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GLACIER

PLAIN BEARING DAMAGE

by

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ABSTRACT

Correct diagnosis is the first step towards improved reliability. The paper investigates in some detail, cases of bearing damage in turbomachinery, for plain cylindrical and tilting pad journal and thrust bearings.

Types of damage discussed include: cracking, pitting, scoring, wiping and thermal faceting. These are related to the causes which include overloading, overheating, corrosion, electrical discharge, dirt, static fretting, lubrication arrangements, assembly and adverse features of design and environment. Experimental and theoretical studies have lead to a better understanding of bearing behavior.

INTRODUCTION

Plain bearings of the hydrodynamic type have been used for many years in all types of turbomachinery and the vast majority give excellent service for many years. When, however, they suffer damage the consequences can often be very costly, both in terms of actual damage to the machine and in terms of interruption to plant operation and production.

It is general machine design philosophy that if something goes wrong, the more complex components should be protected and the damage confined to relatively small replaceable elements. Bearings fall in this category and when damage occurs, it is in many cases not attributable to any fault in the bearing, but is due to some malfunction of the machine or the bearing environment.

The identification of the damage is generally straightforward, and is often obvious to the naked eye: scoring, wiping, cracking or pitting of the bearing surface in severe cases are quite obvious. In other cases, a hand held x 10 magnifying glass can reveal further details. The real difficulty is to establish the cause of the observed damage. It is the intention of this paper to examine some cases of similar types of bearing damage easily identifiable on site, and by relating these to likely causes, indicate the appropriate corrective action which can be taken. In some cases it is not possible from one bearing to make a complete diagnosis, but the cause can be narrowed to a relatively few possibilities which can be investigated further, either in the metallurgical laboratory or by examination of other bearings from similar installations or after further controlled operational experience.

SCORING

Parallel or circumferential grooves in the bearing surface are normally formed by abrasive particles carried in the circulating oil. Small particles may bounce between the bearing and mating surface, causing a series of intermittent contacts, but larger particles score the soft bearing surface and may eventually become embedded. Fig. 1 illustrates where this has occurred on start up, the particle movement being more irregular than if it had occurred at high speed. It may be concluded in this case that the dirt was present on assembly. Fig. 2 shows a less severe scoring, which has occurred at high speed. A large number of embedded particles are present, and these have been identified as ferrous particles by means of an iron print (Fig. 3). The iron print

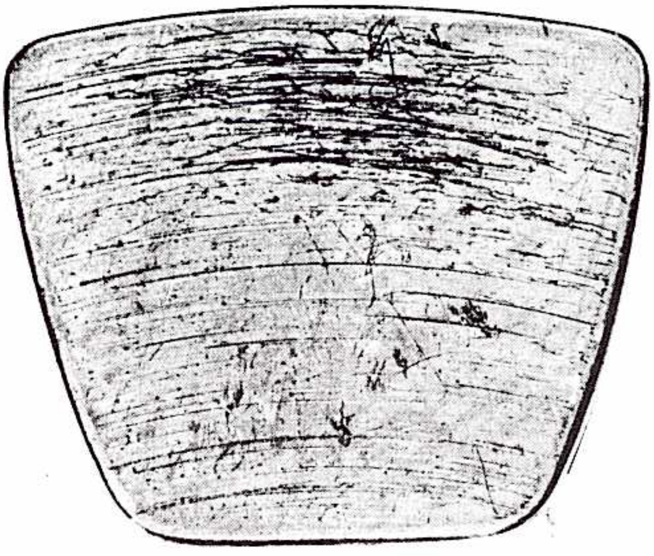

Figure 1. Scoring by dirt entering the bearing at start-up.

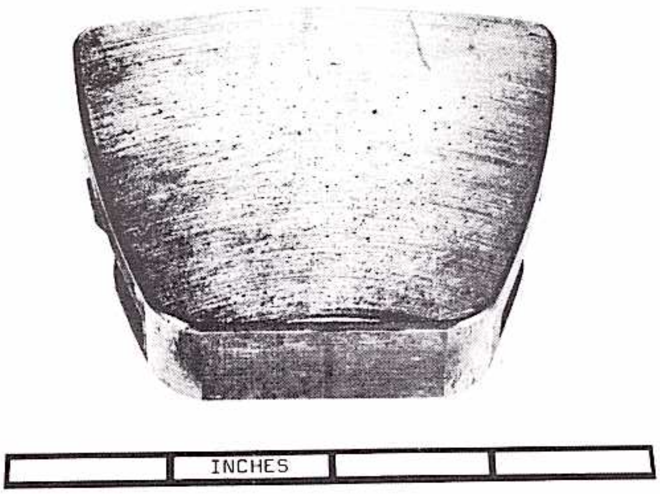

Figure 2. Scoring by embedded particles entering the bearing at high speed.

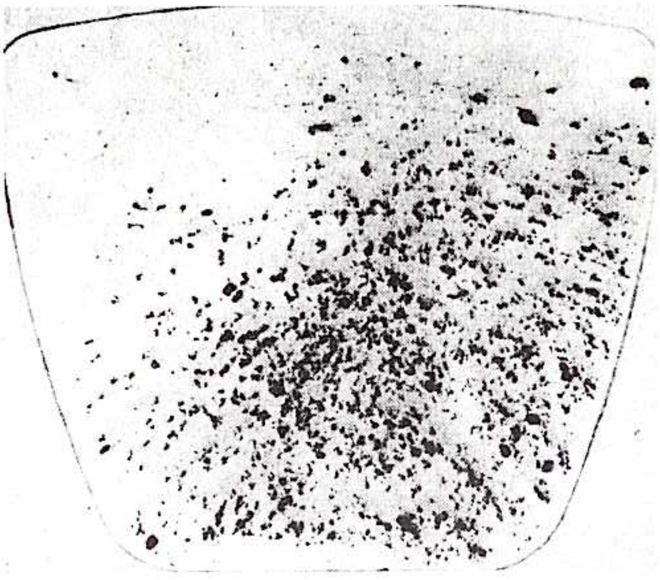

Figure 3. "Iron print" of ferrous particles from pad in Figure 2 (note that print is reversed left-to-right).

