Ball and Roller Bearings - Design, Operation, and some Failure Analysis

by

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My hopes and goal for today

Have you understand more about:

1. The general construction of ball and roller (rolling element) bearings.
2. How rolling element bearing lubrication works at different relative component speeds
3. The critical importance of correct shaft and housing dimensions
4. The contrast between the design failure mechanism and the most common failure mechanism.

We'll go through some of the slides very rapidly. My intent with those is to give you a reference for future use.

Some questions

1. What is the most common metallurgy for rolling element bearings?
2. Where are ceramic components used? Why?
3. With rolling element bearings, why is a VERY SLIGHT internal interference a good idea?
4. What is the mechanism that allows the typical lubricating oil to separate the rolling elements from the bearing rings?
5. How flat should a typical machine base be?

Rolling Element Bearings

- We'll discuss ball, roller, and needle bearings, not plain or sleeve bearings.
- Earliest rolling element bearing concept was in ancient times, i.e., logs acting as rollers
- Modern steel bearings became practical in the late 1880's with the ability to precisely control the element dimensions.
- Most bearings are through hardened and, in the industrial world, there are several standards for through hardened bearing steels. In North America, it's AISI 52100.
- Some Timken tapered roller bearings and some special use bearings are case hardened with numerous alloy options.

A little history

- Earliest Historical Evidence – around 300 BC when Greek engineer Diades developed a roller supported battering ram, maybe earlier on pyramids .
- Oldest existing examples of bearings are in the Danish National Museum and date from around 200 BC.
- In the mid-18th century Dutch windmills had centerposts that were supported by cast iron balls.
- Later in the 18th century carriage wheel bearings were developed. They were filling slot bearings, used cast iron balls, and had no cages.

More History

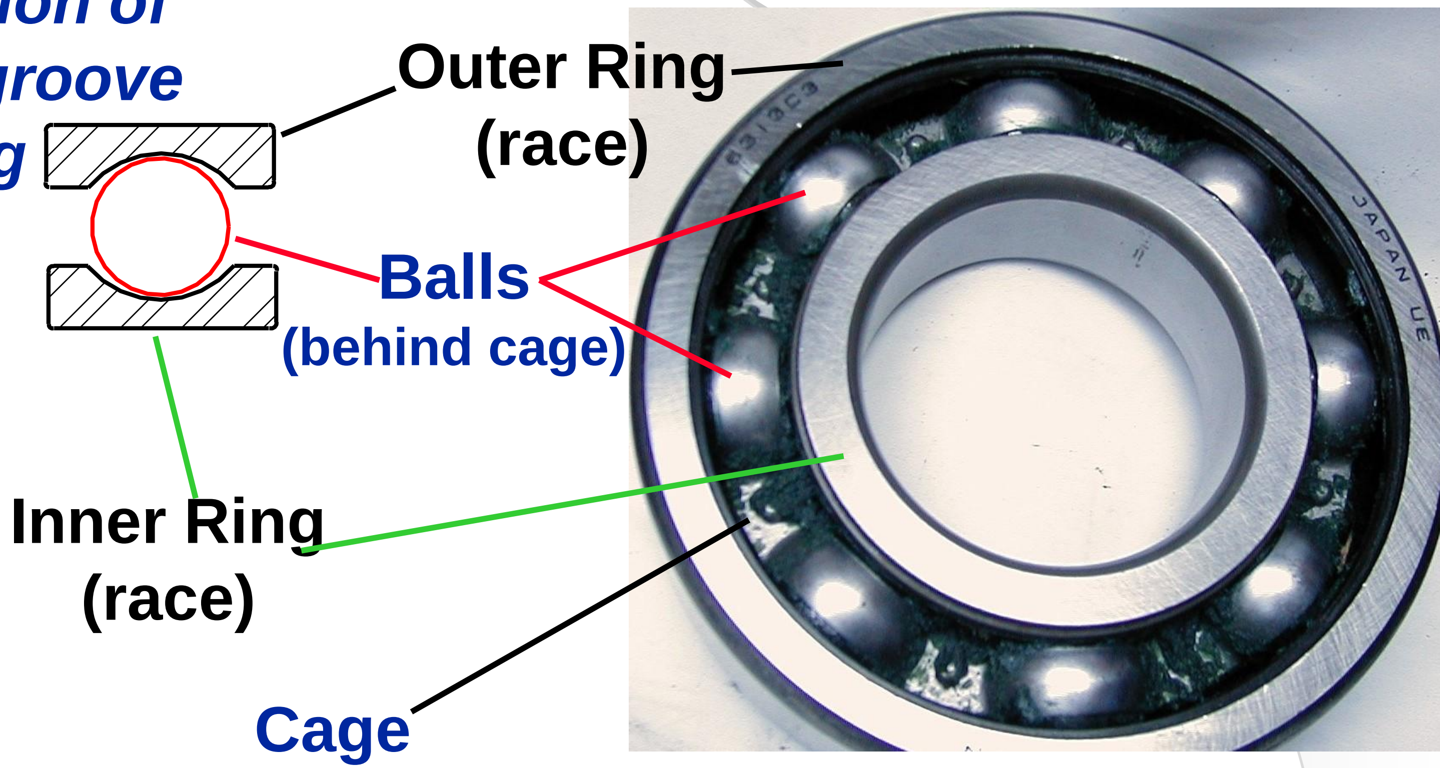
The major problem with these early applications was the lack of control of the rolling element diameters. (In discussing bearings, 0.0005” [12.7 microns] is a large overall dimension. With the rolling elements, 0.00005” [1.3 microns] is a common tolerance.)

With that poor dimensional control, a few of the elements took the majority of the load, resulting in high *Hertzian Fatigue Stresses* on the larger elements.

However, in 1883 Freidrich Fischer (FAG) developed a ball grinding machine with relatively good tolerance control. In 1898 Henry Timken produced the first tapered roller bearings and in 1907 Sven Wingquist (SKF) developed the self-aligning ball bearing.

Ball Bearing Parts

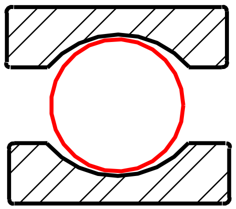
Cross section of this deep-groove ball bearing



Balls, rollers, and rings are usually made from hardened steels

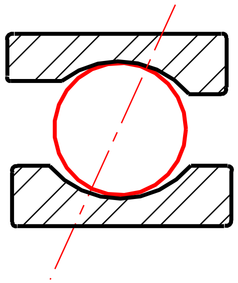
Cages are made from a variety of materials and really depend on the application

Some other types



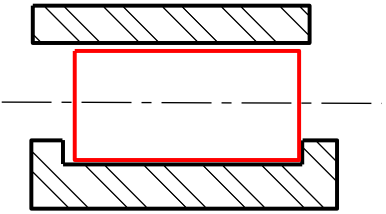
Typical Deep Groove (Conrad) Ball Bearing

Common everyday "general duty" bearing. Good radial and some thrust capacity



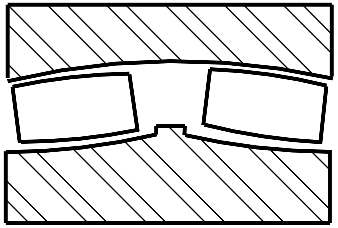
Angular Contact Ball Bearing (more thrust capacity)

Applications where heavier thrust loads are expected such as pumps and fans . ***Must*** have some thrust loading.



