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Technical Article

Experimental And Analytical Methods For Assessing Bearing Performance:

Under Debris Contaminated Lubrication Conditions

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Abstract

Debris particle contamination in lubricants has been identified as a major cause of premature bearing and gear failure, with accompanying costs in equipment downtime, warranty, and lost productivity. Various experimental and predictive methods have been developed to assist the design engineer in analysis and development of equipment that is less sensitive to such contamination. This paper provides an overview and new data comparing bearing life test results and predictive analysis methods for various tapered roller bearings operating under debris-contaminated conditions. As a baseline, some past work in these areas is briefly summarized and referenced. Recent work has refined one analytical method (using a surface characterization technique), correlated this method with bearing test lives in debris conditions, and pointed to design and manufacturing modifications in the bearings themselves, making the bearings live longer in debris-contaminated environments.

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Introduction

Much has been published concerning the predominantly detrimental influence of debris particle contamination on bearing performance[8,11]. Many theories have been proposed concerning the manufacturing process, materials, and metallurgical practices that can be used to optimize such performance. The purpose of this paper is not to expound on this detail, but to present a practical comparison of some experimental performance results of various bearing products and of analytical methods used to predict and assess such performance. An overview of current methods to quantify the effect of debris contamination on bearing life is initially discussed. Most of these methods have, as a basis, a technique to determine the lubricant debris content rather than the damage inflicted on rolling contact surfaces. The inference of these methods is that if you understand the contamination content of a lubricant system, you know the damage levels on the components of the system. Based on the results from field testing, some precautionary conclusions are drawn about efforts seeking to link such lubricant analysis methods directly to life prediction. Accordingly, a new life prediction model using direct surface characterization is presented with appropriate discussion on correlation to life test results. This model is an extension of prior work[12,13] that combines a stress based analytical procedure with a debris dent surface mapping procedure to more accurately capture the actual debris damage incurred in a particular debris environment.

Contamination Characterization

In regard to contamination characterization, equipment design engineers currently have many contaminated lubricant analysis tools to help them assess the detrimental effects of debris particles on machinery wear and by their use can monitor the resulting loss in performance. Some of these existing analysis tools include wear particle and contamination analysis by ferrographic methods[1], gravimetric filtration methods[2], atomic absorption spectroscopy[3], and SEM (EDAX) spectroscopy methods[4], all of which are aimed at understanding the material make-up and characteristics of the lubricant contamination. In addition, particle size distributions and concentration levels are sought by particle sizing and counting techniques. Such methods employing both manual microscopic methods, as well as automatic direct counting through equipment using light scattering methods[5]. Most of the analysis tools just mentioned are used in monitoring and understanding the evolution of equipment failure, as well as the level of lubricant contamination for predicative and preventative maintenance. The ISO 4406 rating method is a popular method used to describe contamination levels. Many seek to use this rating method and link it directly to performance prediction. While these techniques and methods are useful in understanding wear mechanisms and wear rates, they do little in helping to evaluate the impact debris damage has on finished gear and bearing surfaces as it relates to fatigue life of their materials.

Surface Characterization Method

A direct method, using surface damage characterization, has been developed for assessing the detrimental effect of debris contaminated lubrication environments. Nixon and Cogdell describe this method, in reference[6]. It seeks to provide a practical approach to determining contamination effects and is appropriately labeled Debris Signature Analysis℠.

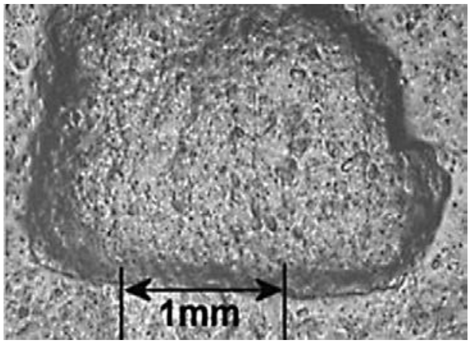


Figure 1:
Micrograph of typical bearing load carrying surface with extremely large dent.

