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A comparison of the performance of AISI 52100 and AISI 440C ball bearings in a corrosive environment

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The paper describes experiments to compare the performance of two ball-bearing steels in an unusual environment based on conditions in a power station application. The materials tested were the conventional AISI 52100 ball-bearing steel (which had been suffering from corrosion damage in the application) and an alternative material, the martensitic stainless steel AISI 440C. The test atmosphere was moist carbon dioxide at a pressure of about 3 MPa, and bearings were deliberately contaminated with a representative amount of sodium chloride. The objective of the tests was to compare the rolling-contact fatigue performance of the materials and to look for other failure mechanisms such as hydrogen embrittlement. Actual ball-bearing assemblies were used as test specimens. Failure rates were found to be between 1 and 2 orders of magnitude higher than would have been expected under ideal conditions, but in spite of various differences in morphology rolling-contact fatigue appeared to be the only significant failure mechanism. Results were analysed statistically by assuming that failures fitted an exponential distribution, and it was shown that the stainless bearings performed more than twice as well as those made from conventional steels.

1. Introduction

During routine maintenance, superficial corrosion was discovered on certain ball bearings removed from components operating inside the pressure vessel of a CEGB nuclear power station. These bearings were grease lubricated, made from conventional En31 or AISI 52100 type steels, and compatible with their location in a relatively cool region of the reactor. It appeared likely that condensation of water on or near the bearings during moisture level excursions had caused the corrosion, perhaps enhanced by the presence of chloride ions of uncertain origin. Although no operational problems had occurred, it was thought prudent to examine ways of preventing further corrosion.

One of the possible options was to replace the bearings with similar components manufactured from a corrosion-resistant steel such as AISI 440C. Whilst it was known that this would prevent the corrosion it was thought possible that the fatigue properties might be inferior. A search of the literature revealed no adequate comparative fatigue data even in air. In addition it was not clear whether, in the presence of chloride and of moisture, AISI 440C might be more susceptible to non-fatigue processes such as stress corrosion cracking or hydrogen embrittlement.

It was therefore decided to mount comparative rolling-contact fatigue tests of the two materials in a simulated reactor environment of CO_2 at a temperature and pressure of 160° C and 2.8 MPa, respectively, moisture level <30 vpm with chloride contamination of the grease. Loads and speeds were increased in order to produce results on a reasonable timescale, but care was taken not to exceed the limits which might alter fundamental processes. For example, it was thought acceptable to move from the "partial" to the "full" elastohydrodynamic lubrication (EHL) region because the quantitative effect of film thickness is reasonably well known (at least empirically).

2. Test procedure

Two similar multi-bearing test rigs were developed from those already described by Radcliffe [1]. Each consisted of a pressure vessel in the form of a vertical cylinder 2 m high and 230 mm bore. From the upper flange was suspended an a.c. motor (1450 rpm) driving a "stack" of 12 double-shielded bearings, 6000 series, on a silver steel shaft 330 mm long. The outer races were mounted in individual steel housings which were loaded radially and prevented from rotation by a coil spring, adjusted by a screw. A constant load of 445 N (100 lbf) was used. The main improvement over the original rig design was the use of drying and wetting columns containing magnesium perchlorate and molecular sieve, respectively, which were switched manually in and out of the gas supply line to control the moisture level. The CO_2 was supplied from a bulk tank and no recirculation was employed, but a continuous gas flow was provided by the bleed for electrolytic moisture meters.

With the exception of bearings for two unlubricated tests, all were lubricated by the supplier with Burmah-Castrol Nucleol G121, a "nuclear" grade mineral oil based grease which is compatible with CO_2. In order to contaminate bearings with a pessimistic level of chloride, the bearings were immersed in a sodium chloride solution and dried in an oven at 110° C for two hours before fitting. Analysis of grease from such bearings showed chloride levels of 2900 ppm, compared to 40 ppm in virgin grease samples. After this treatment, followed by 820 h in pressurized CO_2 at 160° C, some "static" bearings were examined microscopically. The tracks and rolling elements of the stainless bearings appeared as new, but the standard En31 steels were just perceptibly tarnished. However there was no evidence of pitting corrosion or other undesirable features at magnifications up to 40×.

Details of testing and results are given in Table I which shows that durations of ~300 to 900 h at the loads chosen gave an adequate proportion of bearing failures. Failure was defined as the presence of any visible spalling or pitting on the running surface of any races or rolling elements. After each test all the bearings were dismantled and cleaned before examination under a binocular microscope at up to 40× magnification. As expected, the comparatively high test temperature (160° C) resulted in some grease degradation. The grease had invariably darkened, was often stiffer than new, and particles of a solid, brittle "lacquer" were found on many of the races. A variety of solvents and techniques were tried unsuccessfully, but eventually the following effective technique for removing the grease residues was developed. After removal of the shields the bearings were placed (several at a time) in polythene bottles with a mixture of 10% phenol and 90% dichloromethane. The bottles were sealed and placed in a flask-shaker for half an hour, longer periods leading to some attack of the En31 steel. After this treatment the bearings were thoroughly washed with dichloromethane and dried at room temperature.