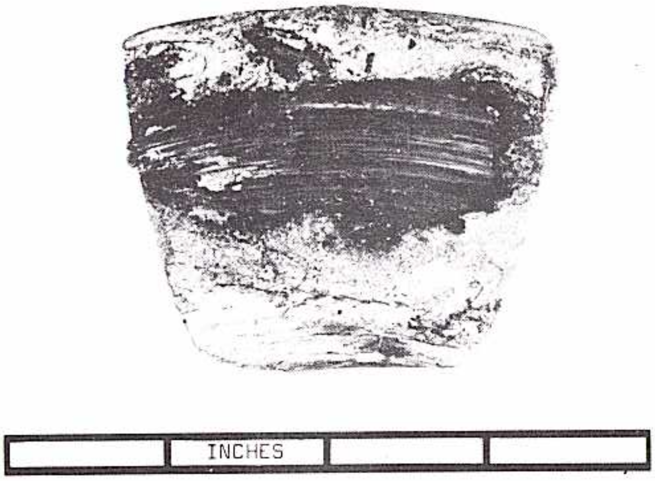

Figure 4. "Black Scab" formation on whitemetal lined thrust pad.

is perpared by soaking a piece of filter paper in 1% potassium ferricyanide and sodium chloride solution and placing the filter paper on the bearing surface. Within a few minutes, any iron particles present react to form the characteristic "Prussian Blue" stain and identify the severity of the contamination. In this particular case, the trouble was traced to excessive wear in adjacent reduction gearing. Light scoring can be accepted, providing the roughness caused does not exceed the thickness of the oil film which will generally be of the order of 0.01-0.05 mm (0.0004-0.002 in.). Excessive embedded particles, such as in Fig. 2, can result in scoring of the mating surface, and the bearing should be replaced.

Very severe cases of damage due to embedded particles can occur when the mating shaft is a steel containing chromium. A large particle probably not less than 1 mm (0.040 in.) across is required for the initiation, but upon becoming embedded in the bearing surface, it may form a hard deposit ("black scab") of material by reaction with the steel journal or thrust collar (Fig. 4). This scab will then cause very severe damage to the mating steel surface which is literally machined away with a formation of characteristic "wire wool." This mechanism is self-propagating when started, and susceptibility to scab formation appears to depend upon the nature of the lubricant and the metallurgical composition of the shaft or collar. Steels containing chromium or manganese in excess of 1% appear to be particularly susceptible to black scab formation, especially in high speed machines with bearing sliding speeds over 20 m/s (65 ft/s) (Ref. 1 and 2). Hard chrome plating of the mating surface has generally been found effective in avoiding this problem, or alternatively a separate sleeve or collar of unalloyed low carbon steel may be used. In addition, particular attention should be paid to cleanliness during assembly, taking care to avoid contamination of bearing surface and oilways with swarf, etc.

WIPING

Bearing materials are normally chosen for their ability to conform to the mating surface, or accept slight metal-to metal contact without serious damage. Preferably the bearing surface should polish smoothly by a wear process, but in more severe cases it may be necessary for the surface layers to melt and wipe in order to accept, for example, misalignment. Whitemetals (babbitts), both tin based and lead based, are specifically chosen for this property, and in many cases a slight wipe near one edge of the bearing only indicates that the bearing has performed as required. Severe wipes of this type indicate need for better alignment. If the damage to the bearing is more general, further investigation may be required. For instance, if the wiping extends all round a journal bearing, in both top and bottom halves, it is probable that the bearing has been assembled with inadequate clearance. As a general guide for a cylindrical bore bearing, the minimum diametral clearance ratio should not be less than $(N^{0.25}) / 6{,}000$ where N is the shaft speed in rev/min. In lightly loaded high speed machines, there is a possibility that oil film whirl may occur with a plain cylindrical bore, and it is common to use a profile bore of some type which will have regions of reduced clearance in order to give more positive control of the journal position. Particularly on vertical machines, designers often require a relatively high stiffness from the bearing oil film in order to ensure the critical speed of the rotor is away from the operating speed range. Greater stiffness can be obtained by reducing bearing clearance, but at the expense of the bearing running hotter and the possibility of damage to the bearing surface.

Another problem concerning the use of tight clearances occurs during rapid start up of a cold machine, where heat generated within the oil film may cause the shaft temperature to rise more rapidly than the bearing housing. Differential expansion of the shaft can cause temporary reduction in bearing clearance, which in severe cases may cause metal-to-metal contact in the zones of minimum clearance in profile bore bearings. Fig. 5 shows a typical seizure of a turbine bearing with a "lemon bore" (2 lobe) in which the vertical diametral clearance ratio was 0.0007. The effect is particularly pronounced if the bearing has a massive housing which takes a long time to heat up, or if the shaft is hollow so that it heats more rapidly. As a guide, it is unwise to utilize profile bore bearings with a diametral clearance ratio of less than 0.001, unless it is possible for the machine to be thoroughly warmed before being run at full speed.

