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Pump shaft failures — a compendium of case studies

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Abstract

This paper presents a collection of pump shaft failures that have been encountered during the consulting activities at the University of the Witwatersrand and the Plant Infrastructure and Pipelines Centre at the Council for Scientific and Industrial Research (CSIR). © 2001 Published by Elsevier Science Ltd.

Keywords: Bearing failure; Corrosion; Fatigue failure; Pump failures; Shafts

1. Introduction

During operation, pump shafts usually suffer from degradation as a result of corrosion and/or mechanical degradation, usually in the form of fatigue failures. In many cases corrosion precedes fatigue failure and can actually accelerate the rate of failure.

Pump shafts are generally exposed to the liquid being pumped either on a continual basis or at certain locations along the length of the shaft. Specialised sealing arrangements comprising sleeves and o-rings can be used to reduce the amount of liquid ingress, however, where these sealing systems are not implemented or where the integrity of these seals is compromised, damage to the shaft in the form of corrosion may occur.

2. Corrosion failures on shafts

One of the most catastrophic forms of corrosion encountered on shafts is pitting attack. This localised form of corrosion results in the formation of holes or cavities in the metal and generally results in the

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shaft having to be scrapped due to the depth of penetration of the pits. The relatively stagnant liquid conditions, which exist between the shaft and sleeve during pump operation as well as periods of shutdown, create ideal conditions for pit initiation. The photograph in Fig. 1 shows a portion of a water pump shaft which had been in service for approximately 17 years. The bronze shaft sleeve has been removed revealing severe pitting in the area directly under the sleeve. The solution being pumped in this case was river water, a general composition of which is presented in Table 1. As can be seen from this table, the water had a relatively neutral pH of 7.21. The severity of the attack in this case thus suggests that pitting may have been assisted by a galvanic effect between the steel shaft and the bronze sleeves.

From this water analysis it can be seen that the water does not exhibit scaling tendencies, as predicted by the Langelier and Ryznar indexes, and as such the water would tend to be corrosive to steel (see Table 2).

All metals have a corrosion potential when immersed in a corrosive electrolyte. Thus, when two dissimilar metals are in contact with one another in a solution, a galvanic potential is set up between the two and may result in preferential corrosion of the more active metal. The galvanic series gives an indication of the potentials between various metals when immersed in seawater. The further apart the metals in the table, the greater the potential for galvanic corrosion between them. Using the galvanic series in Table 3, it can be seen that the steel shaft, being the more active metal, would corrode in preference to the bronze sleeve.

Methods of preventing pitting failures of this type would be to prevent any liquid ingress under the shaft sleeves. This can be achieved by using o-ring or other suitable seals between the shaft and the sleeve. Although lap joints are commonly used, poor quality machining will result in water ingress and subsequent corrosion. The use of a more corrosion-resistant material may also reduce the problem of pitting corrosion. Coatings can also be applied to both the shaft and sleeve, but the suitability and performance of these coatings would depend on the type of liquid being pumped.

