EROSION, CAVITATION, AND FRETTING CORROSION

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I. OVERVIEW

Erosion-corrosion, cavitation corrosion, and fretting corrosion are corrosive processes that combine with wear to increase damage on a part. The combination of physical erosion and the presence of a corrosive solution can have a significant effect on the life of a part. In erosion-corrosion and cavitation-corrosion, erosion and wear increase the corrosion rates on a part through disruption or destruction of the protective surface film and/or coating. In fretting-corrosion, corrosion and its products serve to increase and enhance the erosion and wear damage on a part. In this paper, we will examine the physical appearance of these three wear-corrosion processes, the mechanisms behind them, and we will entertain a brief discussion on various methods that can help to reduce the effect of these types of corrosion.

II. EROSION -CORROSION

Erosion-Corrosion: Mechanisms

Erosion is the disturbance of the surface film of a material, caused by high velocity flows past the given material. The removal of the protective surface film is called corrosion. Erosion and corrosion have a synergetic effect on each other, and as a result, the two are often grouped together as one phenomenon (Thiruvengadam, pg. 28).

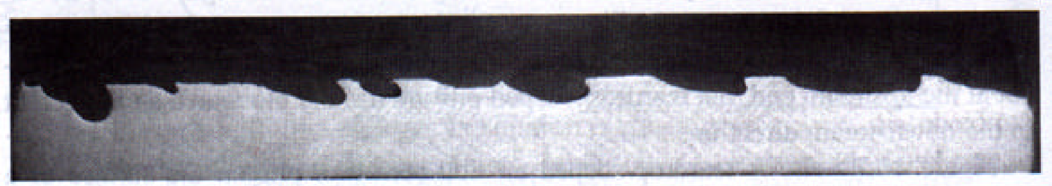

Figure 1: Erosion-corrosion of brass condenser tubing showing individual teardrop shaped pits with undercutting in the downstream direction.
(Source: Jones, pg. 344)

Erosion-corrosion is often accelerated at pipe elbows, tube constriction, and anywhere fluid flows are altered and there is an increase in turbulence. Other aspects that increase erosion-corrosion are the corrosivity of the flowing corrodant, a two-phase flow, such as steam and water, or a flow in which suspended solids are flowing with the fluid (Jones, pg. 343). Higher pressures and temperatures of fluids have also been shown to increase erosion-corrosion (Thiruvengadam, pg. 23).

Low strength, low corrosion resistant alloys, such as carbon steel, copper and aluminum are much more susceptible to erosion corrosion than the high strength, high corrosion resistant alloys like stainless steels, nickel alloys, and titanium. The three later alloys have a much more durable passive surface film, indicating that this may be one factor in choosing the right material for erosion-corrosion resistance.

The mechanism for erosion corrosion is not completely known. Many models have been suggested, but each one has a particular flaw. The platelet mechanism of erosion is a good way to explain the basic mechanism for corrosion (Levy, pg. 12). Small turbulences in the flow of fluid may cause a small divot in the passive film of the material (Figure 2a). The small divot then causes increased turbulence and the fluid can cut into the protective oxide film on the surface, removing material (Figure 2b). The increased turbulence increases the speed at which the divot forms, until the rate of corrosion is faster than would exist under stagnant, regular corrosion conditions (Figures 2c-d). Erosion corrosion takes the form of grooves, waves gullies, and tear dropped shaped pits.