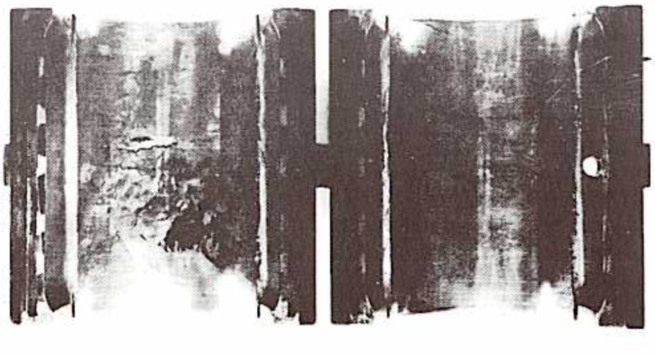

Figure 5. Lemon bore bearing seizure on start-up due to inadequate vertical clearance.

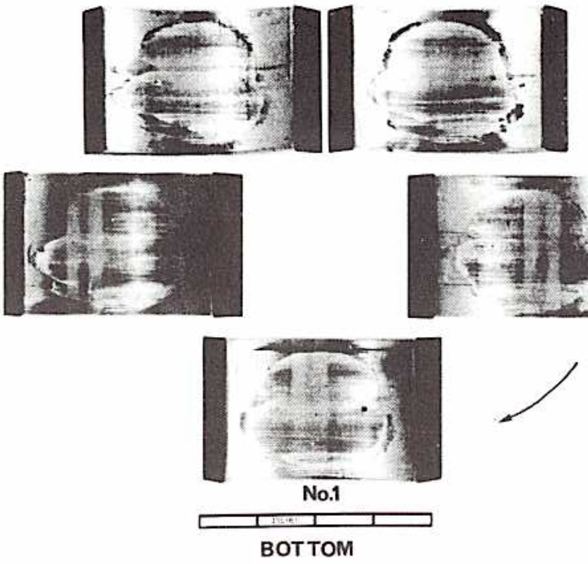

Figure 6. 160 mm (6.3 in.) bore tilting pad journal bearing with minimum diametral clearance across the pivots of 0.160 mm (0.0063 in.) which wiped and seized on rapid start-up to 5,000 rev/min from cold.

For tilting pad journal bearings, the situation is more severe because the heat flow from pad to housing is particularly poor causing the pads to expand inwards at start-up. Fig. 6 illustrates a wipe which occurred in a 160 mm (6.3 in.) bore tilting pad journal bearing under light load which was started from cold to 5,000 rev/min within a period of 2 minutes in a test rig. The bearing had a positive preset, i.e. the pad surface had been bored to a diametral clearance of 0.247 mm (0.0097 in.) but the pad pivots were shimmed to bring the minimum bearing diametral clearance over the pivots of the pads to 0.160 mm (0.0063 in.). Table 1 illustrates that although full speed was reached within 2 minutes, the temperatures continued to rise until after a further 4½ minutes sudden wiping occurred. A pad temperature of 145°C (293°F), although high, would not normally be expected to cause wiping and previous tests had shown that the bearing could operate without damage at temperatures in excess of 160°C (314°F) providing the load or speed was increased slowly. Fig. 7 shows measurements of loss of radial clearance as seen by proximity transducers mounted in the seal housings adjacent to the ends of the pads.

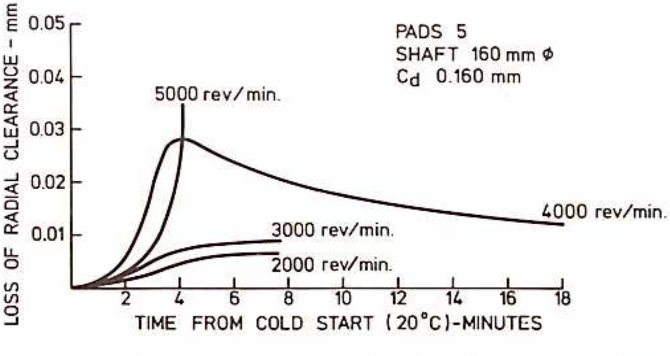

Figure 7. Graph showing loss of radial clearance in tilting pad journal bearing against time from starting, as seen by proximity transducers at the seal housing.

TABLE 1. TRANSIENT BEARING SURFACE TEMPERATURES IN TILTING PAD JOURNAL BEARING STARTING FROM COLD

TIME FROM			TEMPERATURE ° C					
			1	2	3	4	5	6
START MIN	SEC	OPERATING CONDITION	OIL INLET	OIL OUTLET	PAD BEFORE BOTTOM PAD	BOTTOM PAD	PAD AFTER BOTTOM PAD	HOUSING
					4000 REV/MIN			
0	0	Before Starting	30	Not Connected	34	34	34	35
-	55	Full Speed	30	”	46	70	68	35
2	0	”	30	”	52	80	80	38
3	0	”	30	”	54	84	84	40
4	0	”	30	”	56	86	88	41
5	0	”	31	”	58	90	90	43
7	0	”	35	55	62	94	94	47
8	0	”	35	56	64	95	95	48
10 MINUTES LATER								
18	0	”	42	58	63	92	92	52
					5000 REV/MIN			
0	0	Before Starting	22	22	21	21	21	21
2	5	Full Speed	23	46	65	102	103	29
3	0	”	23	48	77	113	115	33
4	0	”	24	49	87	118	120	37
5	0	”	24	51	100	125	127	40
6	0	”	26	52	120	135	137	43
6	35	Just Before Wiping	27	52	135	145	145	44
6	43	Max Temp At Wiping	27	53	200	195	170	45
6	54	Temp At Trip	28	40	170	160	145	45