Contaminated Lubricant Analysis

The following field study is an example of the advantage that such a surface characterization method might provide in evaluating equipment systems. In cooperation with an equipment manufacturer, field testing was conducted with their units by sampling lubricant systems at appropriate service periods.

The standard method for determining particle size distributions and concentration levels was used to monitor contamination levels in an actual customer field application. Bearings from these field units were then removed from service after an extended period of time. These bearing surfaces were then examined for debris damage both visually and by the surface characterization method in order to quantify the damage levels. Table 1 shows a few typical particle size distributions and concentrations observed through the period of service by the equipment. Figure 1 shows a typical visual appearance of some of the bearing load carrying surface after the same period of service.

It was quite evident in just these visual comparisons alone that the lubricant analysis did not illustrate the level of surface damage that might be expected. By a comparison of the data in Table 1 to the damage evident by the visual appearance, it is certain that the lubricant sampling did not predict any particles much greater than 300 µm in size. However, the visual comparison of dents, some on the order of 6 mm in diameter, indicates the presence of huge particles on the order of 100 times larger than the 300 µm size particle from the lubricant sample.

Table 1

SAMPLE TIME – HOURS	NUMBER OF PARTICLES > (PER 100 ML)						
				ISO CODE			
METER / LUBRICANT	5 µm	15 µm	25 µm	50 µm	100 µm	300 µm	
0 / 0	44718	7578	769	150	15	0	16 / 13
113 / 113	745800	98280	8820	300	90	30	20 / 17
446 / 446	679800	67500	14700	300	0	0	20 / 17
722 / 276	147990	10990	1400	30	0	0	18 / 14
1130 / 684	343260	36060	2460	60	0	0	19 / 16

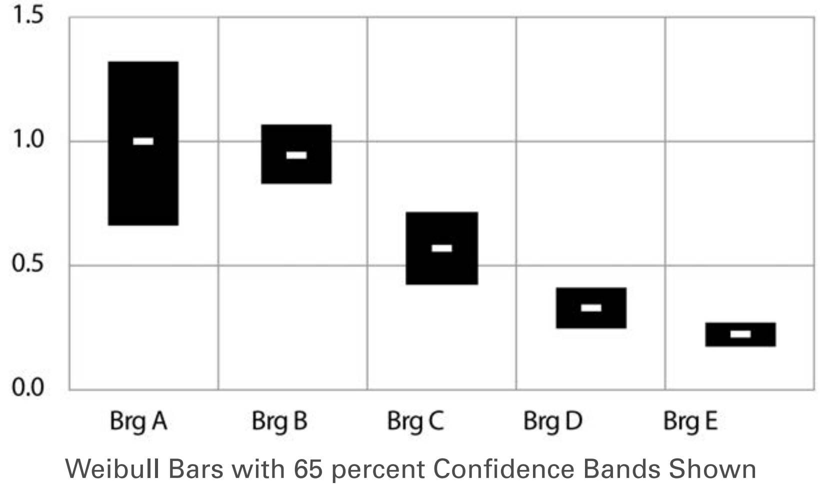
The Debris Signature Analysis℠ method was used to more accurately characterize the surface damage by the detailed method developed[6]. This method of direct surface analysis indicated a 42 percent life reduction would be predicted, while the lubricant analysis results did not indicate major detrimental effects. In addition, the surface analysis results correlated better with actual field performance. This example serves to illustrate the need for surface characterization in linking performance to contamination damage. It was concluded that at least for heavily contaminated systems, lubricant analysis alone might not be a reliable method for linking bearing damage and resulting field service. See Table 1.

Product Performance Comparisons

As part of the evaluation process for assessing and predicting bearing performance under conditions of debris contamination, numerous bearing life tests have been run. For these comparisons, a standardized method to apply debris damage was used[7]. Tested bearings were predented and no additional debris was added during these tests.