TABLE I Results of tests of lubricated bearings

Test number	Bearing material	Number of bearings	Number failed	Hours run	L_0
1	SS	12	9	746	633
2	SS	6	3	575	1027
3	En	6	3	575	1027
4	En	6	3	482	861
5	SS	6	4	482	569
6	SS	6	2	480	1427
7	En	6	6	480	247
8	SS	12	6	888	1434
9	En	6	5	572	457
10	SS	6	0	572	–
11	SS	12	7	820	1061
12	En	12	10	526	359
13	En	6	6	330	170
14	SS	6	1	330	2141
15	En	12	7	569	736

SS: stainless steel (AISI 440C).
En: 1%C–1½%Cr (AISI 52100).

3. Observations

A metallographic examination of unused bearings showed that the structures of the steels were fundamentally similar, being a matrix of tempered martensite containing chromium carbides. In the standard En31 steel the carbides were small (~1 μm) and even in size and shape. However primary carbides in the stainless AISI 440C steel were up to 10 μm across, and more variable in size and shape; micron-sized secondary carbides were dispersed more evenly. The general cleanliness of both the steels was good.

The analysis performed subsequent to these experiments concentrated on the surface and sub-surface condition of balls and races. (Whilst there were a few cage failures, these were thought to be secondary to the surface damage). As mentioned earlier, the basic failure criterion adopted was the presence of any visible pitting or cracking on any ball or race, as observed by binocular microscopy.

As a result of the multi-bearing test philosophy many of the failures were fairly advanced. On inner and outer races progressive spalling from the initial pit was the usual behaviour, and this is illustrated in Fig. 1. Advanced race failures are more difficult to interpret than ball failures because of the amount of secondary damage caused by repeated passage of the balls over the pits. Balls show less secondary damage, mainly in the form of plastic indentation and three-body abrasion as a result of loose fatigue fragments. Therefore most of the examination was concentrated on the conditions of the balls.

3.1. En31 bearings

Sections of failed En31 rolling elements showed sub-surface cracking and associated white etching phases fairly typical of normal rolling-contact fatigue (Figs. 2 and 3). However the visual appearance of many of the balls was more unusual (Figs. 4, 5 and 6). The common feature of these pits was a "concentric" appearance with a pronounced central "peak", often apparently consisting of undamaged surface material. This will be described as Type 1 damage.

3.2. AISI 440C bearings

Sections of failed stainless rolling elements also showed what appeared to be normal sub-surface cracking but once again the surface features of the balls were unusual. Two distinct types of surface spalling were observed. The type shown in Fig. 7 resembles classic rolling-contact fatigue in that the primary cracking was at a fairly constant depth and the bottom of the "pit" was rough. However, the pits were very wide and had apparently been formed by progressive cracking from the edge of an initial small pit. In En31 ball bearings in a con-