It will be seen that although there was negligible differential thermal expansion for low speed starts, at 4,000 rev/min a peak was reached after 4 minutes following which housing expansion increased the clearance and the bearing operated satisfactorily. From the photograph, Fig. 6, it is clear that the differential expansion was considerably greater near the centre of the pads than at the edges near where the proximity transducers were positioned. Measurements show that the pad thickness at the centre was reduced from 22.000 mm (0.8661 in.) to 21.960 mm (0.8645 in.). Measurements of other pads were all similar. This indicates that at the centre of the pads the differential thermal growth at the time of wiping exceeded the available diametral clearance (0.160 mm=0.0063 in.) by 0.080 mm (0.0032 in.) giving the total maximum differential expansion of 0.240 mm (0.0095 in.). The shape of the wiped area is typical and indicates that the journal has become barrelled, due to greater temperature at the surface in the centre. It is probable that the pads have also suffered "pin cushion" distortion as a result of the oil cooling effect on their sides and back.

Wiping may be caused by excessive loading, particularly during starts and stops. Fig. 8 illustrates a typical example which shows that the wiping has occurred in successive thin layers. In this case once sufficient speed had been generated an oil film was established and the bearing operated satisfactorily. This may be compared with Fig. 9 which shows a bearing which has operated for extended periods under heavy loads at low speed. Not only has wiping occurred, but the local high temperatures in the thin oil film have resulted in breakdown and carbonisation of the oil giving rise to lacquering and blackening of the surface. This bearing has worn 0.125 mm (0.005 in.) at the inner edge, the outer edge being unmarked. There was clearly a serious misalignment between the mating collar and the pad mounting. This may have been exaggerated by thermal deflections of the collar as a result of the high temperatures on its surface.

The common way to overcome wiping due to high loads and low speeds in to use jacking oil. On tilting pad thrust bearings, high pressure oil is introduced to a circular groove

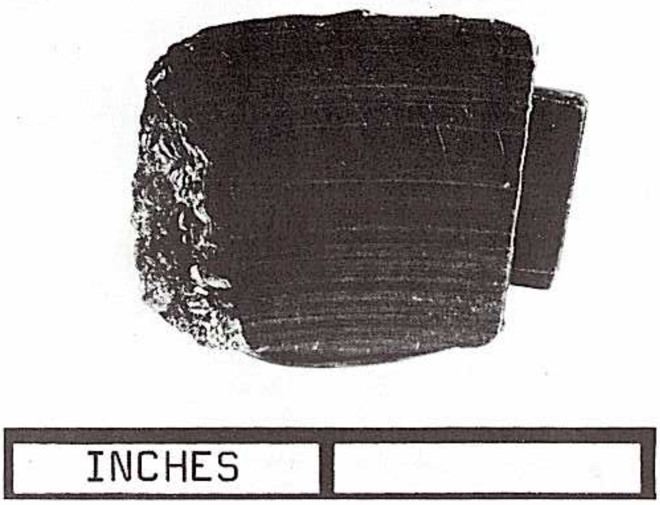

Figure 8. Surface wiping of whitemetal lined pad, in successive thin layers due to excessive steady load at start-up.

Figure 9. Wiping and lacquering due to heavy load and low speed operation, combined with radial misalignment of collar or pad mounting.

in the centre of the thrust pads to act as a hydrostatic bearing. However, in a recent vertical installation wiping was observed after a few starts and stops (Fig. 10). The extent of the wipe was similar on all the pads in the bearing thus indicating equal pad heights and good alignment of the bearing. Since the wipe occurred over the central areas of the pad where the pad crowning is normally accentuated by the thermal distortion of the pad in operation, it was not clear whether the damage occurred at high speed operation, possibly due to interference with the hydrodynamic oil film by the jacking oil groove, or whether it occurred during stopping as a result of faulty jacking oil supply. Tests conducted in the laboratory with different groove configurations and with ungrooved bearings demonstrated that the minimum oil film thickness at full speed was not significantly affected by the presence or shape of the groove. For example, at a specific load of 1.75 MN/m^2 (250 lbf/in^2) on a 90 mm (3.5 in.) pad at 60 m/s (200 ft/sec) the measured minimum oil film thickness was 0.031 mm (0.0012 in.) for an ungrooved pad compared with 0.032 mm (0.0013 in.) for a pad with a circular groove 20 mm (0.8 in.) diameter with no leakage. If the groove was fully vented, which would occur for example in the case of a leak in a jacking oil system, the minimum oil film thickness dropped to 0.019 mm (0.00075 in.) but no damage occurred to the bearing surface. It may be noted that 1.5 liter/min (0.4 US gal/min) oil leakage occurred under these conditions. The test was repeated at twice the specific load over a range of speeds at the lowest of which (10 m/s=33 ft/s) there was still no damage or wiping of the bearing surface; in this case the minimum film thickness was reduced to about 0.007 mm (0.0003 in.). Maximum pad temperature recorded in these tests was 151°C measured within 0.5 mm (0.020 in.) of the surface of the whitemetal.