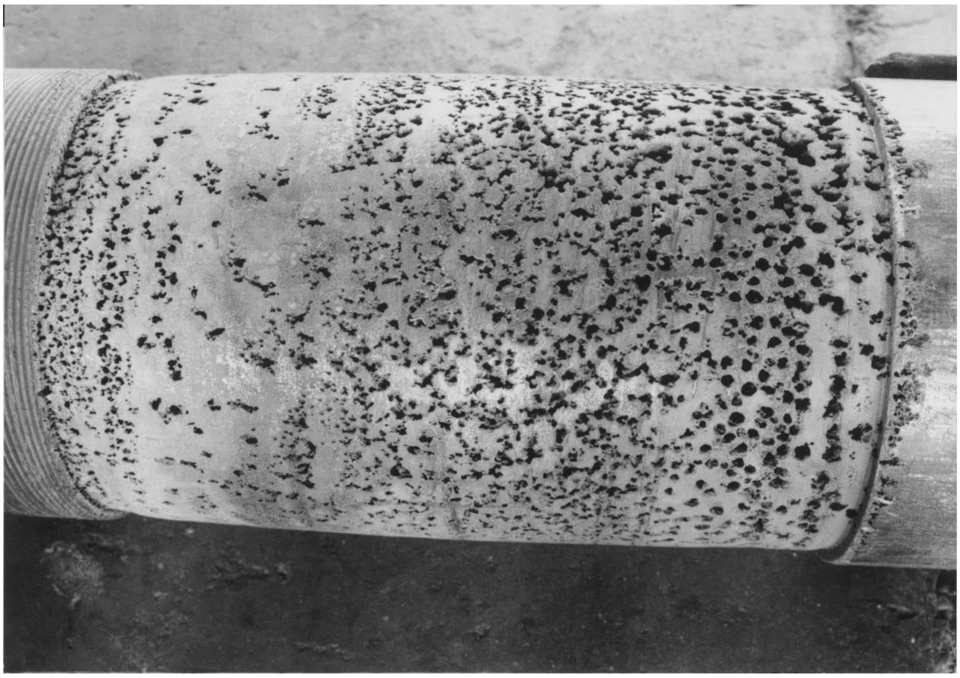

Fig. 1. Water pump shaft showing severe pitting.

Table 1
Analysis of the river water[a]

River water analysis	
Total dissolved solids	180
Total hardness ($CaCO_3$)	90
Calcium hardness	70
Magnesium hardness	20
Total alkalinity	80
Chloride as NaCl	45
pH	7.21
Soluble iron	0.03
Appearance of sample	Clear
Appearance of sediment	Brown
Ryznar index (RSI) (20°C)	9.12
Langelier index (LSI) (20°C)	−0.96
Ryznar index (70°C)	7.64
Langelier index (70°C)	−0.22

[a] Concentrations given in mg/l unless otherwise stated.

3. Fatigue failures on shafts

Probably the most common cause of failure on pump shafts is fatigue. In order for fatigue to occur, a cyclic tensile stress is necessary as well as a crack initiation site in the form of a stress concentration. Thus, rotating elements on pumps, such as the shaft, are susceptible to fatigue by the nature of their operation.

Should the shaft be slightly misaligned or become slightly misaligned due to incorrect installation or worn bearings, a bending moment is created in the shaft and the following types of fatigue may result:

1. Unidirectional bending — occurs when the shaft flexes in one direction only and thus one point on the shaft surface experiences a maximum tensile stress.
2. Reversed bending — occurs when the shaft flexes in two directions opposite to one another and two opposed points on the shaft experience maximum alternating tensile and compressive stresses.
3. Rotating-bending — occurs when all points along the circumference of the shaft experience alternate tensile and compressive stresses.

Fatigue failures on centrifugal shafts are most commonly of the rotating-bending type. Schematic diagrams of the various fractures, which can be expected from rotating bending conditions, are

Table 2
The use of Ryznar and Langelier stability indexes to predict the corrosive nature of water

Prediction of water characteristics		
LSI	RSI	Tendency of water
2.0	< 4	Heavy scale forming — non-aggressive
0.5	5–6	Slightly scale forming and mildly aggressive
0	6–6.5	Balanced or at $CaCO_3$ saturation
−0.5	6.5–7	Non scaling and slightly aggressive
−2.0	> 8	Under-saturated and very aggressive

presented in Fig. 2[1]. Fig. 2(a) and (c) illustrate the expected appearance of the fracture surface from a single origin under moderate and high degree of stress concentration while Fig. 2(b) and (d), illustrate the expected appearance of the fracture surface which has originated from multiple origins and which was subjected to moderate and high stress concentrations respectively.

Stress concentration sites on shafts where fatigue cracks may initiate are illustrated in Fig. 3[1]. The most common areas of crack initiation are at the stress concentrations occurring at the keyway root radius and sharp changes in cross-sectional area of the shaft. These stress concentration sites should thus be avoided when designing shafts. The stress concentration associated with various geometries can be calculated [2] and is referred to as a stress concentration factor. Stress concentrations serve to reduce

Table 3
The galvanic series

↑ Noble or cathodic	Platinum
	Gold
	Graphite
	Titanium
	Silver
	Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
	Hastelloy C (62 Ni, 17 Cr, 15 Mo)
	18–8 Mo stainless steel (passive)
	18–8 stainless steel (passive)
	Chromium stainless steel 11–30% Cr (passive)
	Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
	Nickel (passive)
	Silver solder
	Monel (70 Ni, 30 Cu)
	Cupronickels (60–90 Cu, 40–10 Ni)
	Bronzes (Cu–Sn)
	Copper
	Brasses (Cu–Zn)
	Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
	Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
	Inconel (active)
	Nickel (active)
	Tin
	Lead
	Lead–tin solders
	18–8 Mo stainless steel (active)
	18–8 stainless steel (active)
	Ni-resist (high Ni cast iron)
	Chromium stainless steel, 13% Cr (active)
	Cast iron
	Steel or iron
	2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
Active or anodic ↓	Cadmium
	Commercially pure aluminum (1100)
	Zinc
	Magnesium and magnesium alloys