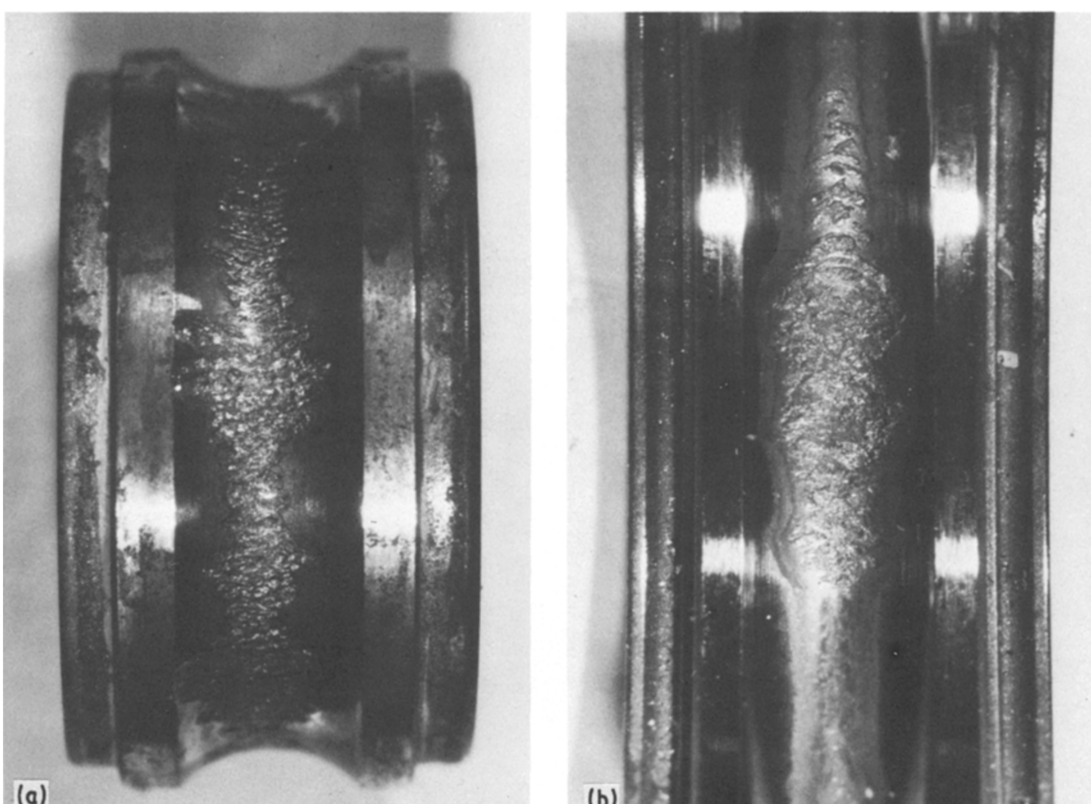

Figure 1 Fatigue damage on surface of inner (a) and outer (b) races (En31 steel), (a): × 6.2, (b) × 6.2.

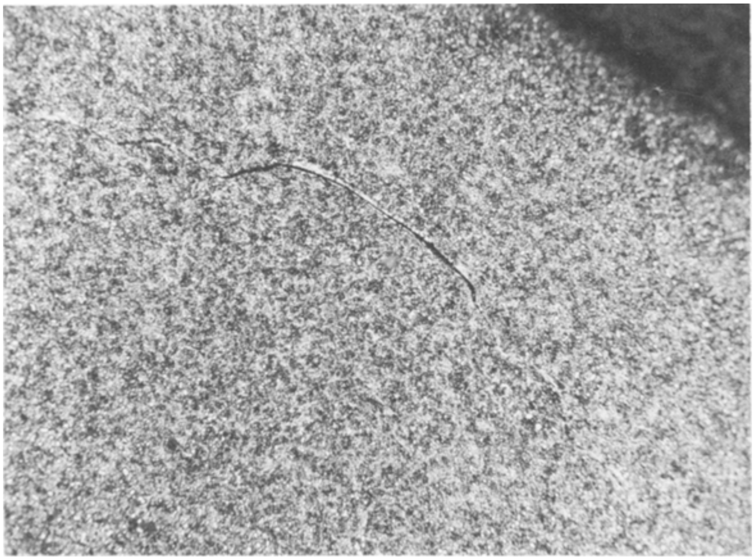

Figure 2 Sub-surface micro-crack and associated white etching phase found in section of rolling element (En31 steel), × 353, etchant: 2% nital.

ventional environment numbers of isolated pits generally form in a period of running after the initial failure, especially on the balls. The progressive spalling observed on the stainless balls is more reminiscent of that seen on races and rollers of roller bearings. This will be described as Type 2 damage.

The other type of spalling seen on stainless balls, Fig. 8, will be called Type 3 damage. This appeared to progress by the delamination of relatively thin but large layers perhaps 10 to 20 μm thick and a few hundred microns wide. Note the smooth appearance of the fracture surface and the relatively ill-defined edge of the pit compared to Fig. 6 (En31) or Fig. 7 (AISI 440C).

Another unusual feature observed on several lubricated stainless bearings is shown in Fig. 9. This is a small pit perhaps 200 μm wide and probably similar in depth, surrounded by a lighter zone 1 mm in diameter. Scanning electron microscope (SEM) examination with electron probe micro-analysis (EPMA) failed to show convincingly the presence of corrosion products in the pit. However it was decided that these were most probably the result of corrosion, and that corrosion products had been removed by the cleaning pro-