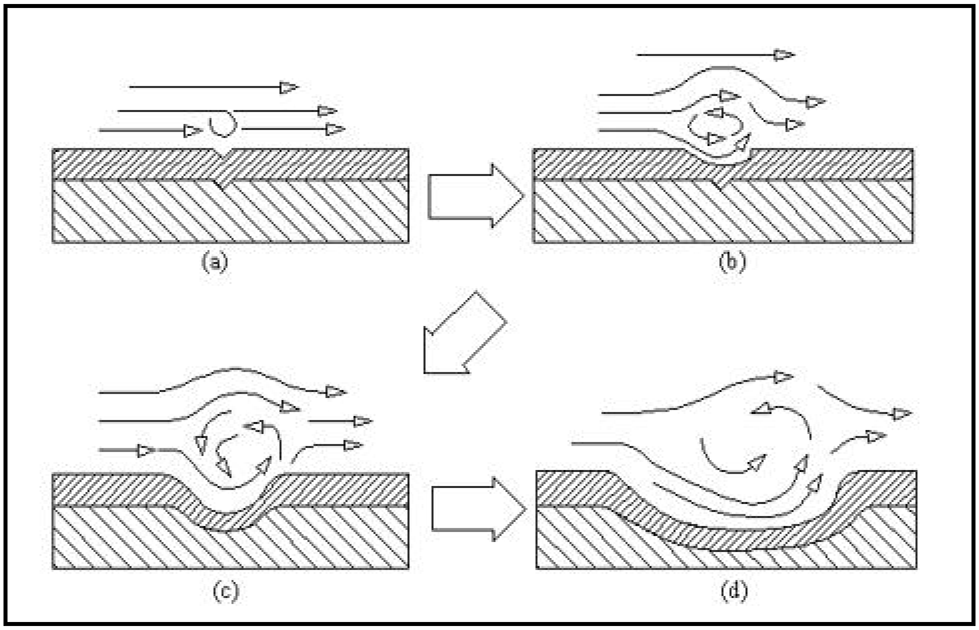

Figure 2. Erosion-Corrosion Process
(Source: Jones, pg. 345)

Erosion-Corrosion: Prevention

There are two ways to prevent or reduce erosion-corrosion. One method involves redesigning the flow of the fluid to ensure there is less turbulence. This can be accomplished by adjusting the design to use larger elbows in pipes that gradually curve. However, it can also be more feasible to design parts that can be easily replaced if the part will be subjected to erosion-corrosion. If this is uneconomical, then material selection will play an important role. Selection of a material that is more resistant to erosion-corrosion will also aid in reduction of damage, and can be particularly effective in combination with an efficient design.

III. CAVITATION-CORROSION

Cavitation-Corrosion: Mechanisms

Cavitation-corrosion belongs to a subset of erosion-corrosion wear processes. Like erosion, cavitation involves fluids accelerating over the surface of a material; however, in cavitation, the fluid flow is not causing the damage. Rather, cavitation occurs when the pressure in the liquid drops below the vapor pressure, and small pockets of vapor form in the fluid (See Figure 3). The mechanics of cavitation bubble formation can be explained by the inviscid equations of motion detailed in fundamental fluid mechanics texts.

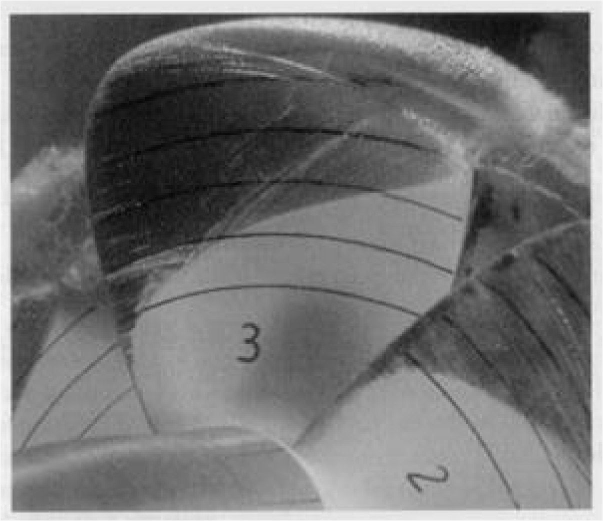

Figure 3. Bubble Cavitation on a Model Propeller
(Source: Kuiper, pg. 43)

These pockets collapse when they reach a region of higher pressure, creating a microjet of fluid (Kuiper, pg. 37). There is some debate over whether the microjet or the shock wave of the imploding pocket causes the erosion. Removal of the passive scales that cover the exterior of a metal surface constitutes the corrosive damage in cavitation. Repeated exposure can remove significant amounts of material, forming pits in the surface. These pits cause turbulence and other fluid effects that will decrease the efficiency of mechanical systems.