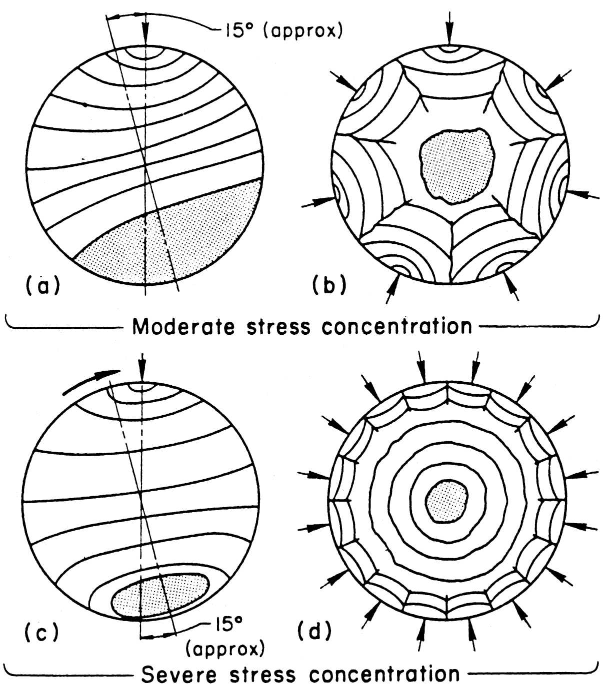

Fig. 2. Schematics of fatigue failure fracture surfaces in rotating bending.

the fatigue strength of the component. Steels (with the exception of stainless steels) have what is known as a fatigue limit which is a stress below which fatigue crack propagation will not occur regardless of the number of cycles [3]. Thus, the presence of stress concentrators decreases the allowable stress on the shaft at that point, making it more susceptible to fatigue. Stainless steels on the other hand have an endurance limit ie. the material can endure a finite number of cycles before failure as a result of fatigue will occur.

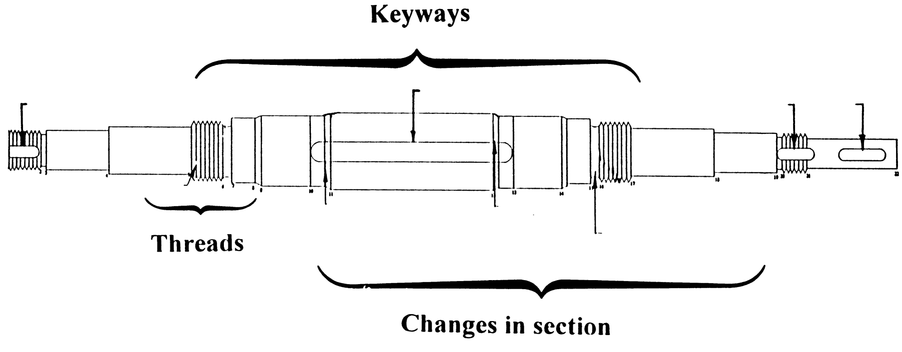

Fig. 3. Typical stress concentration sites on shafts.

3.1. Single origin fatigue failures

Fig. 4 shows a fatigue fracture on a multistage pump used to pump mine water with a pH of 7.5. In this case a crack initiated at the keyway root radius and propagated approximately midway through the section before final fast fracture occurred. The large fast fracture zone (labelled 'f') indicates that the shaft was under a high nominal stress. The pump reportedly had a service life of more than 3000 h before failure occurred. Referring to the various modes of fatigue failure in Fig. 2, it can be seen that the fracture presented in Fig. 4 occurred in bending, under a moderate stress concentration from a single origin. The stress concentration created by the keyway root radii was probably exaggerated by the presence of corrosion pits noticed in the keyway. It is predicted [2] that the stress concentration factor associated with a pit is 2. As stress concentrations are cumulative, pits occurring on keyway radii will increase the effective stress concentration. An illustration of the effect of pitting is given in the photograph in Fig. 5 which portrays a fatigue crack growing from a corrosion pit observed on another pump shaft. This particular pump was used to pump river water and suffered numerous fatigue failures initiated by corrosion pits.