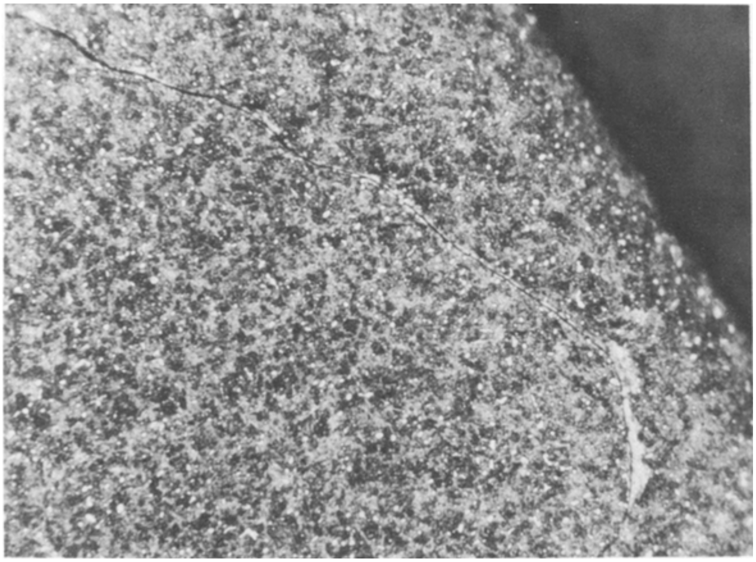

Figure 3 As for Fig. 2, × 546, etchant: 2% nital.

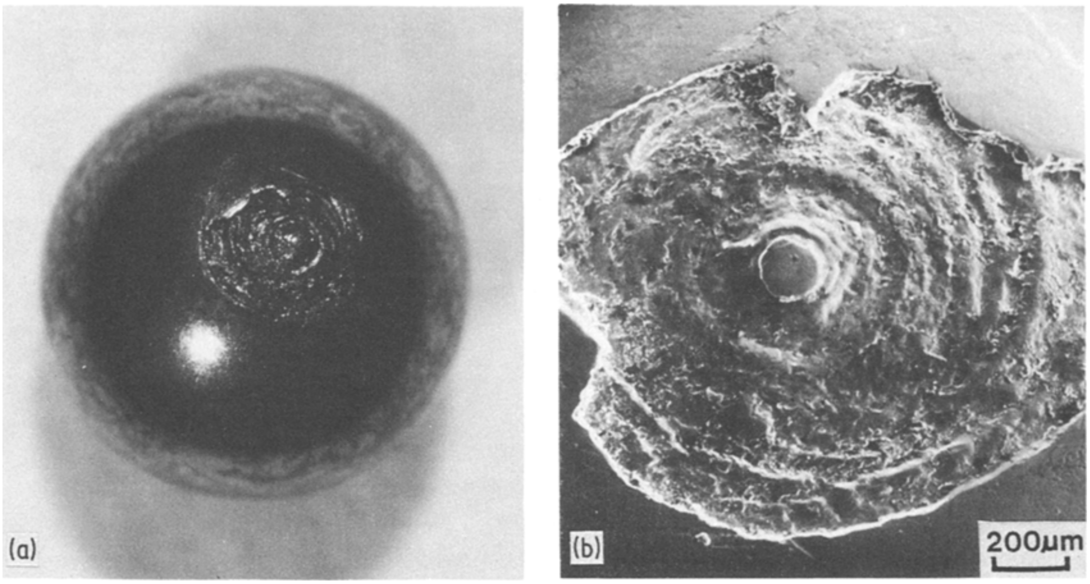

Figure 4 Showing Type 1 spalling of En31 rolling element, (a): × 11.2.

cess. The origin of the apparently polished annular zone was however not clear.

3.3. Unlubricated tests

As an additional check on the performance of bearings with no effective lubricant, unlubricated bearings were run in two tests; the results were slightly unexpected in that En31 bearings performed very badly, but stainless bearings performed quite well. (Earlier unpublished work in low pres-

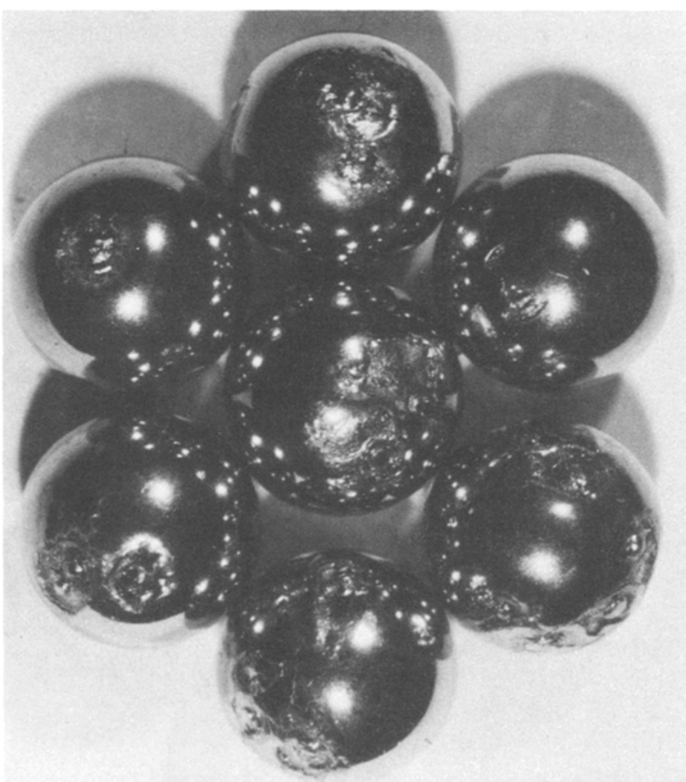

Figure 5 Showing similar, but more severe damage to that shown in Fig. 4 (En31 rolling elements), × 6.2.