Roller Bearing - high radial but no thrust capacity

Used where heavy radial loads are present, i.e., large presses, rolling mills, etc.

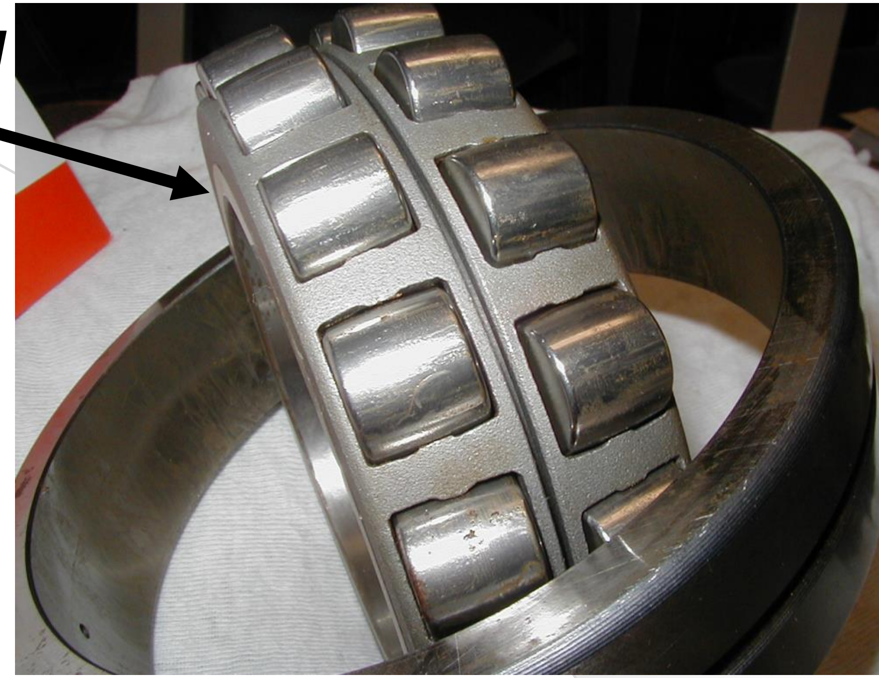


Spherical Roller Bearing - good radial and thrust load capacity

Very common where precise alignment is impossible, but heavy radial loads are present. Conveyor head drums, large fans, etc..