In Figure 2, the performance comparison for five major tapered roller bearing manufacturers is shown. This testing was previously reported[11] and was performed on what is considered to be standard product, manufactured with the conventional process common to each given manufacturer. The results within this group varied by a factor of about three with Brg A having the highest relative performance. Bearing B and Bearing E used through hardened material and processing. Bearings C and D were manufactured in part or completely of case carburized components, including Bearing A.

Figure 2:
Life test comparison of five conventional process bearings from different manufacturers, bearing O.D. 73 mm.



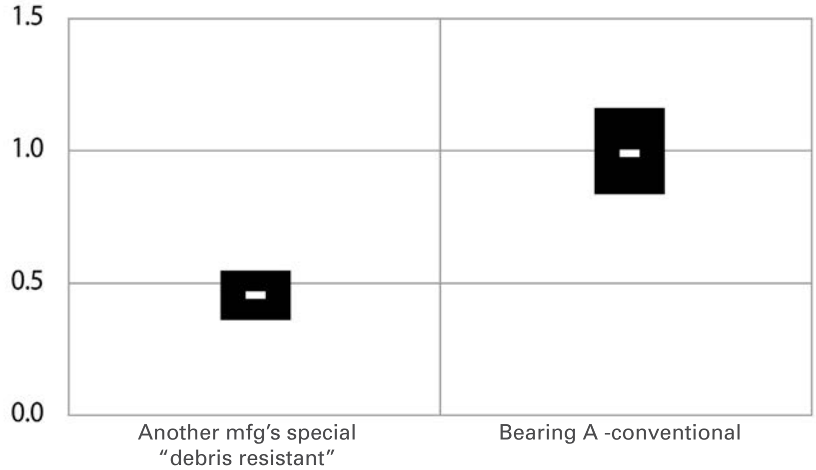
For statistical comparison purposes, the life test results are shown bracketed with 65 percent confidence bands. The width of these bands is calculated based on the sample size and scatter of testing failures and is a function of the Weibull slope. When such bands overlap between test groups, no statistically significant difference in performance can be claimed at the 90 percent confidence level.

Debris Testing Of Conventional Versus Special Debris Resistant Bearings Made By Different Manufacturers

Comparative debris damage testing of special bearing products has also been performed (Figures 3, 4, and 5). This life testing compared the conventional product from one manufacturer (Bearing A) to that of special "debris resistant" products from two other manufacturers. Here the special debris resistant products were claiming up to ten times life improvement over conventional processes. Three separate tests were performed (Figure 3 = test 1, Figure 4 = test 2, Figure 5 = test 3). The test conditions and bearings varied between these separate tests.

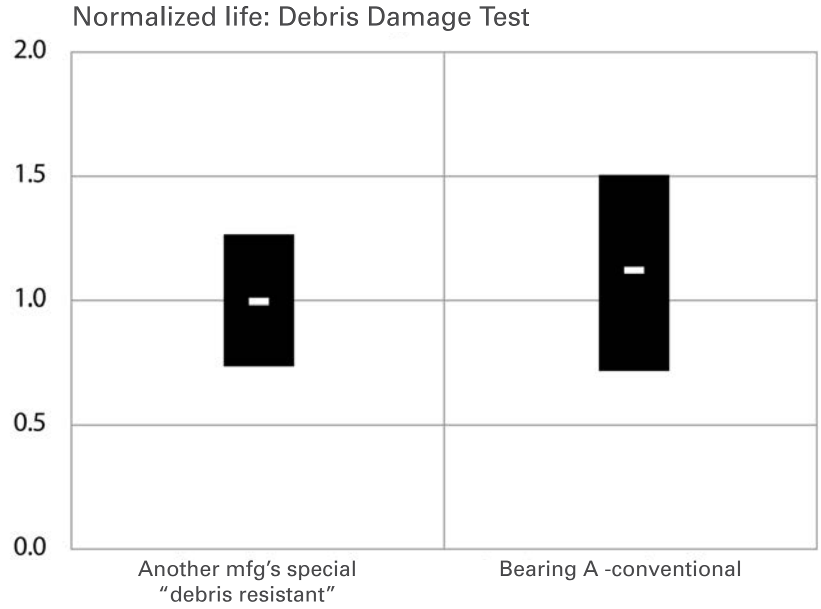
Figure 3 shows the normalized results for debris damage testing with conditions identical to Figure 2. These results were previously reported[7]. This shows that Bearing A, using a conventional process by one manufacturer, had life test results that slightly exceeded the results of another manufacturer's special debris resistant process.