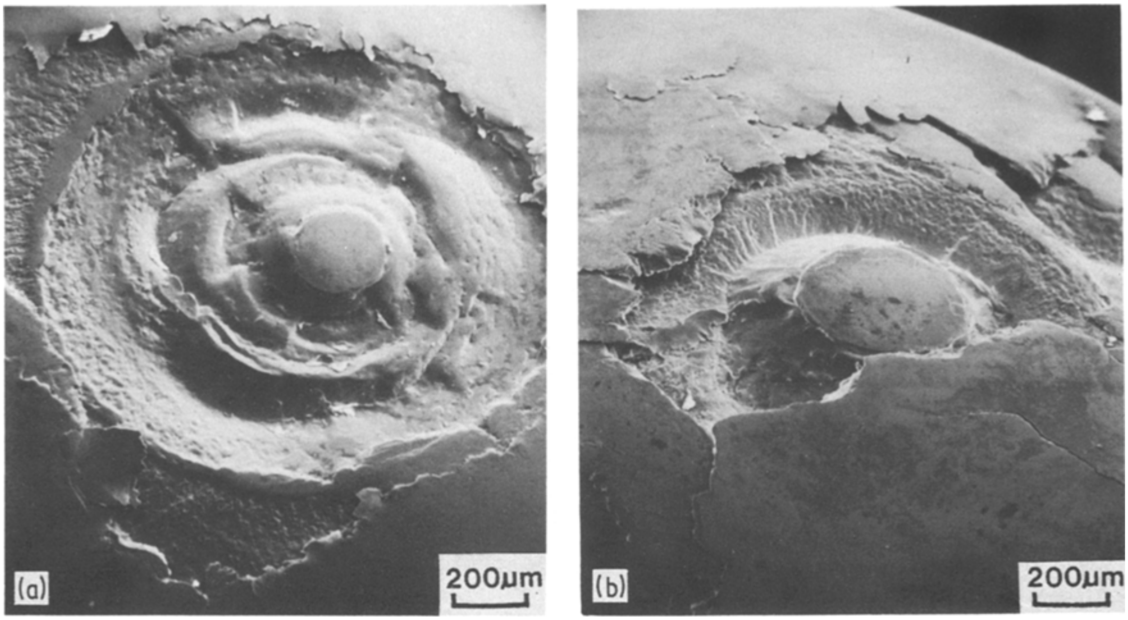

Figure 6 Scanning electron micrographs of Type 1 spalling as in Fig. 5.

sure CO_2 at 200° C gave the reverse result.) In the first test lasting 2 h, all three standard bearings failed, but the three stainless bearings survived; in the second only one stainless bearing out of six failed in 120 h.

The surface deterioration of rolling elements from an unlubricated non-stainless bearing is shown in Fig. 10. Interestingly, some lubricated bearings developed a similar appearance (Fig. 11) suggesting that considerable lubricant deterioration had occurred, but in others (Fig. 6) there was no lubricant failure as indicated by smooth regions outside the damaged area.

4. Analysis and results

According to the formulae of the bearing manufacturers (Barden), under ideal conditions in air the test conditions should lead to a B_{10} life (i.e. life at which 10% of bearings will fail by fatigue) for En31 bearings of about 7000 h. Barden state