Large, deep grooves and pits in a surface are the primary effects of cavitation. Cavitation pits are distinguishable from erosion pits by their size and shape, which tend to be larger, deeper and more localized. Cavitated surfaces do not erode uniformly, but instead the larger pits are formed through repeated cycling of erosion and rest periods, where the crack propagation inward from the pitted surface detaches large portions of material. Cavitation-corrosion therefore also has the fatigue-like qualities of cyclic loading and periods of stress that exceed yield stress.

In addition, a synergistic effect of electrochemical corrosion and cavitation has been shown to exist where corrosion rates are increased in corrosive solutions. Passive films break down easily in corrosive environments, increasing the mass transport and corrosion rates. As shown in Figure 4, the mild steel (1050) and the tool steel (W1) exhibit a lower corrosion resistance in 3.5% NaCl solution than in distilled water (Kwok, Cheng, and Man, pg.151).

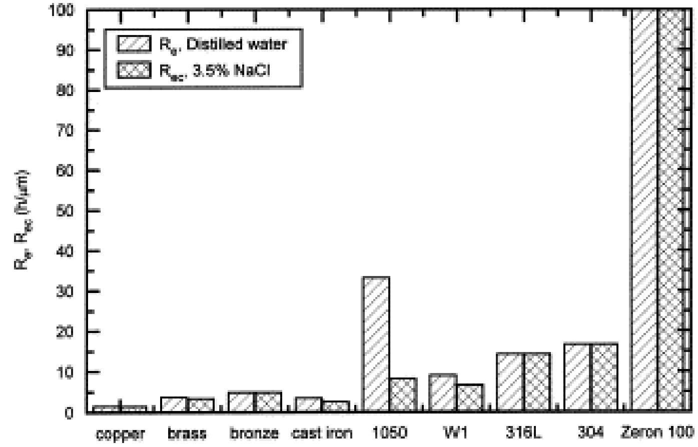

Figure 4. Cavitation Resistance for varying alloys
(Source: Kwok, Cheng, and Man, pg. 151)

Cavitation-Corrosion: Prevention

Since electrochemical corrosion affects the magnitude of cavitation-corrosion, both chemical and mechanical prevention mechanisms are effective in reducing damage. Usually, a combination of these two methods of corrosion prevention is the most beneficial way to reduce cavitation, although there may be applications where only one method is feasible.

Chemical prevention can come in the form of cathodic protection of the material or through the selection of materials with better corrosion resistances. Although cathodic protection is effective in reducing the damage done by cavitation, it does not reduce the rate of formation of corrosion products. Rather, the hydrogen evolved on the surface of the material cushions the impact stress of the implosions and the damage is decreased. (Jones, pg. 348)

Material selection is also a key in limiting the amount of damage done by cavitation-corrosion. It has been shown that an increase in austenitic content in stainless steels decreases the cavitation resistance, and smaller carbide particle size will increase cavitation resistance (Di Vernieri Cuppari, pg. 517). As a rule, cavitation damage increases the environmental damage of the solution, and materials should be chosen to limit the other forms of corrosion. The material properties that best indicate resistance to cavitation are hardness and engineering strain energy (Kwok, Cheng, and Man, pg. 145).