Figure 3:
Life test comparison of a conventional process versus special "debris resistant" process from another manufacturer, bearing O.D. 83 mm.



Weibull Bars with 65 percent Confidence Bands Shown

Figure 4:
Life test comparison of a conventional process versus special "debris resistant" process from another manufacturer, bearing O.D. 68 mm.



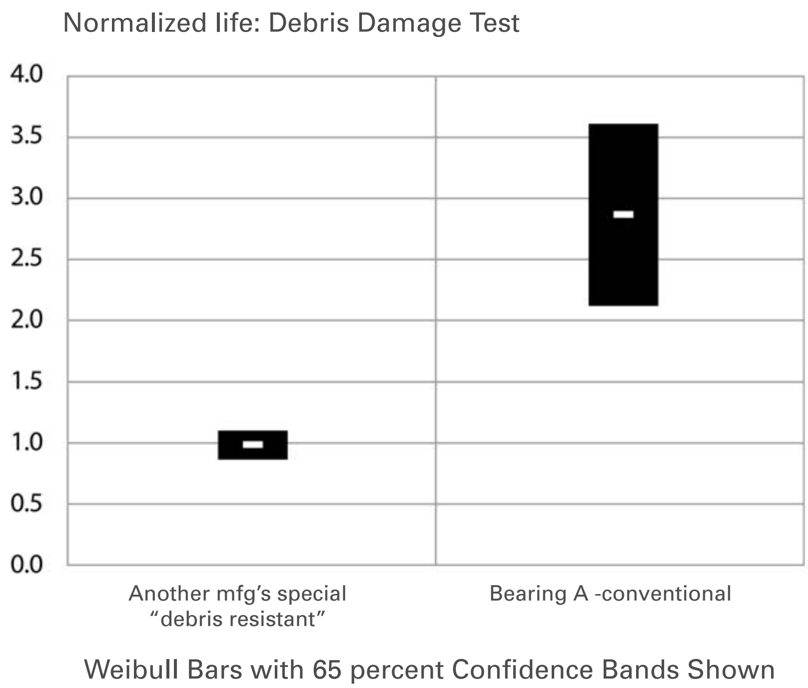
Weibull Bars with 65 percent Confidence Bands Shown

Figure 4 shows the normalized life test results for debris damage testing with conditions similar to that of Figure 2, except the debris media was changed. This resulted in only light debris damage being incurred. Here Debris Signature Analysis was applied to conventional Bearing A, and predicted only threshold life reduction due to debris. Under these conditions, Bearing A, using a conventional process by one manufacturer, had performance results that were equal to the results of another manufacturer's special debris resistant process.

Figure 5 shows the normalized results for debris damage testing with a large, 318 mm O.D. bearing. A different set of life testing conditions was applied as well as new debris media and new method to apply the debris media. These changes were caused in part by the use of the larger test bearing. This resulted in moderate-to-severe debris damage. Debris Signature Analysis was applied to conventional Bearing A and predicted up to a three times life reduction. Under these conditions, Bearing A, had life test results that significantly exceeded the results of another manufacturer's special debris resistant process.

One conclusion from this testing is that differences in the manufacturing process, materials and metallurgical practices used in bearings produced by different manufacturers impacts fatigue life of bearings operating in high-debris environments.