Different Bearings

Spherical Roller Bearing

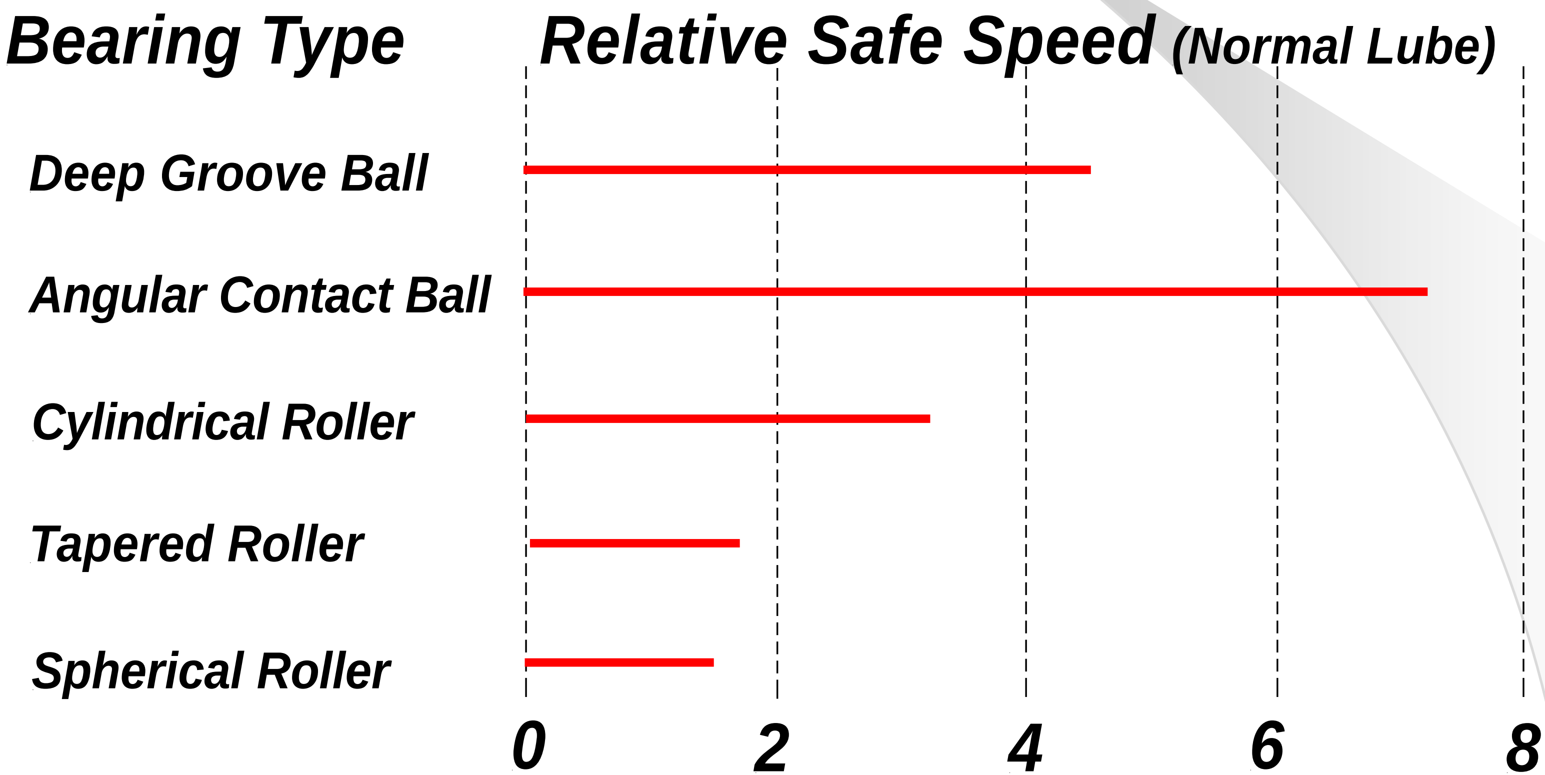


Tapered Roller

ACBB

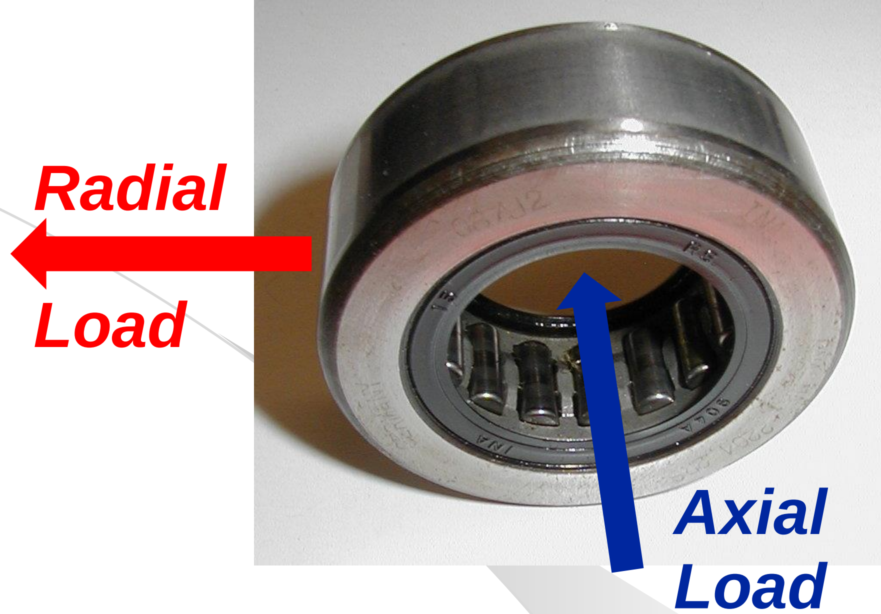
Roller Thrust Bearing

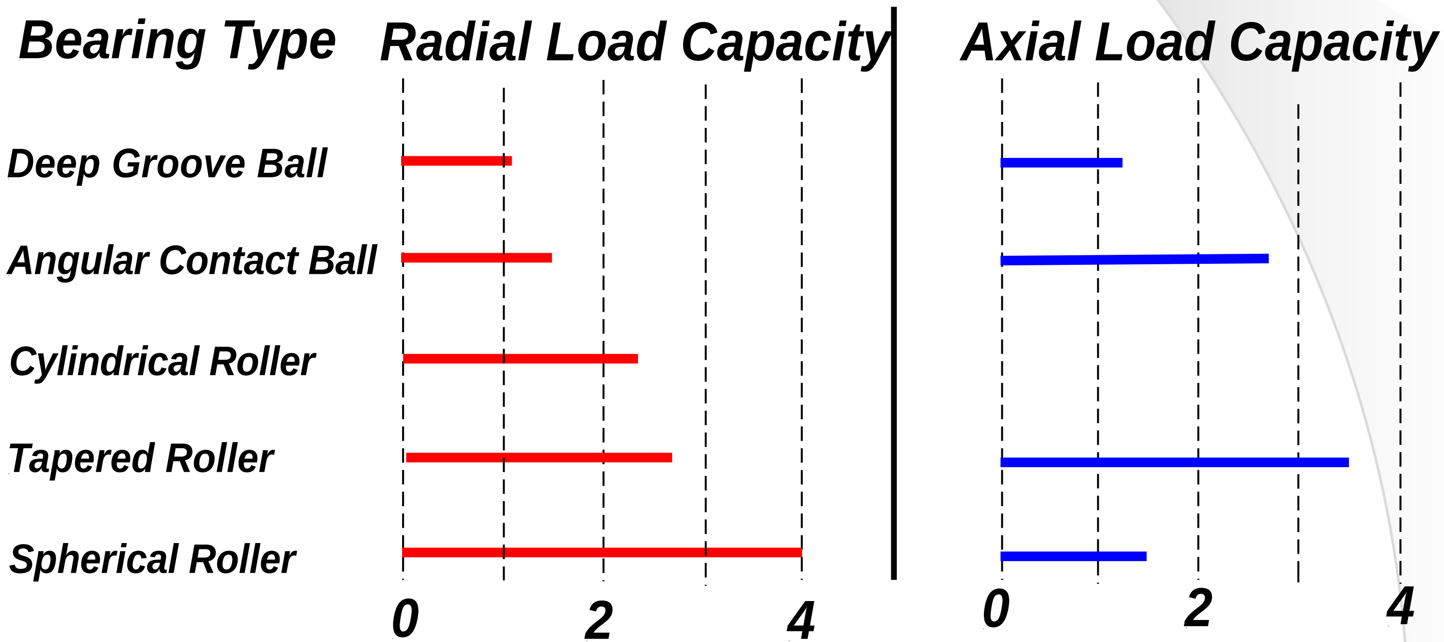
Speed Ratings



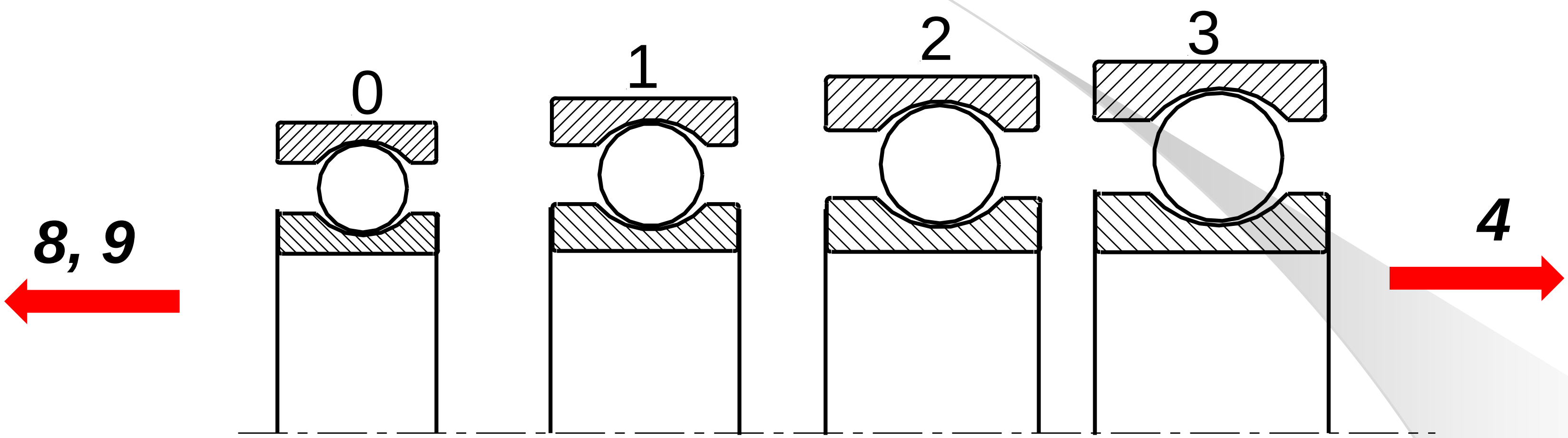
BUT, with special processing these can be doubled!