Another approach to decreasing or eliminating cavitation damage is to alter the mechanical system. Since cavitation occurs only with large pressure gradients, these should be avoided whenever possible. In the case of a ship's propeller, this clearly is infeasible due to the nature of propulsion, but in many other cases this change can dramatically affect cavitation damage (Kuiper, pg. 47). Pressure gradients are often related to a change in fluid velocity by Bernoulli's equation. Therefore, abrupt changes in velocity such as fluid passing through turbines and pumps should be carefully monitored so cavitation does not occur.

Cavitation-Corrosion: Case Study

Turbines are very susceptible to cavitation damage as shown on the Hoover Dam turbine runner in Figure 5. The size of this pit is approximately 10 millimeters long, but the increased turbulence caused damaging periodic vibrations in moderately high frequency ranges (15- to 100-kHz). These vibrations damage the rest of the system through a fatigue process not accounted for in the turbine design (Frizell, website).

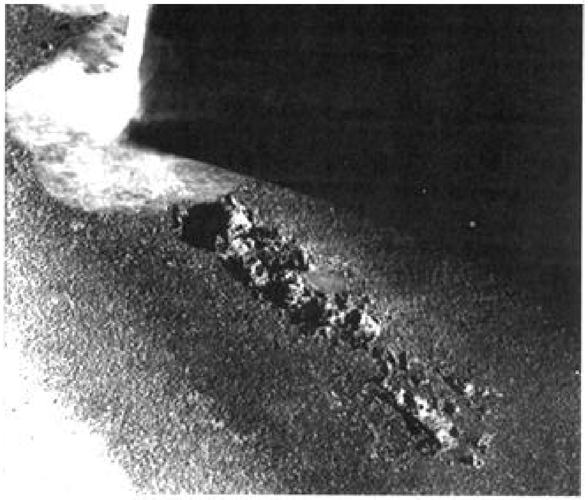

Figure 5. Cavitation Pitting in Turbine Blade
(Source: Jones, pg. 349)

Hydroelectric turbines such as this one are inspected every 3000-8000 hours for cavitation damage, and repairs are made immediately to runner by a process called overlay welding. Some of the stainless steel weld repair material can be seen in Figure 5. Since the runner is made of mild steel, a galvanic corrosion can exacerbate the damage done by cavitation (*Turbine Repair*, website).

To prevent cavitation from occurring altogether, a redesign of the turbine system would have to be undertaken where special consideration is given to the fluid pressure near the turbine runner. By decreasing the fluid velocity (and hence pressure) in this section, cavitation can be avoided. A significant decrease in fluid velocity will also decrease the efficiency of the turbine, and a compromise must be met (*Turbine Repair*, website). Ideally, the design should incorporate a tolerable amount of cavitation damage while minimizing the decrease to turbine efficiency.

IV. FRETTING CORROSION

Fretting Corrosion: Mechanisms

Fretting corrosion results from oscillatory tangential relative movement of two contacting metallic surfaces. In essence, fretting corrosion is a wear process on metallic surfaces that is enhanced by corrosion. Fretting corrosion operates in the reverse manner of erosion-corrosion in that erosion-corrosion is corrosion enhanced by wear. The contact between the two surfaces in fretting can generally be classified into two types. The first type is a flat surface interface, as could be found in the piston of an engine, the joint of an orthopedic implant, or even between the individual strands of a wire cable. The second type of contact is found in pins, or fasteners, with holes. In this case, the metal-metal contact is focused along the circumference of the hole and the contact points are usually subjected to greater interfacial pressure changes.

The cause of fretting lies in the contact and relative motion between two surfaces. This contact creates an abrasive wear on the surface oxide films of both surfaces, removing the passivating layer while leaving oxide debris particles. These debris particles contribute to the wear process, increasing the wear on a part as time passes. The passivating layer on a fretting part is continuously restored and destroyed as new material is exposed to the atmosphere and oxidized. The destruction of the layer only serves to exacerbate the corrosion and wear on the part as the number of debris particles increases. Additionally, the newly exposed material inevitably contains more defects on its surface, and passivation will occur easily on this surface, contributing to the exacerbation of the corrosion.