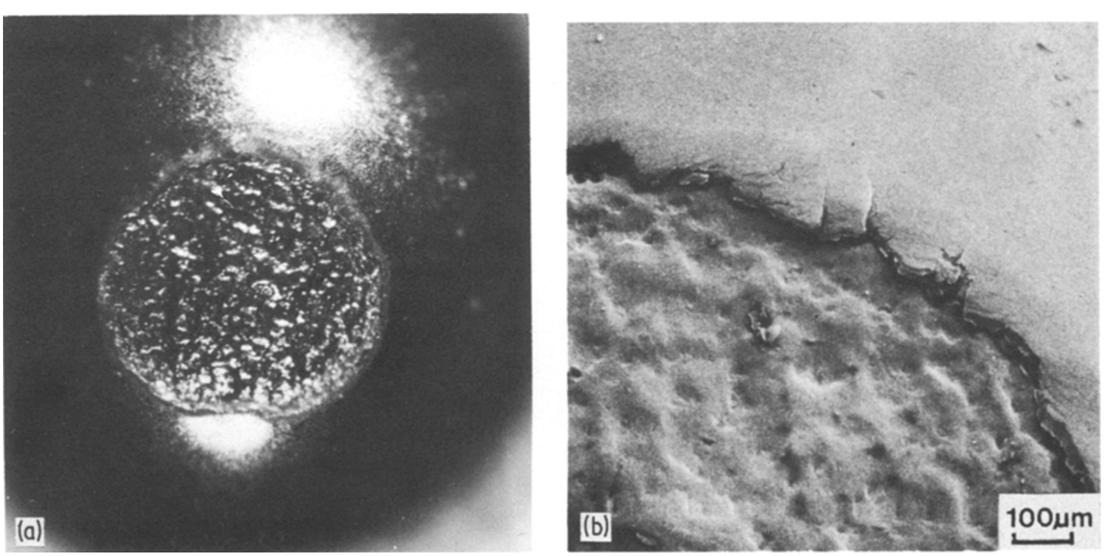

Figure 7 (a) Showing Type 2 spalling of an AISI 440C rolling element, × 22.8. (b) Scanning electron micrograph of damage shown in (a).

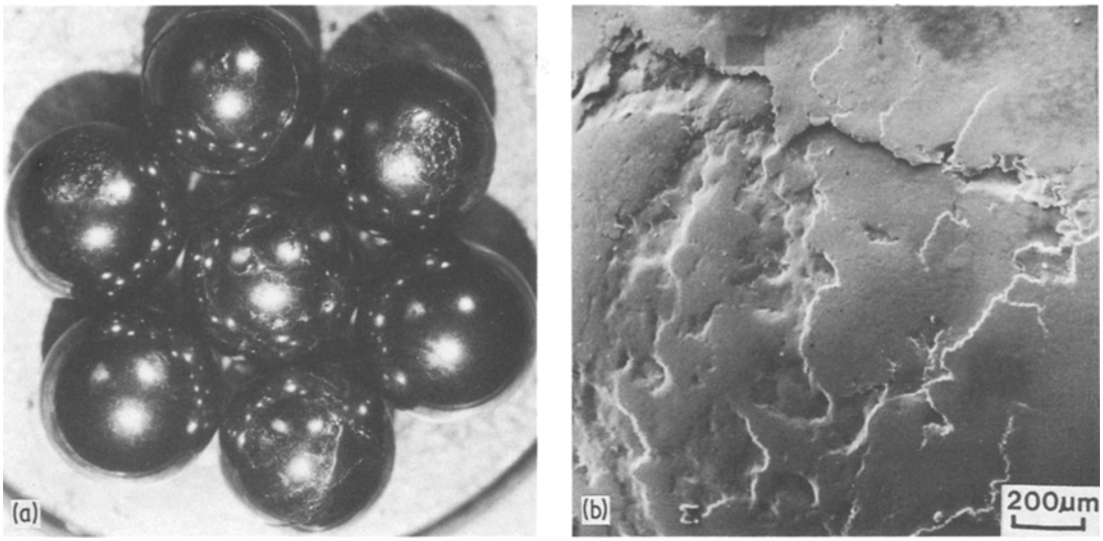

Figure 8 (a) Showing Type 3 spalling of AISI 440C rolling elements × 4.7. (b) Detail of spalled region.

that the fatigue life of stainless bearings should be about half of this.

The results of the fifteen tests on lubricated bearings are summarized in Table I, which shows the considerable range in the number of failures in each test. For the standard En31 bearings the failure rate was between 50 and 100% in 330 to 570 h, whilst for stainless steels the rates were 0 to 75% in 330 to 890 h. The results need to be analysed by a method which recognizes that rolling bearing fatigue failures fit some statistical distribution.