Approximate Capacities





Bearing Nomenclature



6209 Bearing –

Last two numbers – ***09*** - indicates the bore diameter, i.e.,

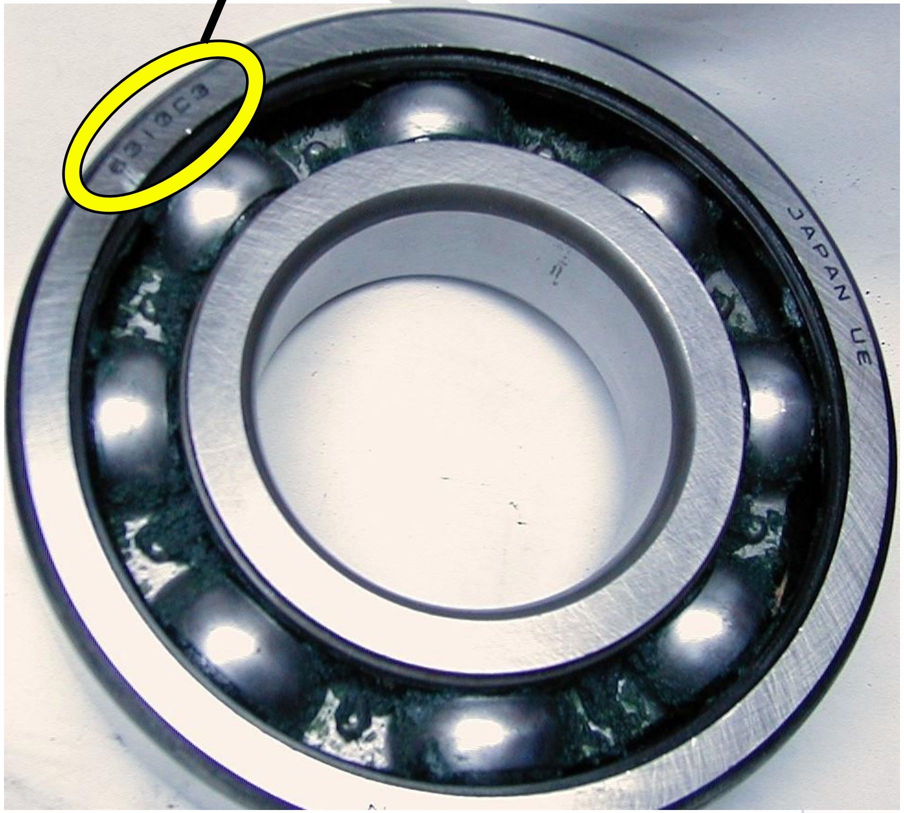
09 x 5 = 45 mm = 1.77 in.

6 shows that it is a deep groove ball bearing

2 shows that it is a #2 diameter series with ***0*** as the lightest and ***3*** as the heaviest in common usage *(Note that the bore doesn't change.)*

Bearing Nomenclature

Says ***6313 C3***



Look carefully for a suffix on that bearing number!

1. ***Seals, shields, special clearances, special cage, etc.***
2. ***With sealed and shielded bearings it will specify the lubricant.***

Internal Clearances for ball bearings

C3 and C4 suffix

Bore Range		Radial Internal Clearance					
Millimeters		Metric (min/max in microns)			Inch (min/max in 0.0001")		
over	up to	Normal	C3	C4	Normal	C3	C4
10	18	3/18	11/25	18/33	1/7	4/10	7/13
18	24	5/20	13/28	20/36	2/8	5/11	8/14
24	30	5/20	13/28	23/41	2/8	5/11	9/16
30	40	6/20	15/33	28/46	2/8	6/13	11/18
40	50	6/23	18/36	30/51	2.5/9	7/14	12/20
50	65	8/28	23/43	38/61	3.5/11	9/17	15/24
65	80	10/30	25/51	46/71	4/12	10/20	18/28
80	100	12/36	30/58	53/84	4.5/14	12/23	21/33
100	120	15/41	36/66	61/97	6/16	14/26	24/38
120	140	18/48	41/81	71/114	7/19	16/32	28/45
140	160	18/53	46/91	81/130	7/21	18/36	32/51
160	180	20/61	53/102	91/147	8/24	21/40	36/58
180	200	25/71	63/117	107/163	10/28	25/46	42/64

Similar values are specified by ANSI/AFBMA for roller bearings.

Thermal expansion of steel is 6.3 x 10^{-6} in/in/^{0}F

Internal Clearances for Ball Bearings

C3 and C4 suffix

Bore		Radial Internal Clearances					
mm	in	Metric (microns)			Inch (0.0001")		
		Original	C3	C4	Original	C3	C4
12	1/2	3/18	11/25	18/33	1/7	4/10	7/13
180	7.0	25/71	63/117	107/163	10/28	25/46	42/64

Thermal expansion of mild steel = 0.0075"/ft/100^{0}F

Thermal expansion of 300 series stainless steel = 0.011"/ft/100^{0}F

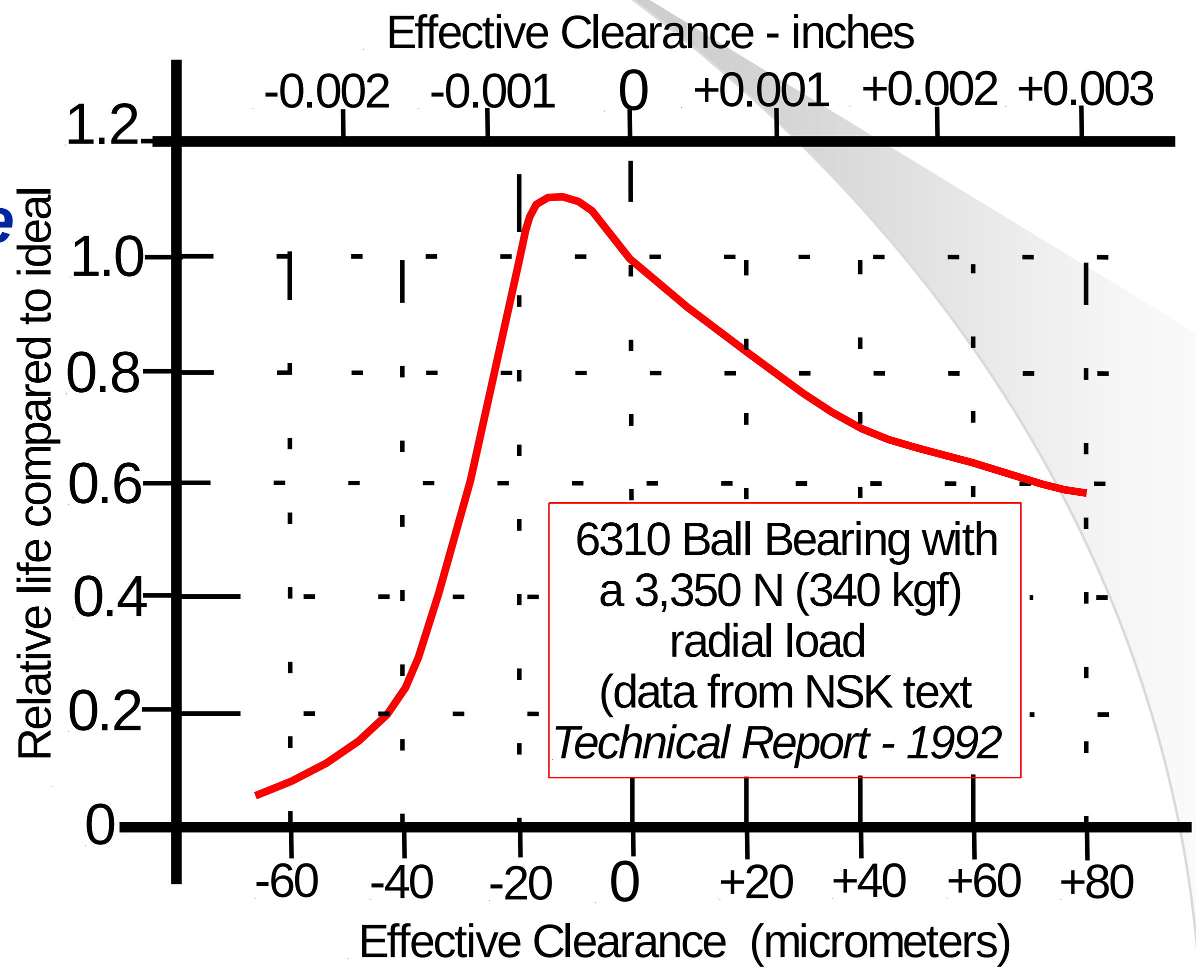
Thermal expansion of aluminum = 0.016"/ft/100^{0}F

One reason why those dimensions are important

Life

vs.