The load on a component will in part determine the life of the component. As fretting corrosion on a part increases, the load will begin to have a greater effect. Fretting corrosion reduces the cross sectional area bearing the load, increasing the applied stress on that section.

Fretting corrosion is also dependent on oscillatory motion, with greater frequencies generating greater fretting corrosion, while lower frequencies tend to exhibit slower fretting corrosion rates. The friction associated with the oscillatory motion results in a local temperature increase in the fretted area. In general, the fretted area will be much smaller than the bulk of the material, and will experience a quenching action, with its higher temperature quenched by the cooler bulk of the material. Typically, a thermal spike of at least 500ºC in steel, held at that increased temperature long enough for diffusion to occur, can result in a transformation to martensite in the fretted area. While martensite is a strong material, it is also a brittle one, and is an ideal material for the formation of fatigue cracks and subsequent part failure.

The most serious concern for systems subjected to fretting is the build-up of residual stresses with the metal. These residual stresses can eventually build to the point where they exceed the yield limit of the material, and result in a crack initiation. These cracks will propagate very rapidly with continued fretting, leading to fatigue failure of the part.

The service environment of a part also plays an important role in fretting wear. From the Arrhenius equation, and from the discussion of temperature above, it should be fairly obvious that the operating temperature will affect the amount of damage done. However, the importance of proper humidity is perhaps not so obvious. In a slightly humid environment, the presence of moisture will serve to speed up the corrosion, thereby increasing the amount of damage done. As humidity continues to rise however, the increased moisture will eventually decrease the amount of damage done as the condensed liquid begins to lubricate the metallic surfaces.

Fretting Corrosion: Prevention

As with all other forms of corrosion, prevention of fretting corrosion hinges on limiting the mechanisms of the corrosion and finding methods to reduce the contributing environmental factors. Combinations of various prevention methods are usually more successful than any one method alone.

Fretting corrosion is caused by the frictional wear of one surface on another, and as such, its effect can be reduced with the addition of a solid lubricant, such as graphite or a nickel-cadmium solid. Roughening the surfaces in contact can also help to reduce fretting, as it will contribute a reduction in the fretting motion frequency. However, it must be noted that even the slightest motion will cause fretting corrosion, so this method should be utilized only after careful study of the fretting surfaces.

Additionally, the use of a sacrificial solid liner can help to reduce the amount of frictional wear. The sacrificial liner is an insulting or cushioning material inserted between the two contacting surfaces. The two contacting parts will no longer experience fretting corrosion. Instead, this lining will fret, and as a consequence, must be periodically replaced. However, a cheap sacrificial liner can help to reduce the cost of fretting associated with expensive parts, offsetting the additional labor costs related to part replacement.

The load on a fretting part also influences the amount of corrosion that part will see. A greater load will create greater fretting corrosion. Reducing the load on a part will reduce the magnitude of the fretting corrosion. However, this comes at a cost of increased motion frequency, which may potentially decrease the life of the part. The reverse process, increasing the load, will also help to reduce fretting. An increased load will help to reduce the fretting motion frequency. However, as noted above, the slightest motion will cause fretting corrosion, so this method should be utilized with great care.

Redesigning the part with a more wear-resistant material can also yield favorable results, however, this method will depend on the hardness and abrasiveness of the fretting debris in the service environment.

Finally, it is worth noting that substitution of more corrosion-resistant (as opposed to wear-resistant) materials is not an effective prevention mechanism. The abrasiveness and hardness of wear particles controls the magnitude of fretting. Typical corrosion-resistant alloys can still form hard and abrasive wear particles, and will offer no particular advantage where fretting is concerned. Similarly, reduction of the corrosivity of the environment is typically ineffective in reducing fretting corrosion. Indeed, fretting has been observed in non-reactive alloys in a total vacuum.