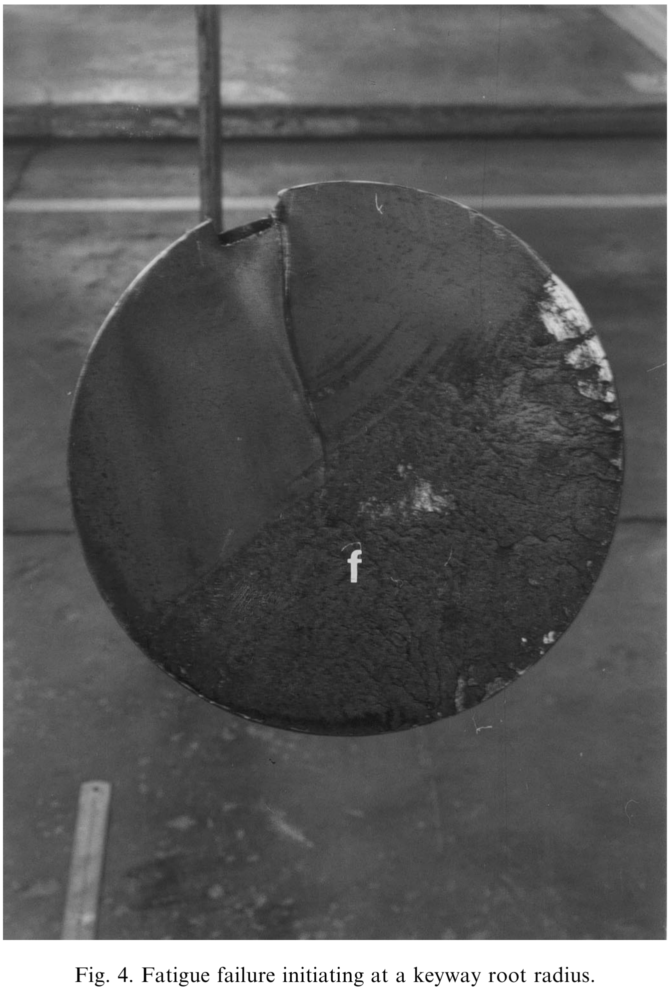

Fig. 4. Fatigue failure initiating at a keyway root radius.

3.2. Multiple origin fatigue failures

The photograph in Fig. 6 illustrates the type of fatigue failure which occurs as a result of multiple crack initiation sites. The ratchet markings indicated by the arrows represent various individual fatigue crack planes, which have propagated across the section and combined to form one large crack. The failure was initiated by a groove, which was abraded into the surface of the shaft as a result of contact with another component during operation. This groove resulted in the formation of a stress concentration around the circumference of the shaft, which subsequently initiated a number of fatigue cracks. The appearance of the fracture surface is similar to the one presented in Fig. 2b, which indicates a moderate stress concentration.

Fig. 7 shows a section of a multistage pump shaft embedded in the hub of a flexible coupling. The pump was used in a mine dewatering application and failed after approximately 600 h in service. Failure occurred at the face of the coupling between the pump shaft and the motor shaft. Multiple fatigue crack planes are visible (arrowed) indicating rotating bending fatigue with multiple crack initiation sites. The teeth of the flexible coupling hub showed significant eccentric wear indicating angular misalignment between the pump shaft and the motor shaft at the flexible coupling. It was concluded that fatigue cracks initiated at the keyway root and at various points along the shaft circumference and propagated under a cyclic bending stress occurring as a result of misalignment.