In Radcliffe's [1] work with these rigs it was shown that fatigue failures in a wetter pressurized

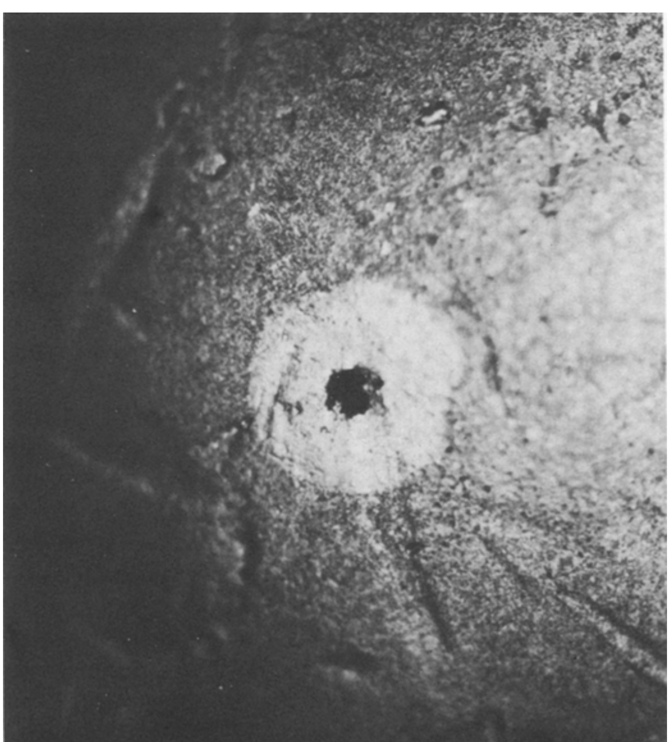

Figure 9 Micro-pit in AISI 440C rolling element, × 30.

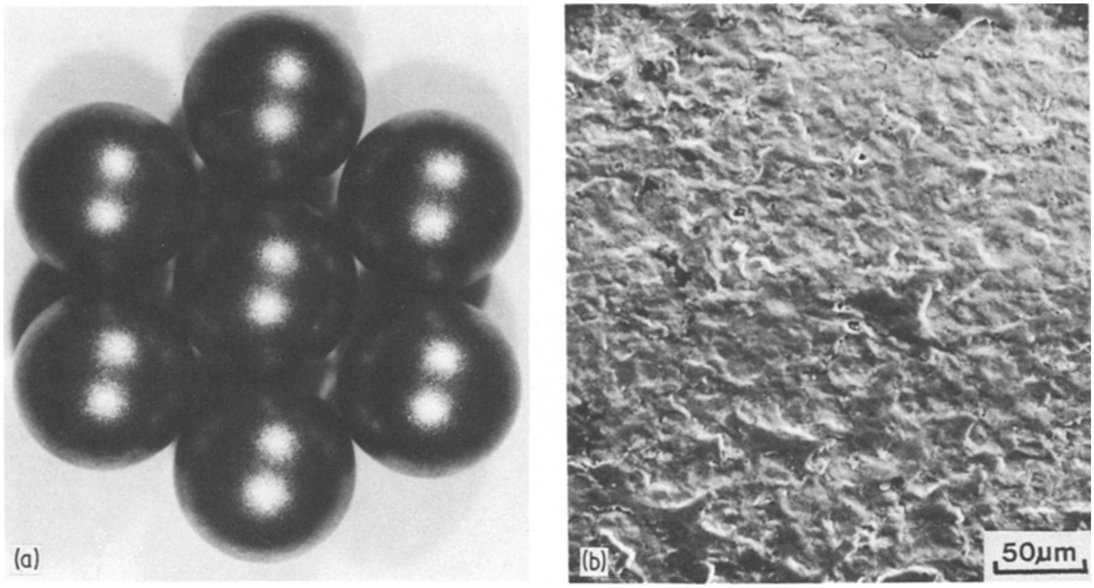

Figure 10 (a) Showing surface deterioration of rolling elements from an unlubricated En31 bearing, × 4.7. (b) Typifying surface condition of rolling elements shown in (a).

CO_2 environment fitted a Weibull distribution with slope 1.0 (the difference from the classical "air" distribution slope of 1.1 was statistically significant). However in the experiments described here there was insufficient data to determine the shape of the distribution, especially for the En31 bearings. It was therefore assumed that the failures would be distributed according to a negative exponential distribution which is defined by a single "location" parameter.

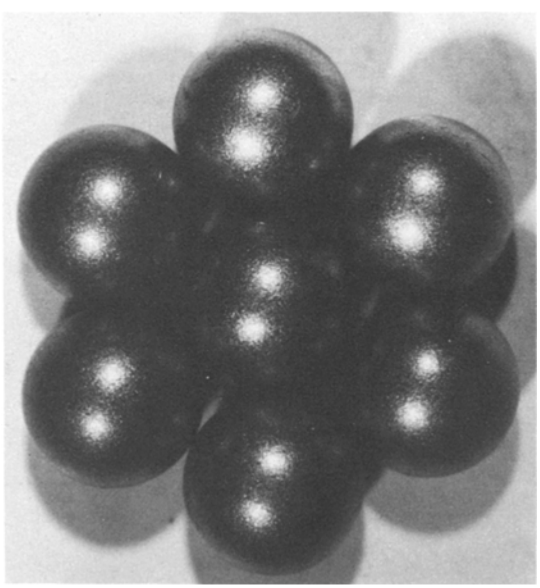

Figure 11 Again showing surface deterioration of En31 rolling elements but in this case the bearing was lubricated, × 4.7.