Fretting Corrosion: Case Study

Fretting fatigue is a significant problem in helicopters due to the high frequency of alternating loads that the aircraft experiences. The most serious consequence of fretting fatigue is a loss of fatigue strength and a resulting loss of component life.

Helicopters utilize titanium in many key components, such as the main rotor hub (Figure 6). The high strength and low weight of titanium offers a dual benefit to engineers designing helicopters, who use titanium extensively in fatigue critical sections of the aircraft. However, if the helicopter design does not properly account for fretting, the titanium parts can experience a loss of fatigue strength exceeding 50% due to vibrations in service (Salkind, 4-1). In the case of the rotor hub, fatigue cracks and loss of fatigue strength originated in the threaded areas of the hub due to motion between the threads in the hub and their mating silver plate steel nuts.

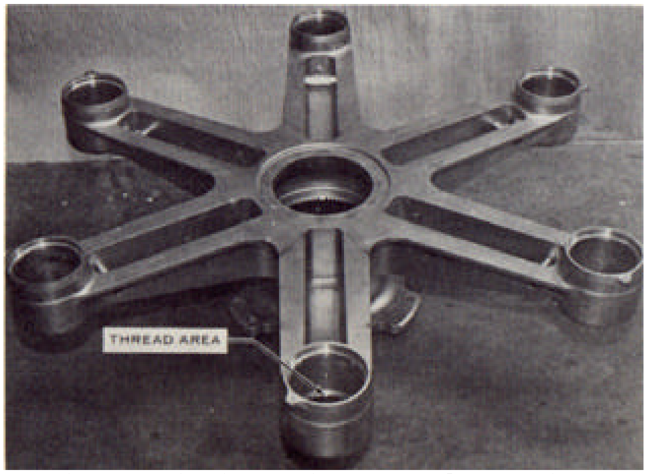

Figure 6: Titanium Main Rotor Hub (Top View)
(Source: Salkind, 4-3)

A complete redesign is the only feasible solution for a reduction in fretting at the rotor hub, as the operating conditions and environment cannot be appreciably altered. In this case, removal of threads in the fretted regions offered some improvement. However, the best solution would require a redesign of the part to eliminate the possibility of fretting. This would more than likely require replacing the threads in the hub with another attachment mechanism, such as a clamp. A comparison of the effects of these hub redesigns is shown in Figure 7.

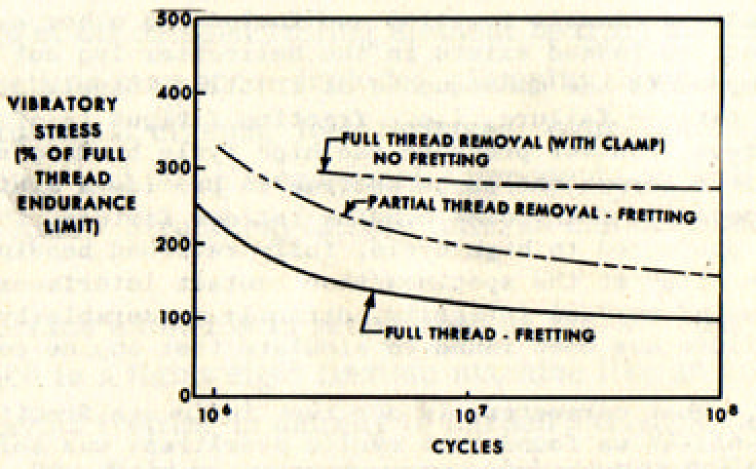

Figure 7: Effect of Redesign on Titanium Hub Fatigue Strength
(Source: Salkind, 4-5)

V. CONCLUSION

Erosion-corrosion, cavitation-corrosion, and fretting-corrosion all present serious design and service problems for practicing engineers. Each of these mechanisms, if left unchecked, can rapidly reduce the life of a part. However, consideration of these effects during the design stage can reduce and possibly eliminate the effects of these forms of corrosion.

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