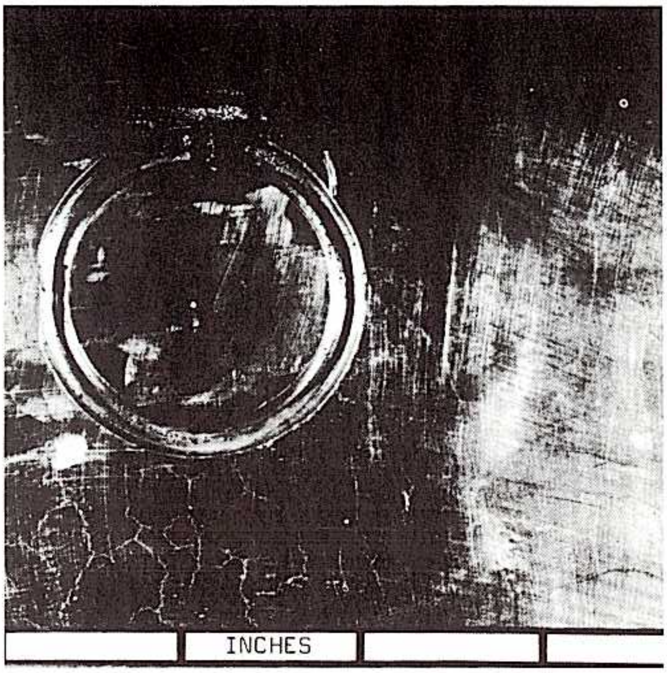

Figure 10. Wiping of thrust pad due to loss of hydrostatic jacking pressure during run down.

A series of tests was then conducted with stops under load, first with the jacking oil groove inlet closed and subsequently with it vented. The rig was operated with a given pad specific load at 40 m/s (130 ft/sec) for about half an hour to establish stable thermal crowning. The drive motor power was switched off and the collar allowed to come to rest. The stopping time varied between 35 and 25 seconds depending on the load. There were no surface marks when stopping with loads up to 4 MN/m^2 (600 lbf/in^2), but at 5 MN/m^2 (750 lbf/in^2) a slight polishing was visible over the trailing half of the pad. The polishing extended over the whole pad width and was not confined to the central area. In the polished area, there were marks which appeared to be a replica of the grinding marks from the mating collar, indicating slight softening of the surface of the whitemetal as the collar came to rest. When the tests were repeated with unrestricted leakage from the jacking groove, there was no damage when stopping under specific loads up to 2 MN/m^2 (300 lbf/in^2) but after stopping with a load of 3 MN/m^2 (450 lbf/in^2) a slight wipe occurred in the centre of the pad very similar to that encountered on the original installation. Although assurances had been given that the high pressure oil system in the original installation was in order, eventually a fault was found in it and rectified.

CRACKING

It is well known that when whitemetal is subjected to overload, cracking occurs which is generally attributed to fatigue. Typically this is seen in engine bearings subjected to repeated cyclic load, and is only occasionally seen in turbomachinery. Circumstances may arise where a machine spends a considerable amount of time operating near a critical speed, or with coupling out of alignment, but generally in these cases the vibration levels are considered too severe and the machine is taken out of service for rebalancing, re-alignment or other modifications before fatigue damage can develop. A characteristic of fatigue damage is that the cracks may reach areas near the bond, but they will then propagate through the whitemetal parallel to the bond leaving whitemetal still adhering to the backing. The remaining whitemetal is often polished by the loose particles fretting over a period of time. If there is no whitemetal adhering to the steel or cast iron backing the original bond may have been substandard.

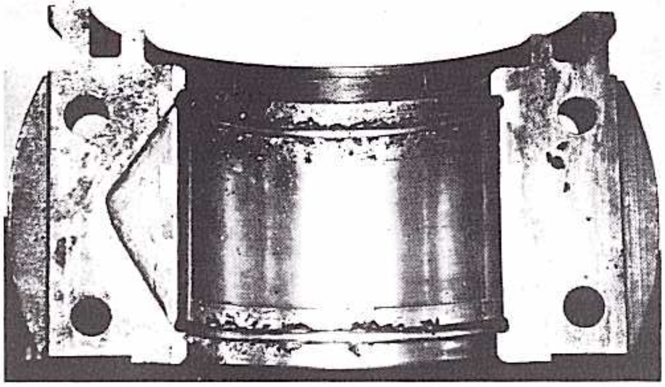

Figure 11. Fatigue on the lands in the chambered top of a turbine bearing.

The fatigue strength of whitemteal decreases markedly with increased temperature (Ref. 3) so that a partial loss of oil supply pressure may result in over-heating and produce fatigue damage in a machine which is only moderately out of balance. This is particularly so if there are narrow lands adjacent to oil grooves or in the "chambered" top half of a turbine bearing (Fig. 11), these areas having reduced load carrying capacity for out of balance forces. Fig. 12 illustrates two pairs of journal pads from the top and bottom of 5-pad bearings from a high speed vertical turbo feed pump which had lost blades in service. Four of the five upper pads were cracked (top, right) and it will be noted that the whitemetal has lifted slightly adjacent to the cracks presumably due to high pressure pulses of oil acting in the cracks. The irregular outline of the polishing is typical of fatigue. The fact that one pad is not cracked (top, left) is also typical of statistical scatter of fatigue damage. In contrast all 5 of the lower pads exhibited a roughly oval area of hard rubbing. This may be compared with Figs. 5 and 6 suggests that the bearing had inadequate clearance to accommodate differential shaft expansion on start up from cold.

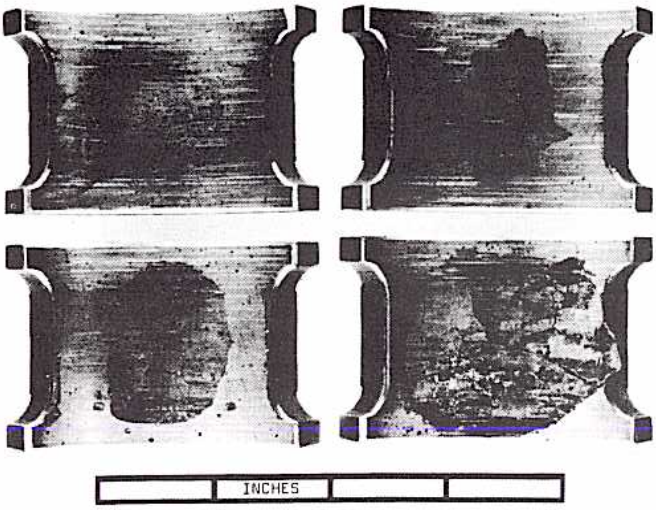

Figure 12. Bearings from a high speed turbo pump which lost blades in service. Top: 4 of the five pads exhibited typical fatigue damage. Bottom: All 5 pads exhibited high temperature rub probably due to inadequate clearance on start-up (Ref. Fig. 6).

