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Bi-Modal Failure Mechanism of Rolling Contact Bearings

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Abstract

The theory of failure of rolling contact bearings is based on fluctuating high level loading and material fatigue. This theory is unimodal, considering only the solid components of the bearing, and ignoring the liquid phase, which is the lubricant. Bearing life is rather dispersed, reaching a ratio of 20 between the extreme values. Since this theory was established, several exceptional phenomena were detected that could not be explained by it, such as: 1) Pitting damage beyond the contact path; 2) Detrimental effect of a minute quantity of water in the lubricant on bearing life. 25 ppm of water in the lubricant brought about shorter bearing life by over than 30%. The bimodal failure theory considers both solid and liquid bearing components. The damaging process of the lubricant evolves from its cavitation. During this process vapor filled cavities are formed in low pressure zones. When these cavities reach high pressure zones they implode exothermally. These implosions cause local high pressure pulses reaching 30,000 at accompanied by a temperature rise of about 2000 degrees K [1]. This paper includes cavitation erosion test results on stainless steel samples by vibratory and water tunnel test rigs. Various methods of lubricant dehydration are presented and evaluated. The main conclusion from this analysis is the use of water-free lubricants, for long life of RC bearings and more uniform service life thereof.

Keywords

Cavitation Erosion, Rolling Contact Bearings, Stainless Steel, Lubricant Dehydration, Critical Erosion

1. Introduction

Rolling contact bearings, RCB, are high precision machine elements, made of high quality materials, see **Appendix A**, and machined by high precision machines. In spite of this, when identical RC bearings are tested under identical conditions they fail after a wide range of test durations. This range reaches a span of 1:20, see **Figure 1** [2]. This wide dispersion cannot be fully explained by material fatigue of the contacting elements. Accordingly, it is impossible to predict the service life of a single RCB. As a result this problem is treated by statistical methods.

A new approach to this problem considers the process occurring in the lubricating oil, namely cavitation. Between the rolling elements and the rings a contact path is formed. Along this path pressure fluctuates, causing the lubricant and the water in it to vaporize and condense in a cyclic manner. Vapor condensation is exothermal, accompanied by high pressure and high temperature rises [1]. This process is known as cavitation, exerting high local pressure within the lubricant and upon the surfaces of the bearing elements. Cantley [3] reported life tests he performed on full scale RC bearings lubricated with SAE-20 oil, containing a minute quantity of water of 25, 100 and 400 ppm. These small quantities of water were chosen to represent extreme conditions of relative humidity. He found that when tested with these mixtures of oil and water, bearing life was reduced by 32% - 48%. He reached the conclusion that water absorption by lubricants can become an important factor in the determination of RCB life.

Water content of lubricants is not considered in bearing life tests. The unimodal failure theory is based on the stress distribution within the contact path, as caused by the metal to metal contact. Since the vapor pressure of water is larger than that of oil, water will cavitate first, thus causing damage to the bearing elements. It should be noted that most lubricant specifications do not contain the following data: 1) water absorption, 2) water content, and 3) oil vapor pressure.

Cavitation erosion of stainless steel specimens in lab tests is further presented. These tests were performed by the "International Cavitation Erosion Test", ICET. From this large reservoir two tests were chosen: one vibratory test and one as performed in a water tunnel. Both tests were performed by the same lab "Institute of Water Problems of the Bulgarian Academy of Sciences, Sofia, Bulgaria", IWP BASci. Both tests were performed on stainless steel specimens, 1H18N9T, which represents bearing materials. These tests simulate the erosion and space formed between bearing elements that will cause critical vibrations and bearing failure.

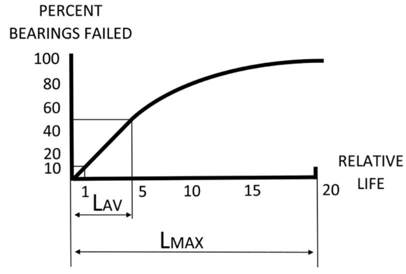

Figure 1. Cumulative failure curve for rolling contact bearings.

Life Scatter of RC Bearings

RC bearings have a final service life. However, the exact life span cannot be determined exactly. SKF Bearing company compiled life test results, see **Figure 1** [2]. The life span of the average bearing is denoted as Lav and is reached after five relative life units. One unit of relative life unit is equivalent to 10% of the failed bearings. The maximal bearing life span seldom exceeds four times the average life, thus the maximal bearing life reaches 20 relative life units.