3.3. Preventing fatigue failures on shafts

Bearing failures due to ingress of water or dirt are common and will result in severe shaft vibration if not maintained. High levels of vibration can exaggerate fatigue and vibration should be monitored regularly. Misalignment of shafts occurs primarily during the installation process and can be avoided if

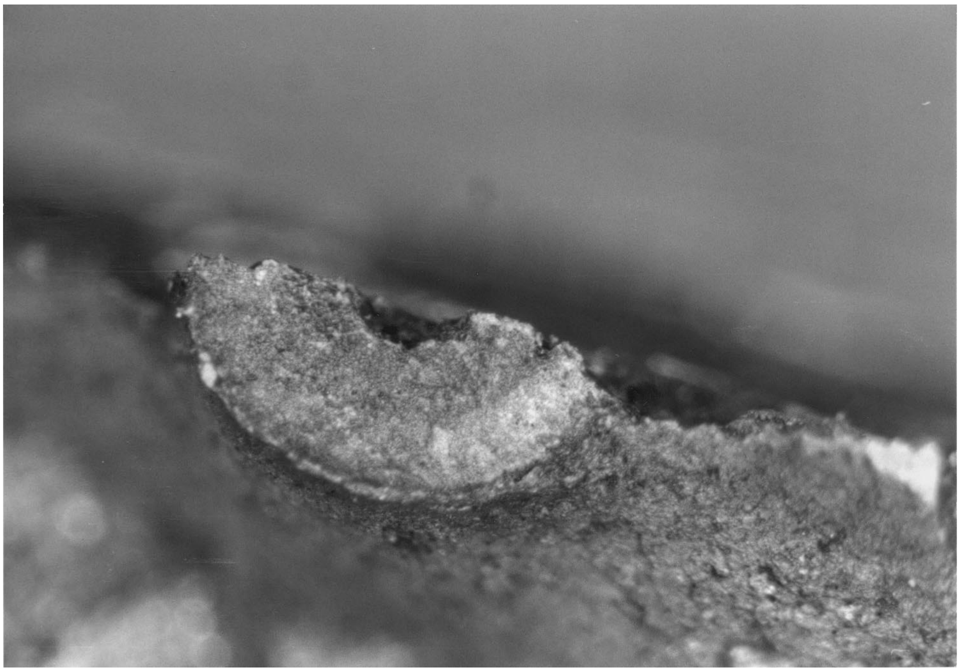

Fig. 5. Fatigue failure initiating at a corrosion pit.

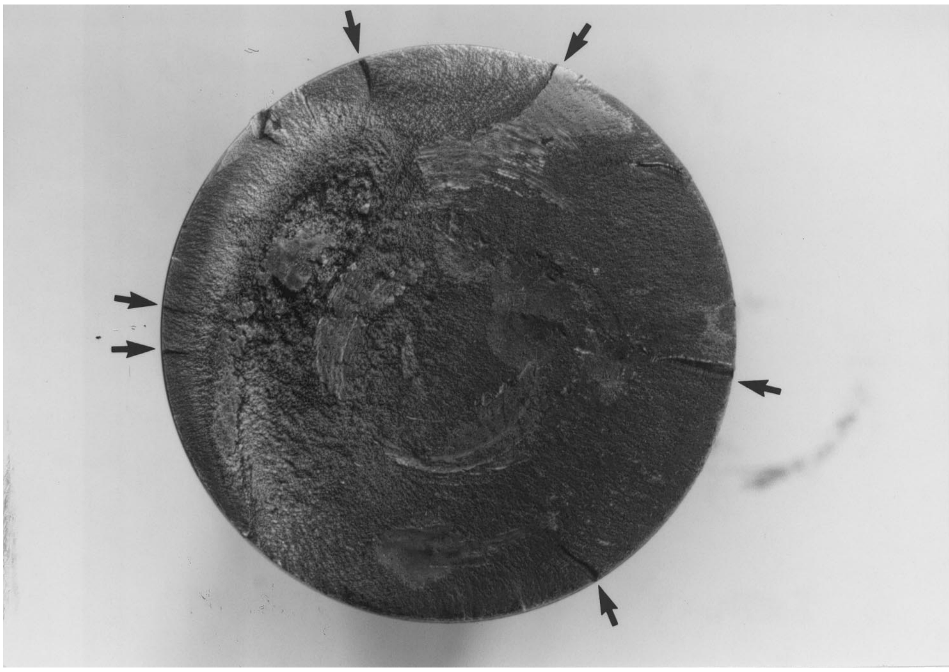

Fig. 6. Fatigue failure with multiple initiation sites. The arrows point to ratchet markings.