Internal Clearance



Bearing bore and housing dimensions are critical because of the internal temperatures and clearances

The specified shaft and housing fits depends on the application.

Both fits can't be tight because the heat generated within the bearing will cause dimensional changes and increased stresses.

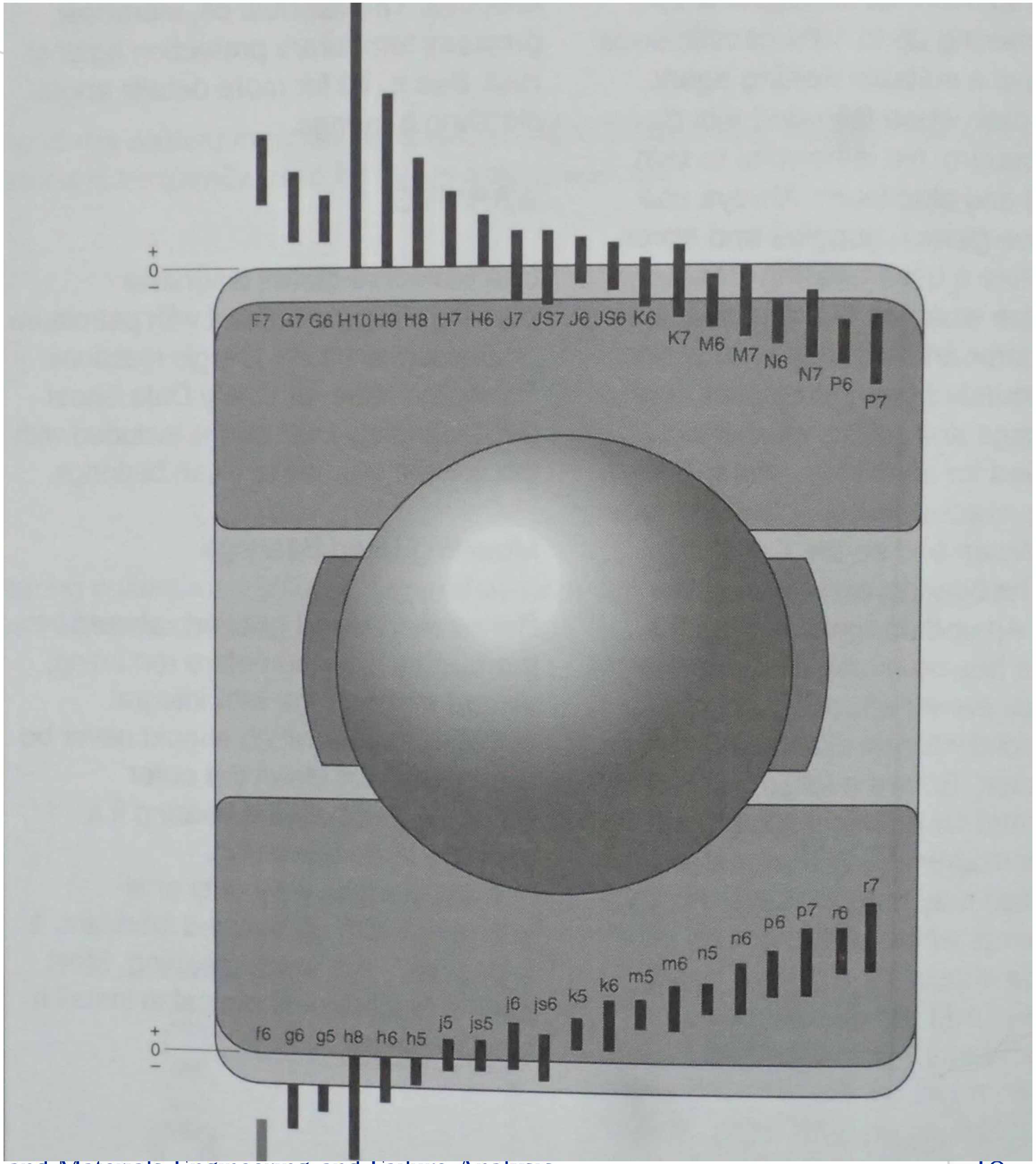
If both fits are tight, enough expansion would eventually cause a seizure. There has to be good thermal conductivity through one of the rings to control expansion and lubricant temperatures.

Typical fan/motor bearing – tight shaft, loose housing.

Typical wheel bearing – tight housing, loose shaft

Heavy loads – very tight fits

Fit examples



Shaft and Housing Fits

- Allowances have to be made for thermal expansion. On a typical shaft, with ***over 18" between centers***, one bearing will be fixed and the other will be floating to allow for thermal growth. On shorter spans the growth allowance depends on the internal clearance.

- The shaft and housing tolerances and fits are critical and depend on the:
    1. Load direction
    2. Load magnitude
    3. Materials of construction
    4. Operating temperatures

Neville's opinion – After lubrication, poor shaft and housing fits are the biggest single cause of bearing failures

Common Bearing Materials

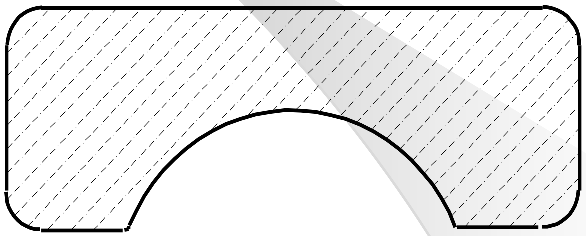
Most bearing rings and rolling elements are made from *through hardened* ≈1% carbon, 1.2% chrome steels. The sketch to the right shows a cross-section of a typical ball bearing ring.

Many bearings subjected to shock loads are *case (surface) hardened.* They are used for shock loads because cracks will not easily propagate through the softer, tougher core. (The original Timken bearings were made this way.)