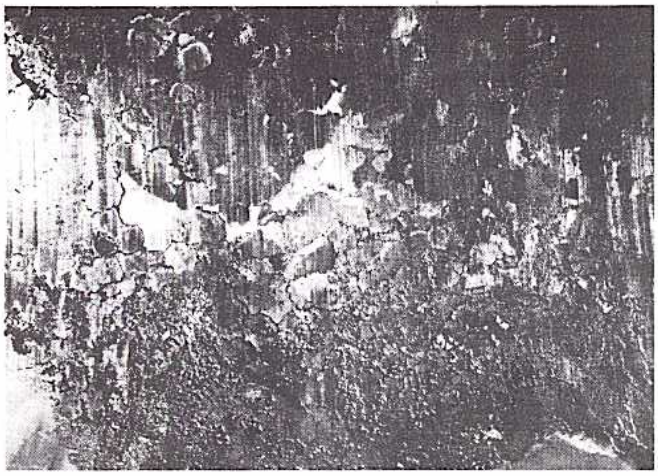

Figure 13. Intergranular craze cracking on whitemetal due to overheating and partial seizure.

The cracking in the lower left bearing is typical of the intergranular craze cracking which is seen more commonly than fatigue in turbomachinery, and may be the result of only a short period of overheating. A typical example in a large steam turbine is shown in Fig. 13. The high temperature zone extends lower than the surface layer of a single wipe, so that more of the whitemetal is weakened. Frictional forces on the surface from contact with the shaft may cause partial shearing of the whitemetal, opening up the cracks, and whitemetal may be displaced into oil grooves or over the edges of the bearing (Fig. 12 lower right). It is often found that fine pores or pits also form in the whitemetal and the lining has a crumbly appearance as can also be seen in Fib. 13. This type of damage often extends only about half way through the thickness of the lining, presumably because the lower layer has more strength, being cooled from the backing. The cause of the overheating may be partial loss of oil supply as in Fig. 13 or excessive overload, as in Fig. 14 which shows the damage caused to a

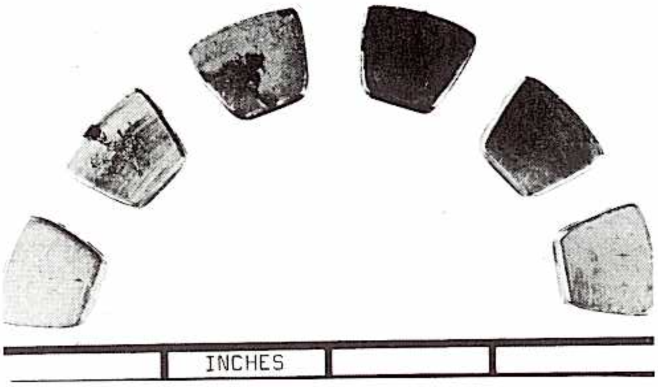

Figure 14. Overload on small steam turbo-generator thrust bearing due to water passing through the turbine.

small steam turbo generator thrust bearing when water passed through the turbine. The fact that there was excessive overload, in excess of 7 MN/m² (1,000 lbf/in²), was confirmed by the size of indentations of the pad pivots in the carrier ring. In this case, the damage was accentuated by misalignment between shaft and housing resulting in 3 out of 11 pads being subjected to the major part of the load. This type of craze cracking is also seen in cases of overheating and overload as a result of loss of clearance due to differential thermal expansion of the shaft on start up. Another case, presumed to be due to the same mechanism, is illustrated by the fine cracks which were observed on the large pads of Fig. 10 after only two or three starts and stops.

Intergranular cracks may be formed by a thermal ratcheting process described by Boss & Honeycomb (Ref. 4). Tin crystals are anisotropic, having different co-efficients of thermal expansion in each crystal axis. Repeated thermal cycling results in faceting of the bearing surface (Fig. 15) which in severe cases may cause undulations in excess of 0.025 mm (0.001 in.).

After as few as 100 thermal cycles through 100°C (212°F) cracks may form in tin based whitemetal, and whilst undesirable, the authors' experience is that although the crack extends from the surface to the bond, it does not propagate further and the authors have never seen whitemetal particles break away through thermal cycling. Nevertheless, it is an indication of high bearing temperature and steps should be taken to reduce it by one or more of the methods indicated in Ref. 5. Alternatively, a bearing material can be chosen with the ability to withstand higher temperatures such as 40% tin aluminum (Ref. 3).