The typical diagram of cumulative failed RC bearings is similar to the exponential transition curve. The time constant, for this type of curve is determined at 63.2% of the observations. Let us examine the possibility that the typical bearing curve can be represented by the Weibull equation. In this case $T = 6.73$ Relative life units, and the equation will be Equation (1):

$$F = 100\left[1 - \exp - \left(t/T\right)\right] \quad (1)$$

Validity test of this equation for the bearing curve in **Figure 1** reveals a good fit, especially for values larger than T. Here the difference between the curves is about 4%. In any case this equation reasonably represents the actual bearing life dispersion.

2. Cavitation Erosion Tests

2.1. General

Water is a polar liquid and lubrication oils are non-polar. Accordingly, these liquids cannot contact chemically. However, they can mix and form an emulsion. When the mixed liquid is under cavitation conditions the water will cavitate first, as it has a higher vapor pressure and is more volatile. The following two examples will illustrate cavitation erosion of stainless steel specimens in water. For this illustration it was assumed that all the erosion in the RCB is caused by cavitation only.

The common data for both tests are:

1) Reference: The International Cavitation Erosion Test, ICET [4].

2) Laboratory: Institute of Water Problems, of the Bulgarian Academy of Sciences, Sofia, Bulgaria IWP BAScia.

3) Test material: Stainless Steel, 1H18N9T, see **Appendix A**.

4) Failure criterion: Cavitation erosion of 12.5 μm Mean Depth of Erosion, MDE. One of the failure criteria of RC bearings in life tests is vibration amplitude of 20 - 100 μm [5]. Accordingly, the cavitation erosion test results were evaluated by this criterion. During bearing operation the rolling elements that are in contact erode, thereby causing a clearance between them. In a vertical cross section eight such clearances are formed. Hence, for the maximal vibration amplitude of 100 μm, each clearance will be 12.5 μm. As a result the cavitation erosion test results are further evaluated up to 12.5 μm.

5) Test equipment: Two types of rigs were used for these simulations.

a) Vibratory rig—with a vibrating specimen.

b) Water Tunnel—with a stationary specimen.

2.2. Vibratory Cavitation Erosion Test

2.2.1. Vibratory Rig

Cavitation cloud is generated here by a horn vibrating with a high frequency in a liquid. Vibrations are usually generated by a magneto-strictive or piezo electric transducer. The obvious advantages of this rig include:

1) High erosive rate;

2) Small size of the rig;

3) Low energy consumption;

4) Easy to maintain steady state test conditions.

Vibratory test method was standardized by ASTM committee on wear and erosion, as a report of an Inter Laboratory Round Robin Test, 1959. This report was later updated as ASTM standard G32 [6]. The test specimen is attached to the end of the vibrating horn and immersed in the liquid. Rig operation is intermitted and mass loss of the specimen is recorded. In this manner a graph of accumulated mass loss versus test duration is constructed.

2.2.2. Test Conditions

1) Vibration frequency: 22 ± 0.2 kHz;

2) Vibration amplitude: 25 ± 2.5 μm;

3) Eroded area: 201.06 mm square;

4) Test Liquid: Distilled water at 20˚C.

2.2.3. Test Results

1) Original test results up to erosion of 24 μm MDE, see Figure 2;

2) Expanded curve up to 13 μm MDE, see Figure 3;

3) Time to reach a critical erosion of 12.5 μm MDE: 815 min.

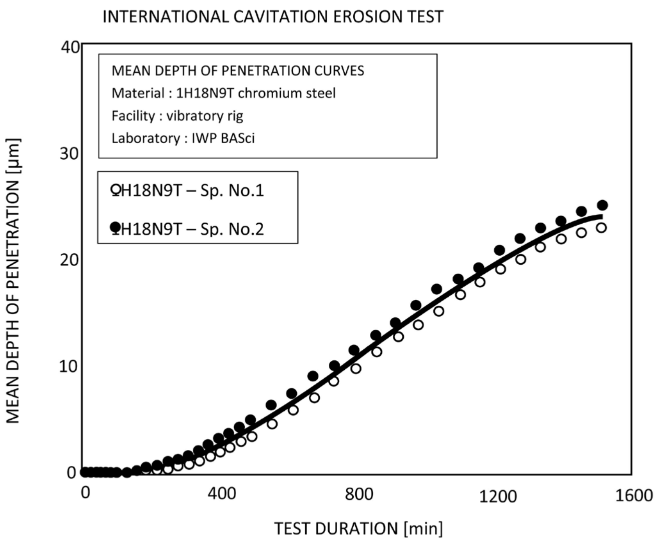

Figure 2. Cavitation erosion test results in IWP vibratory rig with stainless steel 1H18N9T specimens, up to the erosion of 24 μm.