Typical surface hardness – HRC 58 to 60 with balls a point or two higher

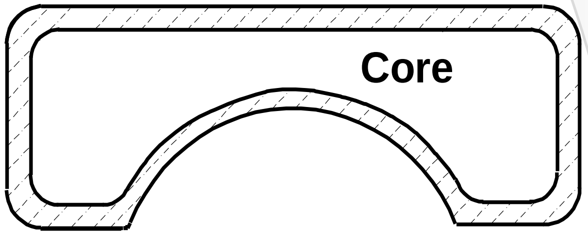
Through Hardened

The hardness is uniform thoughout the bearing ring



Surface (Case) Hardened

Outer layer is hardened while the inner core is relatively soft



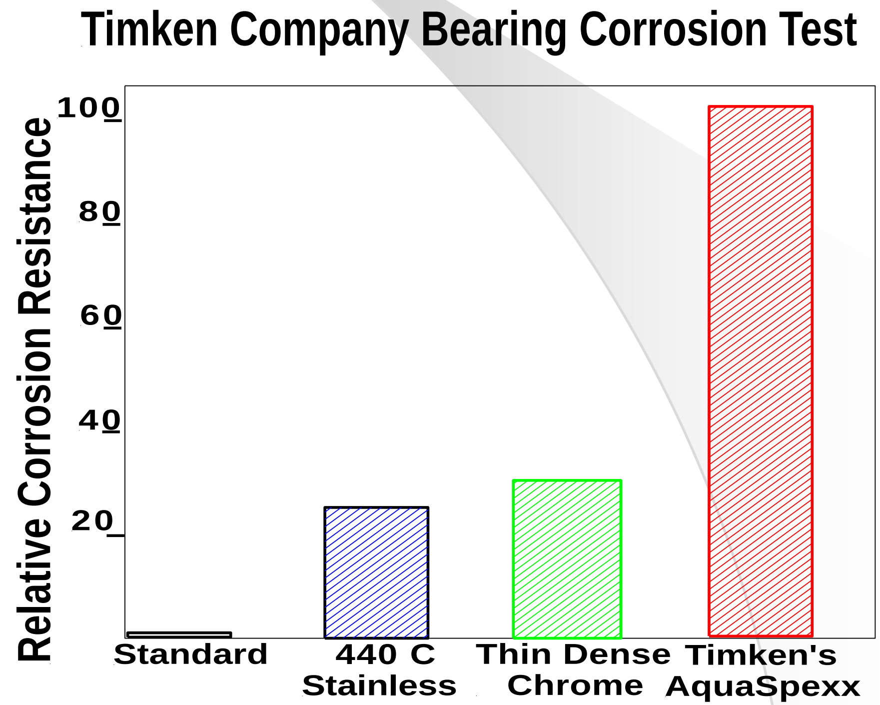
Coatings and Materials for Corrosive Applications

There is currently lots of research going on involving bearing coatings.

This data is from a Timken test showing that alternative materials can dramatically improve bearing life in corrosive applications.

We've worked with TDC bearings and found substantial life (2 to 4 x) improvements in wet and corrosive applications.

440C bearings are ***very*** expensive.



Cage Materials

The common "original" cage material was stamped and riveted steel. *(In 1903 Robert Conrad patented the machinery that enabled the stamped steel cage to be automatically assembled and you'll sometimes hear people talk about "Conrad bearings")*

Some other cage materials are:

- One piece steel – where added strength is needed such as bearings with large rollers
- Stamped bronze – for lower friction
- Machined bronze – for higher strength where variable rotational speed is present
- Non-metallic - about 8 different polymers are used and answer a variety of needs

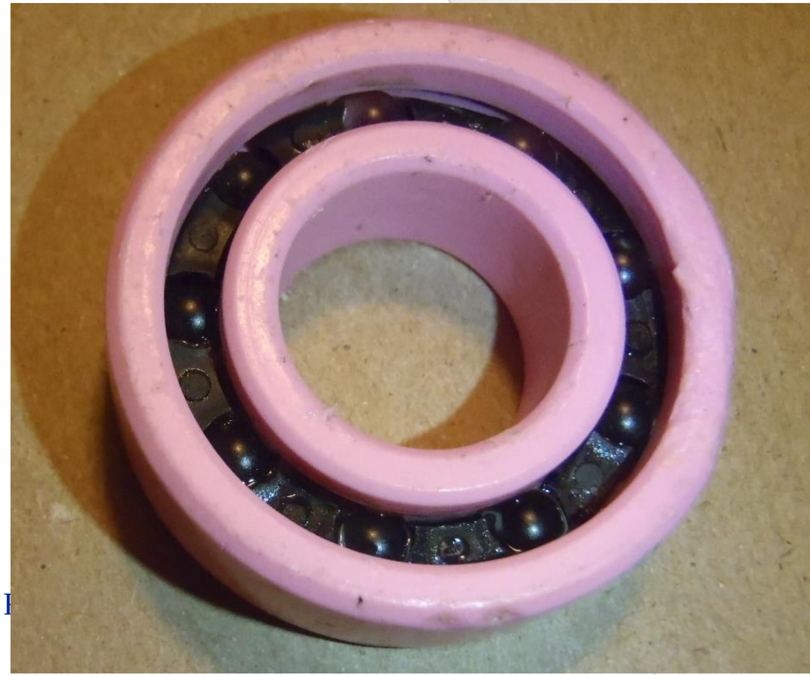
Other Materials

Ceramic rolling elements have been found to greatly improve life in applications such as:

1. At extremely high speed – where their lower mass reduces cage forces

2. Where electrical insulation is needed – Their poor conductivity results in much longer life in applications where there is a voltage difference across the bearing and arcing damage could occur, such as in VFD (variable frequency drives).

Non-metallic bearings have been used in extremely corrosive applications such as photo etching of steel. The photo shows polymer bearing rings with glass balls and a polymer cage.