Figure 5:
Life test comparison of a conventional process versus special "debris resistant" process from another manufacturer, bearing O.D. 318 mm.

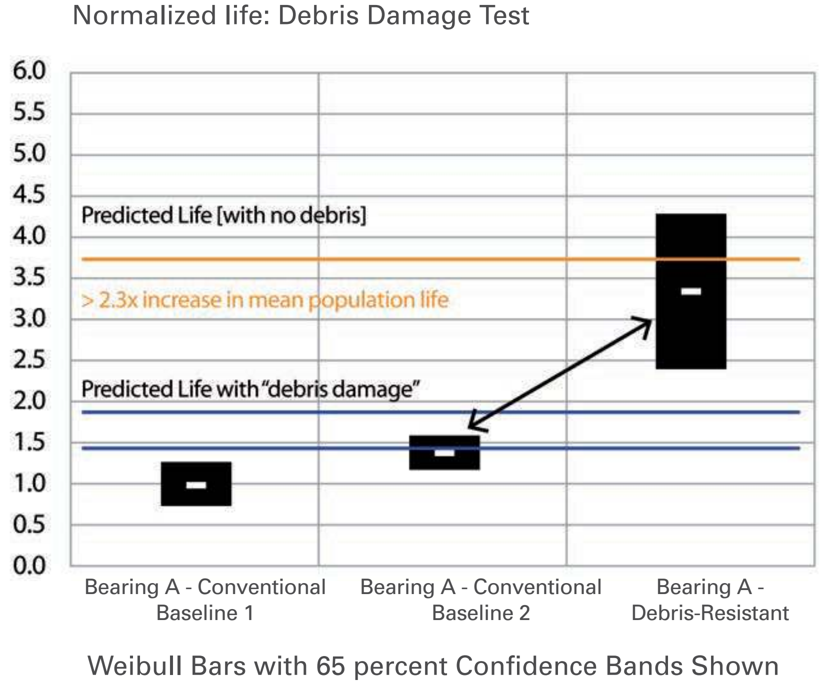


Raising The Performance Level In Debris Testing

By studying the unique metallurgical design and processing parameters used to produce Bearing A, an improved debris resistant approach was developed. The goal was to enhance the bearing mechanical properties of strength, ductility and toughness, particularly at the functional contact (raceway) surfaces. The approach included change to key design specifications and the tightening of process control limits for select parameters particularly during heat treat. A statistically significant improvement in performance was ultimately accomplished, Figure 6. The proprietary specification involves select parameters including material chemistry, retained austenite, microstructure, and post heat treat control of near surface properties.

The performance results of this new debris resistant design and processing approach are shown in Figure 6. The life testing shown was performed on a mid-sized, 248 mm O.D. bearing, where considerable life testing experience was previously established. In this particular testing scheme the lives of two debris dented conventional baseline groups were approximately two to three times less than the predicted life with no denting. Debris Signature Analysis was applied and predicted a debris life reduction factor between 0.4 to 0.5. for these baseline bearings. The predicted results are referenced in Figure 6.

Figure 6:
Life test comparison of one manufacturer's "debris resistant bearing" versus conventional baseline process, bearing O.D. 248 mm.



The debris-resistant bearing performance was shown to be much higher than the baseline groups with its upper 65 percent confidence band crossing the line for predicted life with no debris damage. Thus, for the given testing severity, the new debris-resistant bearing negated the effects of the given debris damage and increased mean population bearing life by up to 2.3 times over the two baseline bearing groups made with conventional processing. This debris resistant bearing is currently being offered as providing up to two times life improvement in debris environments.

Life Prediction Model

The theoretical basis for the debris life prediction tool was presented by Ai[12] wherein the effects of debris dents on raceway contact stresses and fatigue life are determined. The model was verified with controlled debris dent bearing tests using bearings with the performance characteristics represented by Bearing A.