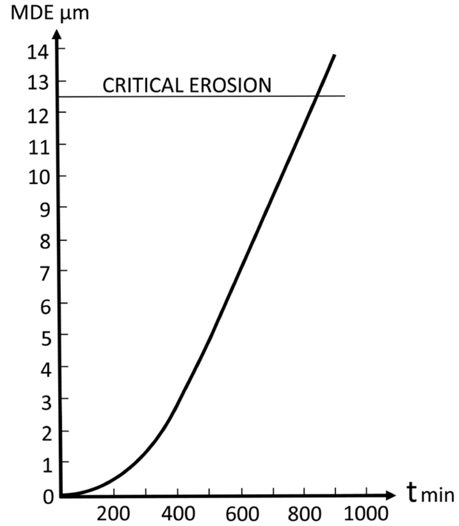

Figure 3. Cavitation erosion test results in IWP vibratory rig with stainless steel 1H18N9T specimens; expansion of original curve up to the erosion of 14 µm.

2.3. Water Tunnel Erosion Tests

2.3.1. Water Tunnel Test Rig

Cavitation tunnels are traditional experimental rigs used to study cavitation phenomena ever since 1895. Various flow obstacles such as: cylinders, bolts, wedges, venturies, or barricades and counter barricades are used as cavitators. Usually, intensity of cavitation can be easily controlled by modifying the flow system geometry, and or changing the hydraulic circuit operating parameters.

2.3.2. Test Conditions

1) Water pressure: 1250 MPa;
2) Water velocity: 22.5 m/sec;
3) Type of cavitator: cylindrical bolt;
4) Type of specimen: Rectangular;
5) Test fluid: Tap water, 7.5 pH, at 15˚C - 19˚C.

2.3.3. Test Results

1) Original test results up to erosion MDE 290 µm, see **Figure 4**.
2) Expanded test results up to erosion of 20 µm, see **Figure 5**.
3) Time to reach the critical erosion of 12.5 µm: 9300 min.

2.4. Summary of Cavitation Erosion Test Results

The critical erosion time, as obtained from the vibratory CE tests, is 11.4 times shorter than that obtained by the water tunnel tests. This clearly indicates that the cavitation intensity of the vibratory CE tests is by far larger.

There is no possibility to determine the complete fit between the conditions in CE tests and those in the RC bearings. However, it is reasonable to assume that the cavitation is adequately simulated. In any case it is possible to apply the CE tests for material classification for RC bearings.

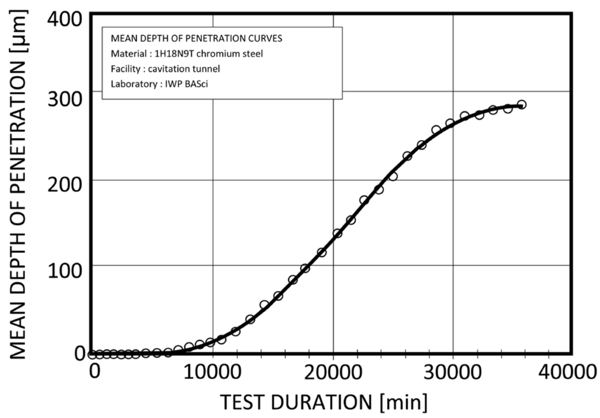

Figure 4. Cavitation erosion test results in IWP water tunnel rig with stainless steel, 1H18N9T specimens, up to the erosion of 290 μm.

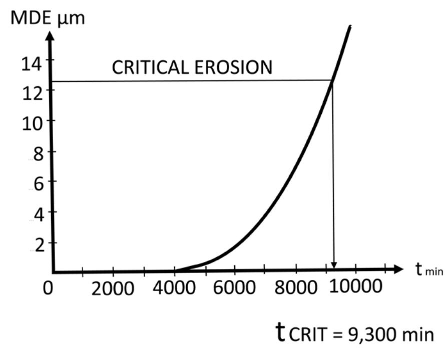

Figure 5. Cavitation erosion test results in IWP water tunnel rig with stainless steel, 1H18N9T specimens. Expansion of original curve up to the erosion of 14 μm.