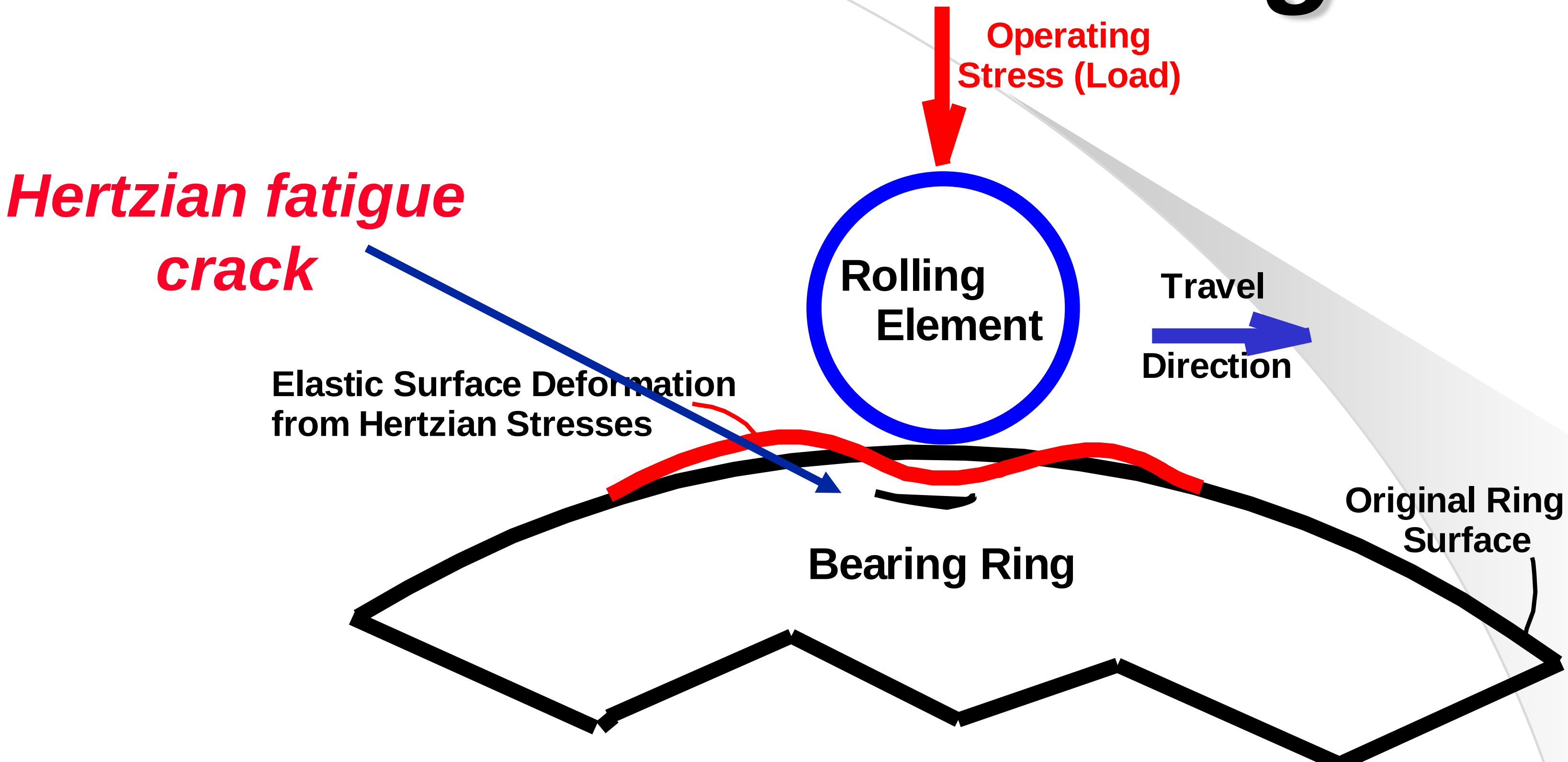
Bearing Load Capacities

Bearing designs are based on speed and two properties, the ***static*** load rating and the ***dynamic*** load rating.

The ***static*** load rating is based on the load required to cause a permanent deformation and is used for the maximum load the bearing can withstand while not moving. [The stress at this loading is in the order of 4.1 GPa (600,000 psi) and the static rating is not commonly used.]

The ***dynamic*** load rating ***(C)*** is the radial load that 90% of a group of identical bearings, with rotating inner rings, can withstand for 1,000,000 revolutions without suffering from ***Hertzian fatigue***. (The actual load for rolling applications is essentially never more than 30% of the static load rating.)

What is Hertzian Fatigue?



As the ball or roller passes over an area of the ring, the ring alternately goes into compression, then tension. Meanwhile, the same type of cyclic loading is happening inside the rolling element. If the stresses are high enough, this will cause ***Hertzian Fatigue*** cracking ***below the surface***.

Dynamic Load Rating

Fatigue Life $L = [C/P]^3 \times 10^6$ for a ball bearing

$L = [C/P]^{3.33} \times 10^6$ for a roller bearing

where

L = fatigue life

C = basic dynamic load rating

P = the *dynamic equivalent* load

These are the ***Lundgren-Palmgren*** equations and are the foundations for all ratings of rolling element bearings and are also used in ISO 281.

Calculating the Basic Dynamic Rating

For a ball bearing:

$$C = b_m f_c (i \cos \alpha)^{0.7} Z^{0.667} D_B^{1.8}$$

where:

- b_m = rating factor depending on material quality
- f_c = shape and material coefficient
- i = number or rows of elements
- α = contact angle (^{0})
- Z = rolling elements per row
- D_B = ball diameter (mm)

But it's a lot easier to look it up in a manufacturer's catalog

Almost all bearing design is based on the bearing failing from Hertzian Fatigue at 1,000,000 stress cycles

Design Load Capacities

C = the basic dynamic load rating of the bearing

Magnitude	Ball Bearings	Roller Bearings
Light	< 0.07 C	< 0.08 C
Normal	> 0.07 C < 0.149 C	> 0.08 C < 0.179 C
Heavy	> 0.15 C	> 0.18 C

Calculating the L_{10} life of that 6209 with a 700 lb (318 kg) load

Fatigue Life $L = [C/P]^3$ for a ball bearing

$L = [C/P]^{3.33}$ for a roller bearing

where, looking at just a radial load for a ***6209 ball bearing***:

L = fatigue life (in millions of revolutions)

C = basic dynamic load rating (Given as ***7460 lbs/3465 kg***))

P = the actual load (***Given as 700 lbs/318 kg***)

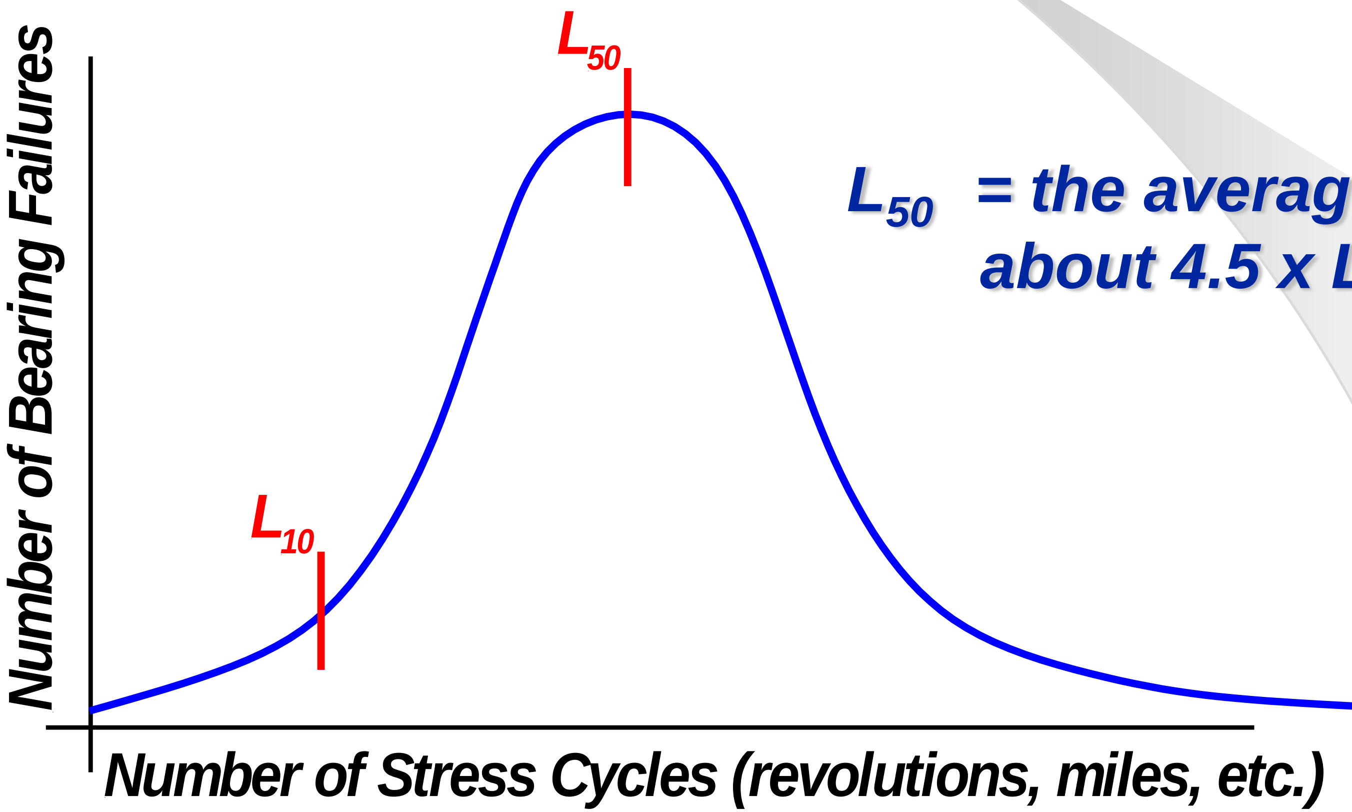
Therefore, for this application, $L = (7460/700)^3 \times 1{,}000{,}000$ revolutions