Since debris in applications covers a large range of particle sizes, a program was put together to determine the effect of lubricant contamination composed of realistic particle size distributions. Two approaches were used. The first approach simulated debris particle size distributions that correlate to ISO 4406 code distributions. 52100 steel debris particle distributions for

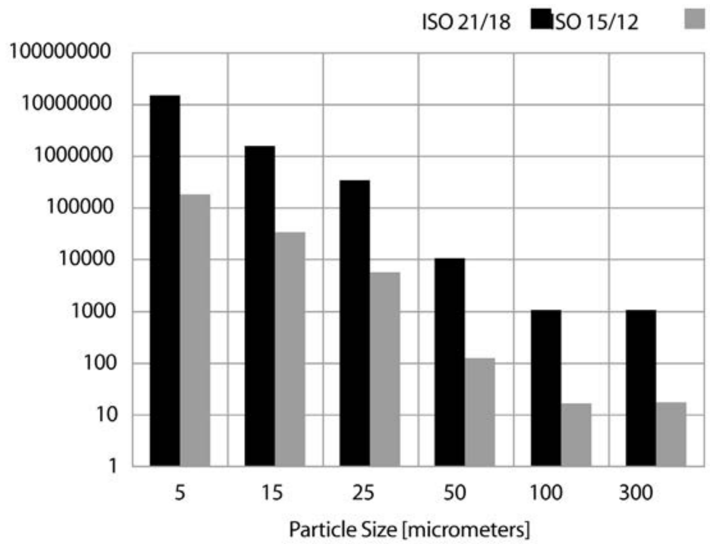


Figure 7:
Particle size distributions for two specific ISO codes.

ISO 13/10, ISO 15/12, ISO 17/14, ISO 18/16 and ISO 21/18 were mixed with lubricant and used to dent bearings as explained by Nixon[7]. As an example, Figure 7 shows the particle distributions used for the ISO 4406 21/18 and 15/12 cleanness levels. These distributions were developed from the analyses and ISO 4406 characterization of debris contaminated used oil. The dented bearing surfaces were then optically mapped to obtain dent size and surface density distributions. Thus obtaining a Debris Signature Analysis profile for each of these debris conditions. Data files containing dent sizes and surface densities were stored for use by application engineers in analyzing the life of bearings which might be operating in these environments.

The second approach was to obtain bearings from actual applications in the field and optically characterize the sizes and surface density of dents on these bearings for future life analyses. These were larger bearings that generally operate in more heavily contaminated conditions and cannot be adequately described by ISO 4406. Photographs of these dented surfaces can then be used by engineers to select a level of raceway surface damage typically seen in their applications.

The analysis of typical life test lubricant taken from standard life test machines have shown that the base cleanness level is ISO 15/12. The debris life factor has a value of 1.0 at this cleanness level. Cleaner lubricant would provide enhanced life and lubricant with more debris would give a reduced life.

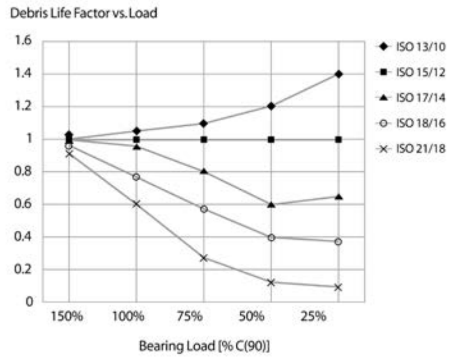


Figure 8:
Debris life adjustment as a function of load and various ISO codes.

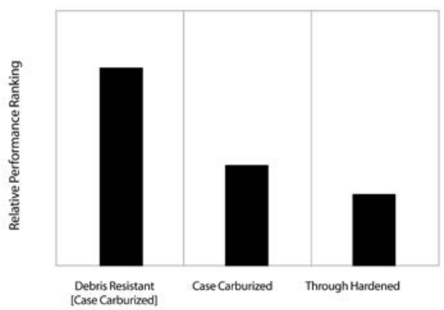


Figure 9:
Relative debris life factor for bearing materials.