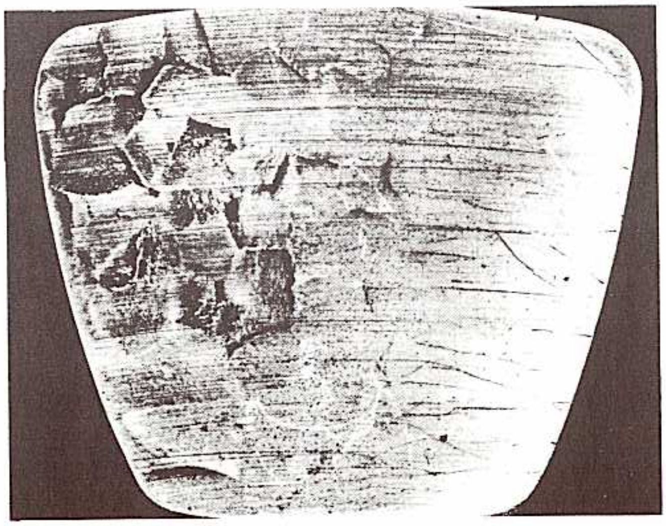

Figure 15. Faceting on a tin based whitemetal pad due to thermal cycling.

PITTING

Attention has already been drawn to one form of pitting (Figs. 13 and 14). This is generally uneven, and associated with cracking and results from overheating and overload. Fig. 16 shows a much more regular pitting (in this case magnified x 25), the details of which may be sometimes seen with the naked eye. Fig. 17 shows a general view of the tilting pad and it will be seen that there is a clear boundary between the pitted (matt) central zone and the unaffected zone on the left. The whitemetal has been tapered down by the pitting so that the underlying steel has been exposed near the right hand edge. The cause of the pitting was traced to the discharge of electric current through the oil film resulting in spark erosion. The pits formed are generally hemispherical, uniformly distributed over the zone of

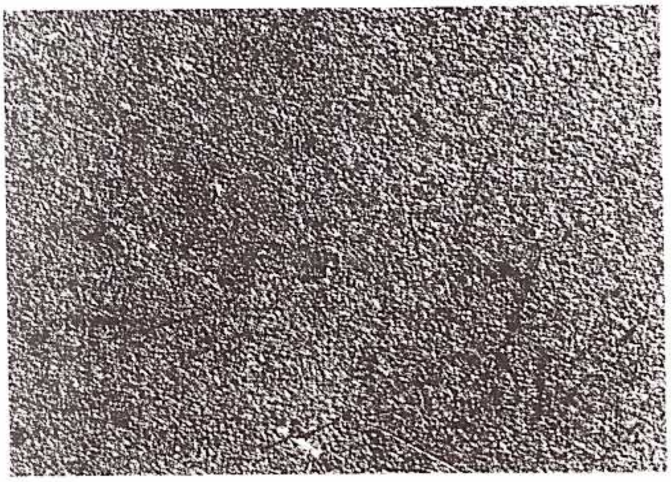

Figure 16. Electrical discharge erosion on thrust pad (x 25).

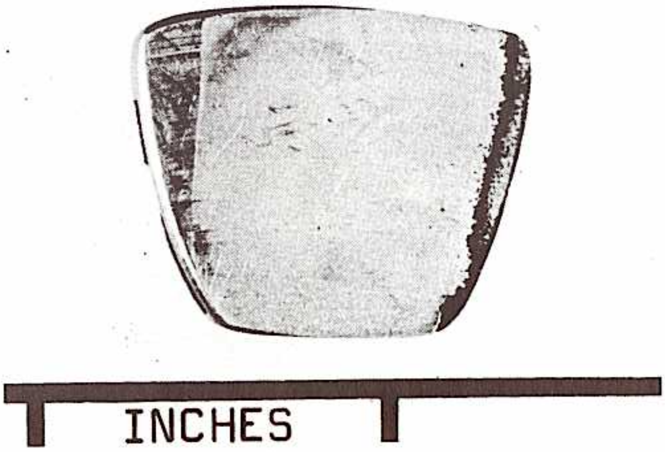

Figure 17. Electrical discharge erosion on thrust pad.

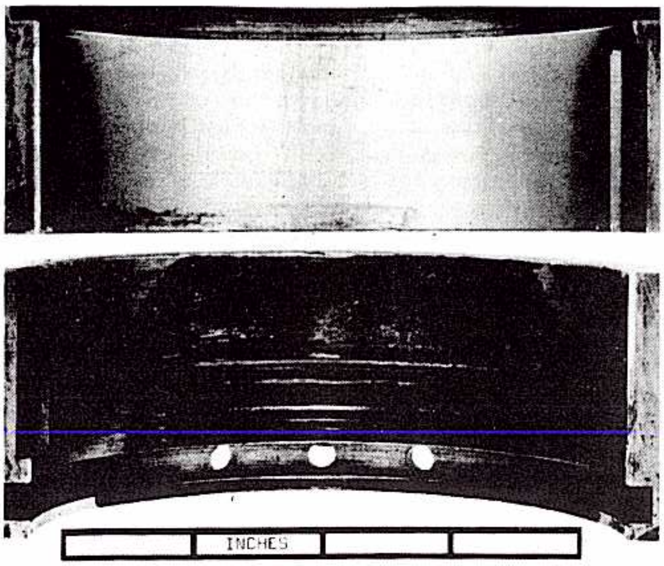

Figure 18. Static fretting damage due to external vibrations.

thin film, and may also be found in the mating surface. The various causes such as stray currents from alternators and inadequate earthing have been described in Ref. 6. A contrasting type of pitting is shown in Fig. 18. Instead of being clean and shining the pits have a black deposit. This is tin oxide formed by the fretting of dry bearings in a machine which is not operating, but subject to external vibration from adjacent machinery. This type of damage is particularly likely to happen in marine applications and generally occurs in the crown of the bottom half bearing. In this case the bearing had not been run subsequent to the fretting, and diagnosis was straightforward. Had the machine been operated, wiping of the roughened surface would have occurred, obscuring the pits and possibly removing the majority of the black deposit.