3. Dehydration of Lubricants

3.1. General

After proving the detrimental effect of water in lubrication oil on RC bearing life, Cantley [3] tried to dehydrate oil by an additive. This attempt failed. Later on this avenue was found to be counterproductive, since additives to lubricants were found to increase their hygroscopic property.

Water exists in lubrication oils in three forms:

1) Dissolved (up to saturation);

2) Dispersed (as in emulsions);

3) As free water.

In each form water is detrimental to the operation of RC bearings, and shortens their service life appreciably. Accordingly, lubrication oils should be dehydrated and kept water-free during their planned service life. Several dehydration methods are further listed [7].

3.2. Lubricant Dehydration Methods

1) Gravity separation: This method is based on the different specific gravities of water and oil. Upon sedimentation the free water is separated and all other forms of water remain in the oil.

2) Centrifugal separation: By this method the oil is passed through a centrifuge, exerting forces of the order of 10,000 g. This method is best fit for low viscosity oils, such as turbine oils. The water forms separated here are the free and emulsified water. Separation efficiency increases with lower temperature.

3) Absorption removal: Cellulose based filters are here used to remove free and emulsified water.

4) Vacuum cleaned: By this method the pressure above the oil is lowered to 635 - 711 mmHg, and the water boils at 49˚C - 55˚C. Here 80% - 90% of the dissolved water is separated.

5) Air stripping: By this method hot and dry air or Nitrogen are passed through the heated oil. Thus water is removed from the solution and from the emulsion. The remaining water is less than 100 ppm.

6) Oil heating: By this method the oil is heated until the water is boiled and thus removed.

7) Membrane treatment: By this method the lubricating oil is passed through a system of membranes and all the forms of water are removed. The advantages of this method are:

a) Can be operated in-line within the system;

b) Requires low activation energy;

c) Does not remove or alter the additives;

d) Water remaining in the oil is 10 ppm or less.

4. Conclusions and Recommendations

In life tests of identical RC bearings, performed under controlled conditions, a large dispersion in life duration is evidenced. The ratio between the extreme results reaches the value of 20, see **Figure 1** [2]. The curve in **Figure 1** is the result of simultaneous operation of two failure mechanisms:

1) Metal fatigue due to repetitive high local loading.

2) Cavitation erosion of bearing components due to fluctuating high local pressures along the contact path.

The fatigue model is considered as the main failure mode, while the cavitation is yet disregarded.

Water is absorbed in lubrication oils and has a detrimental effect on RC bearing life. This effect is considerable. Even minute quantities as little as 25 ppm may shorten bearing life by nearly 30%. Since water has a higher vapor pressure it will cavitate first, causing severe damage in the bearing.

Cavitation erosion of stainless steel specimens can be easily performed in laboratory tests. These tests simulate the process in RC bearings and can be utilized for selection of adequate bearing materials.

It is highly recommended to keep lubrication oils water-free. The best method for dehydration of lubrication oils is by passing it through a membrane system, thus reducing the water content to 10 ppm and less.

The bimodal failure theory for RC bearings renders a new aspect to the understanding of their operation and failure mechanism, and paves the way to improve their future design operation and maintenance.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A: Test Material—Stainless Steel 1H18N9T

X 10Cr Ni Ti; 18 - 10

Chemical Composition

C—0.04%

Mn—1.37%

Si—0.56%

P—0.030%

S—0.010%

Cr—17.0%

Ni—9.4%

Fe—70.04%

Ti—0.6%

Heat treatment: Hyper quenching: 1050˚C, 15 min, Air

Mechanical Properties

Density kg/m^3: 7886

Hardness HV10: 1910

Tensile strength MPs: 605

Yield Point MPs: 225

Modulus of elasticity GPs: 200

Ultimate strain %: 52

Cross Section reduction at fracture %: 64

Nomenclature

CE = Cavitation Erosion

CMS = Compact Membrane System

CTB = Cavitation Tunnel with Barricade Cavitator

F = Percentage Bearing Failure

ICET = International Cavitation Erosion Test

IWP = Institute of Water Problems, of the Bulgarian Academy of Science, Sofia Bulgaria

Lav = Average Bearing Life

LR = Dimensionless Bearing Life

MDE = Mean Depth of Erosion, μm

RCB = Rolling Contact Bearing

t = Time

VRV = Vibratory Test Method with Vibrating Specimen

T = Time Constant of an Exponential Response Curve