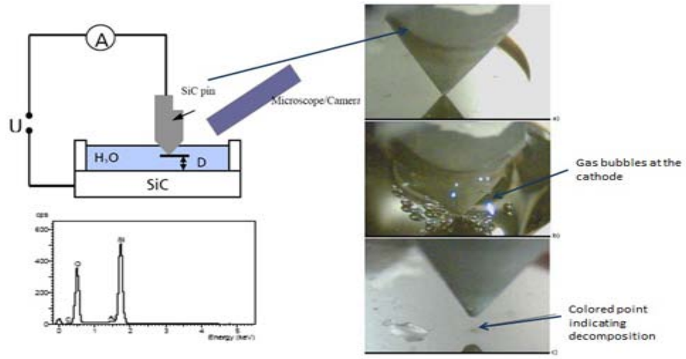

Figure 7: Experimental test #1 at the Fraunhofer Institute

The other test was a dynamic, electro-corrosion test to determine the influence of flow-velocity, pH value, electrical conductivity and material on the created electrical potential. The test apparatus (Figure 8) consisted of a cylinder with the test specimens through which the ultra-pure water was guided at controlled velocities. At a velocity of approximately 131ft/s (40 m/s), a potential of nine volts was measured. The border, where no voltage was measurable, was a velocity of approximately 65 ft/s (20 m/s). This test was performed several times and the results have been repeatable and consistent. Figure 9 shows the condition of the test specimens before and after the dynamic testing.

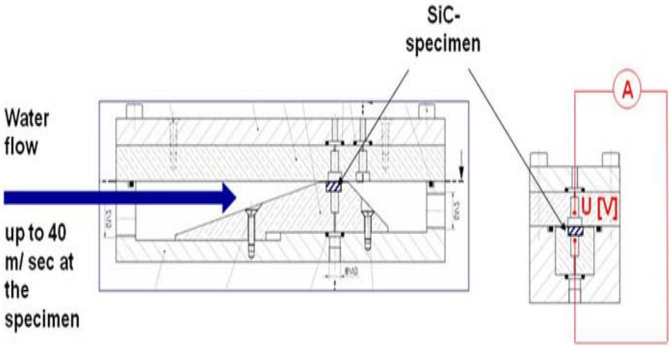

Figure 8: Experimental test set-up #2

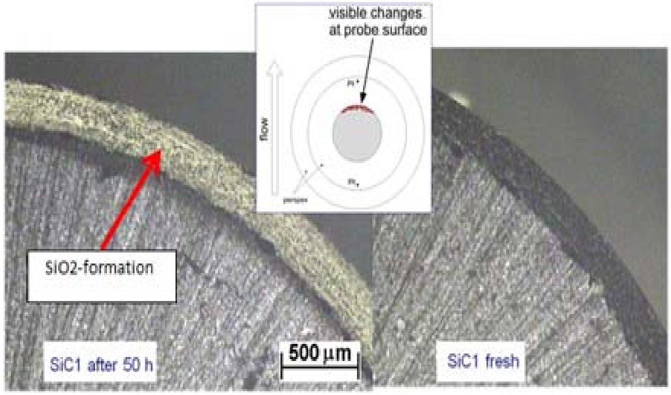

Figure 9: Results from dynamic test

The creation of the current due to a flow can also be found in literature. The Helmholtz-Smoluchowski Formula expresses the relationship between the electrical resistance of a fluid, the pressure drop across a throttle and the resulting current.

$$U=\frac{\varepsilon\varepsilon_0\zeta\rho}{\mu}\Delta p$$

Helmholtz-Smoluchowski formula

U= Flow potential in Volt
ε = Dielectric number of the fluid (80.100 @ 293.2 K/unit-free)
ε0 = Electrical field constant (8.85 x 10^-12 F m^-1)
ρ = Electrical resistance of the fluid Ω m
ζ = Electro kinetic potential of the fluid (zeta potential)/V
µ = Dynamic viscosity of the fluid/Pa s
Δp = Pressure drop across the throttle/Pa

The two experiments demonstrated that a current can be generated at high velocities in low electrical conductivity water and the face materials can be affected by the flowing current. The question about the source of the current is now answered. A part of the current comes from the flow potential created in the seal itself, and another part of the current may come from the pump itself, i.e., electric motor, current flow of the pump's rotating parts, residual magnetism, etc.

DIAMOND-FACE TESTING

The idea of using diamond to solve this problem originated from the power transmission industry where diamond coatings showed excellent resistance against high voltages. In addition, positive experiences with diamond-coated seal faces were obtained in general industry applications.

The dynamic, experimental test was repeated with diamond-coated specimens and the results were promising as no decomposition of the materials occurred under identical conditions. Consequently, the next step was to test conventional, uncoated and diamond-coated seal faces under plant like surroundings (Figure 4).

The first test was successful with uncoated rings in that it was possible to duplicate the damage as seen in the field (Figure 10). The following operating conditions were applied: pressure of 580 psi (40 bar) and a sliding velocity at the seal-face mean diameter of 196.8 ft/s (60 m/s). The second test with coated seal faces was successful since no damage was detectable under identical conditions and run-time. These promising results instigated long-term testing with periodic inspections of the seal faces. As this was a new seal face technology for this kind of demanding applications, the first tests included a series of transient conditions, including slow-roll and start-stop operation to verify and validate the tribological behavior of the seal faces.

Figure 10: Uncoated, conventional seal face after 600-hours on the test rig.

LONG TERM TESTS AT GRAZ UNIVERSITY OF TECHNOLOGY

In order to build confidence for the proposed solution, it was imperative to verify the performance of the seal faces for at least 16,000 operating hours. This project is being handled in collaboration with the University of Graz (Figure 11). Actually, the running time is approximately 20,000 hours (dated 02/01/2012) and the seals show no attack of any kind. All relevant monitored performance indicators such as leakage rate, face temperature and water electrical conductivity at the seal faces are constant and consistent.

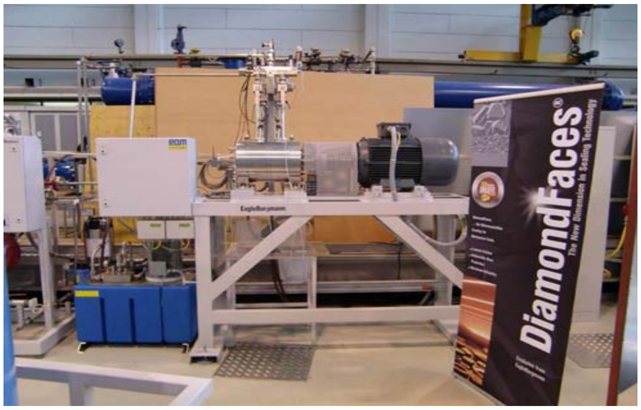

Figure 11: Long term test set- up at the University of Graz

FIELD INSTALLATIONS

In October 2010, the first field installation took place at the nuclear power station Isar I in Germany and startup was on October 17 (Figure 12). The seals performed well without any signs of degradation, but unfortunately the plant was shut down shortly after the tsunami accident in Japan.

Figure 12: Installation of the first seal with Diamond Face® technology in a reactor feed pump at the Nuclear Power Station Isar I

In the USA, the first installation took place in May 2011 in a BWR plant in the Midwest. Three pumps were retrofitted with new seal cartridges. The leakage behavior of the six seals is steady and quite close to the observed leakage rates during the qualification testing of each seal cartridge. The feed pumps of the second unit in the plant are scheduled to be retrofitted in May 2012.

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