Corrosion can also cause pitting although this is not common with tin based whitemetal. Black tin oxide can be produced by excessive water contamination (in excess of 1%), particularly if chlorides are present as in sea water (Fig. 19). The pits formed are uneven and, in the case of flaking tin oxide, relatively large. When tin oxide corrosion occurs large areas of the whitemetal are affected and, if water is present, it is generally accompanied by rusting of exposed steel surfaces.

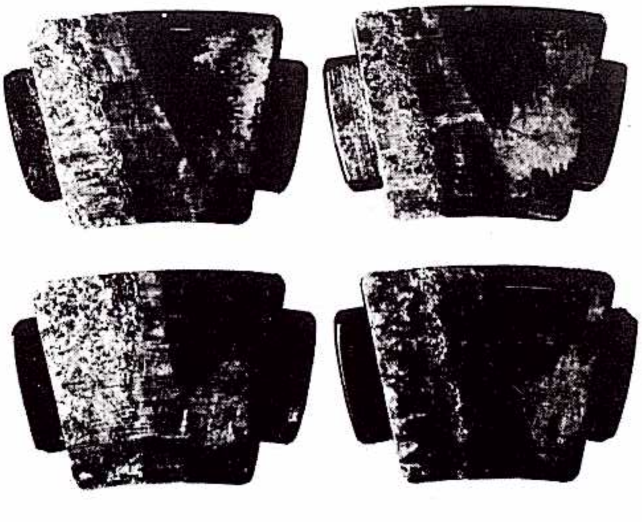

Figure 19. Tin oxide corrosion of tin based whitemetal pads.

An unusual type of corrosion has recently been seen in marine gas turbines and associated gearing (Ref. 7) fed from a common oil supply. Characteristically the corrosion occurs near the trailing edge of each pad, in the zone of thinnest film and highest temperature. Laboratory investigation has shown that samples immersed in a beaker test with used oil are not affected, but in the 124 mm (5 in.) thrust bearing test rig described in Ref. 8 corrosion and blackening occurred after 40 hours at bearing metal temperatures as low as 110°C (230°F) with a mean collar speed of 78 m/s (250 ft/sec). The oil contains EP additives, and while investigations are not yet complete it appears that the additives may have some influence on the type of corrosion taking place and the phenomenon is also associated with the high rates of shear. A rig test at 130°C (266°F) with a mixed set of pads, including a lead based whitemetal and 40% tin aluminum, showed that after 80 hours the lead based whitemetal was more severely attacked than the tin based whitemetal; the 40% tin aluminum was not affected, however. (Fig. 20).

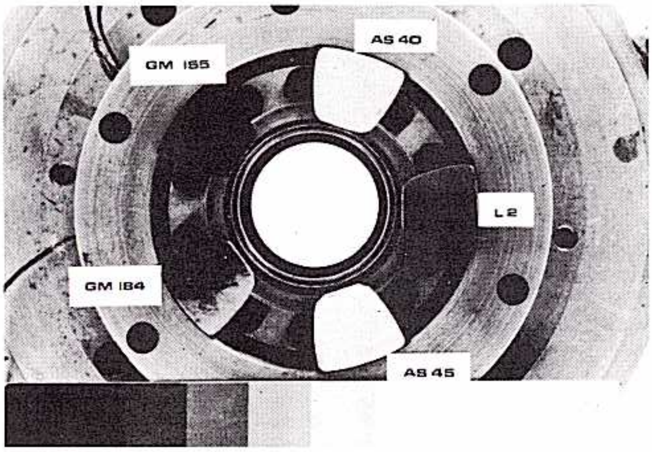

Figure 20. Corrosion of lead (GM 155) and tin (L 2 and HC 2) whitemetal in gearing oil, with no attack on 40% tin-aluminum (AS 45 and AS 40).

OTHER TYPES OF DAMAGE

From time to time types of damage occur which do not fall readily into the above categories. One such case was observed recently and is illustrated in Fig. 21. This shows part of a tilting pad thrust bearing which operates at a speed of 70 m/s (230 ft/sec) in which the pads experienced high whitemetal temperature, 170°C (340°F) as measured by thermocouples mounted 0.5 mm (0.020 in.) below the pad surface.

Adequate oil film thickness had been maintained and there was no wiping of the whitemetal but due to the high temperature, excessive crowning of the pad occurred. The whitemetal in the area of the crown under the combined effect of high pressure and temperature was deformed to form a hollow 0.007 mm (0.0003 in.) below the original pad surface surrounded by a rim 0.010 mm (0.0004 in.) above the original surface. When the pad cooled the rim was

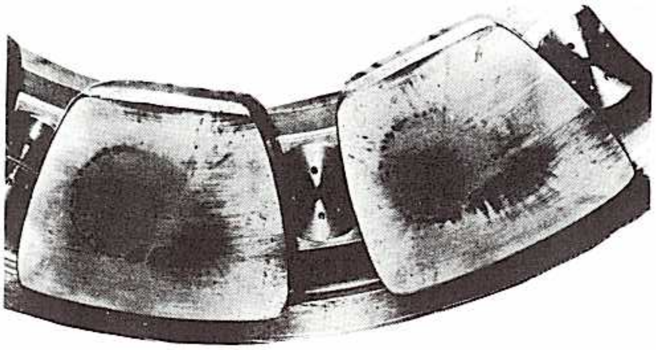

Figure 21. Thrust pad subjected to excessive temperature causing deformation of whitemetal without wiping.

exposed and polished (showing dark in Fig. 21 due to the lighting) presumably during subsequent starts and stops under light load.

CONCLUSION

It is not appropriate to draw specific conclusions to a paper of this kind. If it proves of help in identifying the cause of even a single case of bearing damage, its purpose will have been served.

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