The distribution can be described by the equation

$$F = 1 - \exp - \frac{L}{L_0}$$

where F is the cumulative failure fraction in a test of duration L, and L_0 is the location parameter or characteristic life.

$$\text{Hence } L_0 = \frac{L}{\ln\left(\frac{1}{1-F}\right)}$$

F was calculated using the "mean rank" correction,

$$F = \frac{m}{n+1}$$

where m is the number of failures and n the number of test bearings in each experiment [2]. For each steel, the statistical parameters were as follows. $\bar{L}_0$ is the average location parameter and $\epsilon(\bar{L}_0)$ the standard error of the estimate of the average.

	$\bar{L}_0$ (h)	$\epsilon(\bar{L}_0)$ (h)
En31	551	123
AISI 440C	1185	205

Using a Wilcoxon rank-sum test it can be shown that the probability of these results arising by chance if the steels were in fact identical in performance would be only 1.1%.

5. Discussion

A number of intriguing questions have been raised by these results and not all can be answered satisfactorily. However, there can be little doubt that most if not all of the bearing failures (including lubricant and cage failures) were the result of surface pitting, and that the three main types of damage were caused by rolling-contact fatigue.

The fatigue lives were considerably shorter than would have been expected from "catalogue" calculations, as shown by the following table which gives the L_0 in hours.

	En31	AISI 440C
Expected L_0 (in air)	65 000 h	33 000 h
Observed L_0	551 h	1185 h

It should be noted that the "expected" life is optimistic in that no "service factor" for the test rig has been included. However inclusion of realistic factors would only reduce the expected value by a factor of 2 or 3.

Another interesting observation was the unusual pitting morphology. Consider first the Type 1 damage, namely, the concentric, peaked pits on En31 balls. Since this differed from classical fatigue pitting in these steels, the difference must be associated either with the environment (including lubrication) or with the test rig. The subsurface cracking usually appeared normal, an interesting contrast to the findings of Radcliffe [1] who observed unusual cracking but conventional pits. Radcliffe's tests in these rigs showed reduced fatigue lives caused by high levels of moisture in pressurized CO_2. The inference is that Type 1 damage was related to some environmental feature of these tests, namely, the salt levels, the moisture levels (<30 vpm), the gas temperature and pressure, or the lubricant, or some combination of effects. To the authors' knowledge, similar pits have only been recorded once before in rolling-contact [3]. Tests of grease lubricated bearings in high purity hydrogen produced fatigue pits in rolling elements having a "cod's eye" appearance, a central dome surrounded by concentric cracking. The "dome" appeared to represent the initial crack and was about 100 μm below the surface. The failures were attributed to hydrogen embrittlement but the model advanced (internal pressure generated by recombination and trapping of atomic hydrogen) is not convincing. An important difference between this result and Type 1 is that in the former, the central "dome" originated from a sub-surface crack whereas in Type 1 the central "peak" usually appeared to be original undamaged surface material, the actual pit being annular in plan.

By comparison of these tests with Radcliffe's work [1] the most striking difference was the chloride level, and the authors suspect that this was probably an important factor in Type 1 pitting. More work would be needed to clarify the situation.

Type 2 and Type 3 damage occurred on AISI 440C balls, and the "anomalous" appearance could therefore be related either to environmental or to materials factors. However in "conventional" environments the 440C steel pits in the same manner as En31, so again an environmental factor is probably very significant. In spite of a considerable amount of metallographic, SEM, and microprobe observation no satisfactory explanation of the morphology of these features was obtained. It is perhaps worth noting that whilst the term "delamination" has been used to describe the appearance of Type 3 pitting, the fragments formed were presumed (from the pit dimensions) to be nearly 100 times larger in linear dimensions than those involved in delamination wear, e.g. Suh [4].

6. Conclusions

About 150 rolling element bearings in conventional En31 and stainless AISI 440C steels have been tested in a rolling-contact fatigue rig. The conditions simulated the temperature and gas pressure in a particular reactor, and the grease lubricant was artificially contaminated with sodium chloride. The dominant failure mode involved rolling-contact fatigue, and both materials had lives considerably below the classical expectations.

The reduction is thought to be an environmental effect related to the chloride and moisture levels, and more experimental work would be required to explain the various results. However the clear conclusions were that the stainless steel bearings performed twice as well as the standard En31 bearings in terms of fatigue life, as well as being far superior both for corrosion resistance and for unlubricated running.

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