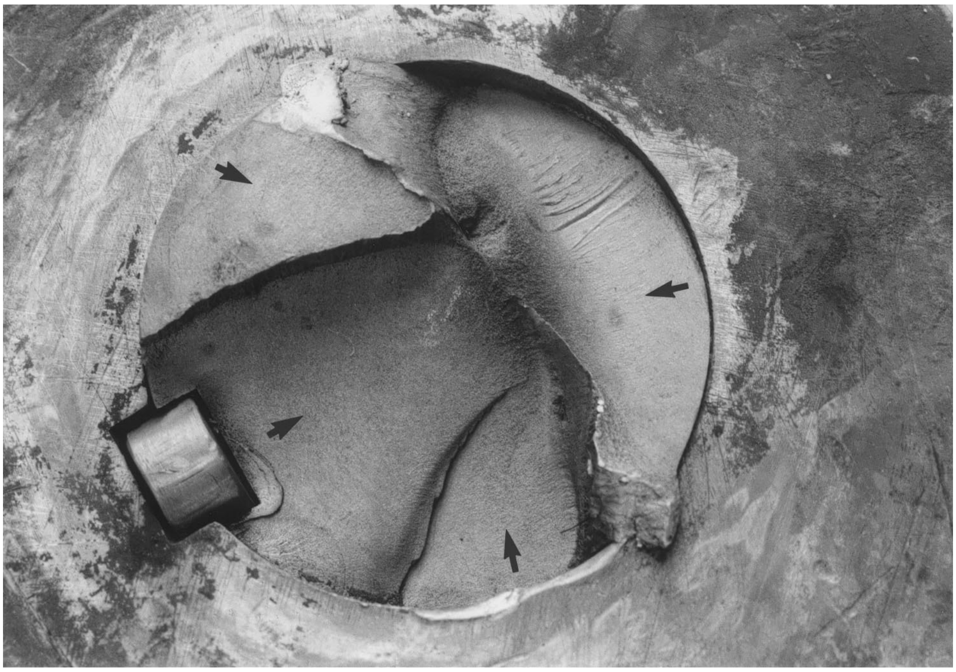

Fig. 7. Fatigue failure with multiple initiation. The arrows point to fatigue crack planes.

the correct procedures are followed. By preventing corrosion of the shaft, the stress concentration factor associated with pitting can be eliminated. Corrosion on shafts can be prevented by either sealing the shaft by means of o-rings on the sleeves or by selecting high alloy steels, such as stainless steels, depending on the application. Galvanic corrosion can be prevented by selecting similar shaft and sleeve materials. Increasing the keyway root radii and shoulder radii at changes in section will also serve to decrease the stress concentration factors at these sites. Elimination of keyways would be the ideal solution, but this is not always possible. Fatigue life can also be improved by selecting materials with higher fatigue limits.

4. Shaft sleeve failures

Sleeves protect the shaft against corrosion, erosion and wear and are mainly found on large hydraulic pumps [4]. However, inadequate sealing of the sleeves will allow ingress of water, resulting in under-sleeve corrosion of both sleeve and shaft as mentioned previously. Common materials for sleeves are cast-iron or bronze. If exposed to water, grey cast irons are likely to corrode fairly rapidly. Liquid ingress under a poorly machined or installed sleeve or shaft will result in a loose fit between sleeve and shaft, with the result that the components will wear against each other. One such example is illustrated in Fig. 8 and shows two sleeves from a horizontal split-casing pump. The sleeve on the left shows severe corrosion and wear when compared with the sleeve on the right. Both sleeves are located on opposite sides of the impeller shaft and were manufactured from cast iron. It is suspected that corrosion occurred due to water ingress under the sleeve, possibly as a result of the sleeve being slightly loose to start with. The sleeve corroded to the extent that it was loose on the shaft, resulting in eccentric wear and

Fig. 8. Cast-iron sleeves showing severe corrosion and wear (left-hand side).

subsequent thinning of the sleeve walls. This type of failure can be prevented by sealing the shaft by means of o-rings or by selecting a more corrosion-resistant material for the shaft sleeves.

5. Conclusion

As can be seen from the collection of failures presented in this paper, many factors can and do contribute towards pump failures, but if we are aware of these factors and how they affect the performance of pump components we will be in a better position to try and avoid these failures in the future.

References

[1] ASM Metals Handbook. Failure analysis and prevention, vol. 11. 9th ed. 1985. p. 463.
[2] Peterson RE. Stress concentration factors. New York: Wiley, 1974.
[3] ASM Metals Handbook. Mechanical testing, vol. 8. 9th ed. 1985. p. 364.
[4] Hicks TG. Pump selection and application. New York: McGraw-Hill, 1957.