To determine a life reduction factor, the dent Debris Signature Analysis data files are then used in the following manner. The rolling element contact loads are determined for application conditions so as to determine contact stresses and contact area. The effect of the size and number of dents on the life of the bearing in this environment can then be determined. Figure 8 shows a plot of debris life factors (a3D) for a 33 mm bore tapered roller bearing for different lubricant cleanness levels and radial loads in terms of percent C(90) rating. It can be seen that, at heavy loads, the effect of varying debris levels is reduced because the net effect on the general stress level is reduced as opposed to the greater effect on modifying the general stress level at light loads. In Figure 2 on page 4, it is shown that bearings made of through-hardened steel can be more sensitive to debris dents than bearings made of case-carburized steel. Figure 6 on page 8 shows that case-carburized bearings can be made even more debris-resistant. Figure 9 shows the difference in model debris life factors for bearings made of these materials relative to case-carburized bearings for a moderately contaminated environment. Bearings made of through-hardened steel will have a somewhat lower life than case-carburized bearings. As might be expected, the debris-resistant bearing microstructure is seen to be more effective in improving bearing life in the more contaminated environments.

A significant number of debris-dented bearings have been life tested in the authors' life test machines. The correlation between the experimentally determined reduction in life due to debris dents and the life reduction predicted by this approach is shown in Figure 10[15]. For the authors' bearing product, this model has been shown to provide a practical connection between actual debris dents and subsequent fatigue damage.

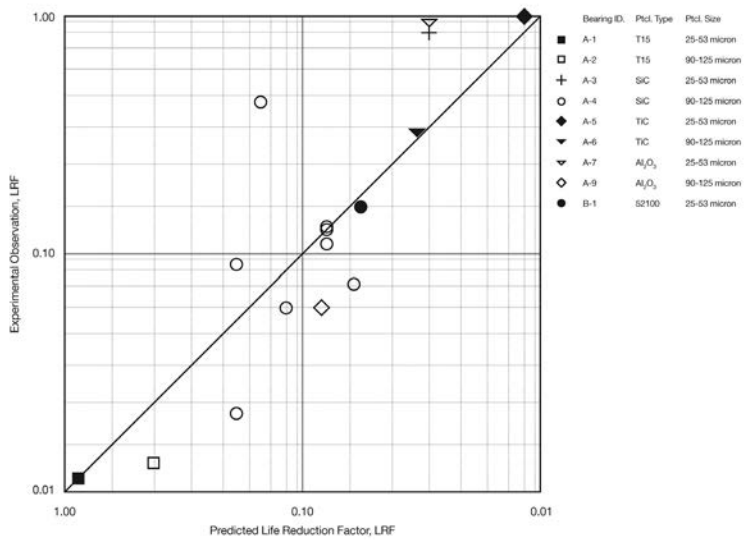


Figure 10:
Comparison of experimental results with model predictions.

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Conclusions

The following conclusions and observations are provided as a result of the analysis experience and experimental test results.

1) For heavily contaminated systems, lubricant analysis methods alone might not be a reliable method for linking bearing damage and the resulting field service.

2) Fatigue life testing of bearings to evaluate debris damage sensitivity, can be a useful tool to differentiate performance of products.

3) Standardized life testing with debris showed that conventional and debris-resistant bearings from various manufacturers perform at significantly different levels. These differences should be considered when making comparisons concerning the relative hierarchy of product debris resistance and when applying performance prediction tools.

4) The direct measurement of damage method encompassed by Debris Signature Analysis is expected to provide more precision over other approaches involving lubricant contamination analysis in quantifying damage differences.

5) Debris Signature Analysis should provide a tool for comparing, in a quantifiable way, the contamination environments of successful equipment performance to those that are not successful.

6) The new life prediction model provides a practical connection between actual debris dents and subsequent fatigue damage.

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