$L = [10.66]^3 \times 1{,}000{,}000 = 1{,}210{,}381{,}738$ revolutions

CURIOSITY – How many years' run is this at 1770 rpm if we operate for 2000 hours/year?

Ans = 5.7 years

Rolling element bearings are usually designed around the L_{10} life, the point where 10% fail with a given load.



L_{50} = the average life = about 4.5 x L_{10}

Typical L_{10} lives

Domestic hand tools - 1500 hrs   Domestic electric motors - 1500 hrs

Industrial Motors – Large (40 hp and up) - 50,000 hrs, Small – 20,000 hrs

Fans - General industrial - 15,000 hrs, Mine ventilation - 50,000 hrs

Industrial compressors - 40,000 hrs

Industrial reducers - 5,000 hrs (x service factor)

Pickup trucks - Light duty - 150,000 miles,
Heavy duty -220,000 miles

Going back to those design equations where

Fatigue Life $L = [C/P]^3$ for a ball bearing

$L = [C/P]^{3.33}$ for a roller bearing

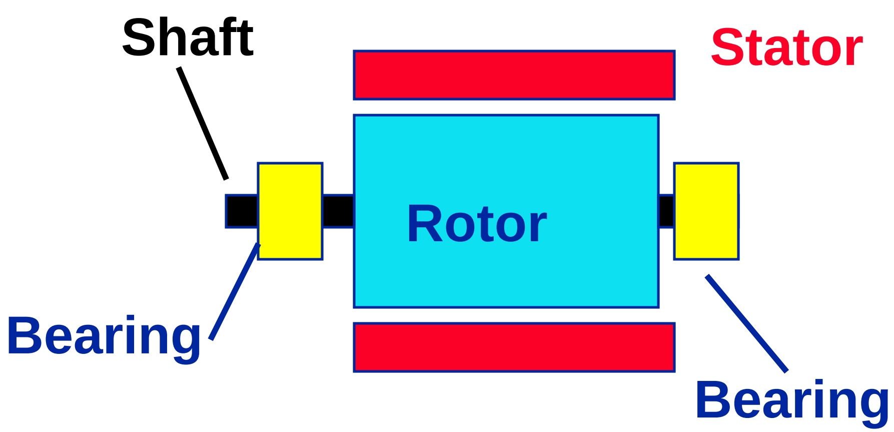
and then looking at the forces acting on the Bearing - the Design Loads plus the Parasitic Loads

we see that doubling the total load cuts the life by a factor of 8 to 10!

Sources of Bearing Loads in a Typical Motor

Design Loads

1. Rotor Weight
2. Windage
3. Allowable vibration and misalignment forces



Parasitic Loads

1. Soft foot, i.e., base and bore distortion
2. Excessive forces from misalignment and vibration
3. Axial thrust
4. Thermal changes

Calculating the Actual L_{10} Life

The design engineer figured that that 6209 motor bearing would last for 1.2 billion revolutions with a 700 pound load [Therefore, for this application, L = $(7460/700)^3$ x 1,000,000 revolutions =1,210,381,738 revolutions.]

What happens if the mechanic does a not-very-careful job of coupling alignment and adds 50 lbs to that 700 pound load.

(7460/750) x 1,000,000 rev = 984,000,000 revolutions

= ***-23%***

Calculating the Actual L_{10} Life (con't)

But if there is a little soft foot, because of a poorly engineered base, only 0.020" or so, and that increases the bearing load by 150 pounds, because of housing distortion, the bearing life now becomes

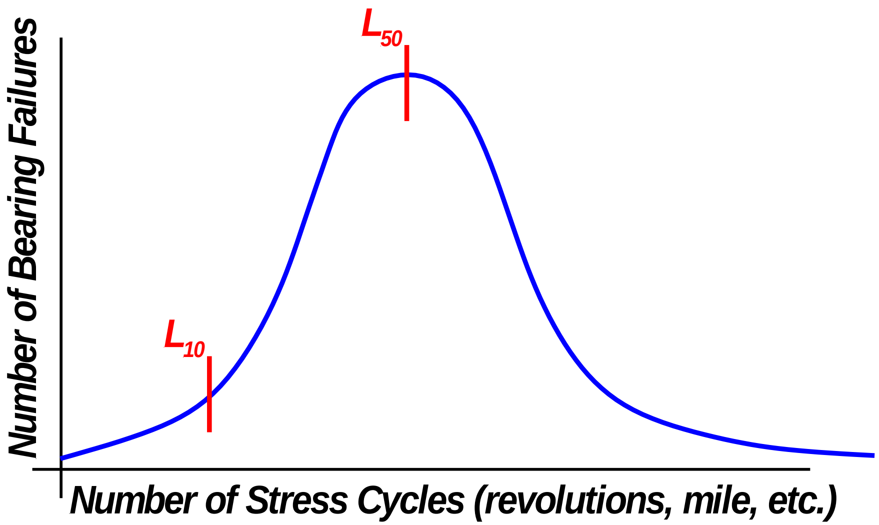
(7460/900) x 1,000,000 rev = 569,000,000 revolutions = ***-53%***

Good mechanical practice says that the base should be flat or shimmed to within 0.002" (0.05mm) at every machine foot.

SO, weak design and careless assembly can cut the motor bearing L_{10} life from 5.7 years to 2.7 years!

Ratings in the Real World,

i.e., corrections for what really happens



$L_{act} = a_1 \times a_2 \times a_3 \times L_{10}$

Where

L_{10} = the load rating at 90% reliability

a_1 = reliability adjustment factor

a_2 = special properties adj. factor

a_3 = operating conditions factor

$$L_{act} = a_1 \times a_2 \times a_3 \times L_{10}$$

a_1 is the life adjustment factor for reliability and is:

Reliability(%)	90	95	96	97	98	99
a_1	1.00	0.62	0.53	0.44	0.33	0.21

a_2 is the life adjustment factor for special material properties and is currently in the range of 1.1, however most manufacturers have accounted for this in their catalogs, so use 1.0.

a_3 is the adjustment factor for operating conditions and takes into account problem areas such as low speeds, high temperatures, lubricant contamination, and misalignment. If everything is great and a high viscosity lubricant is used, it may be 2. But if the lube is contaminated with water and the bearing is running at a very low speed with poor alignment, the factor will be less than 0.1.

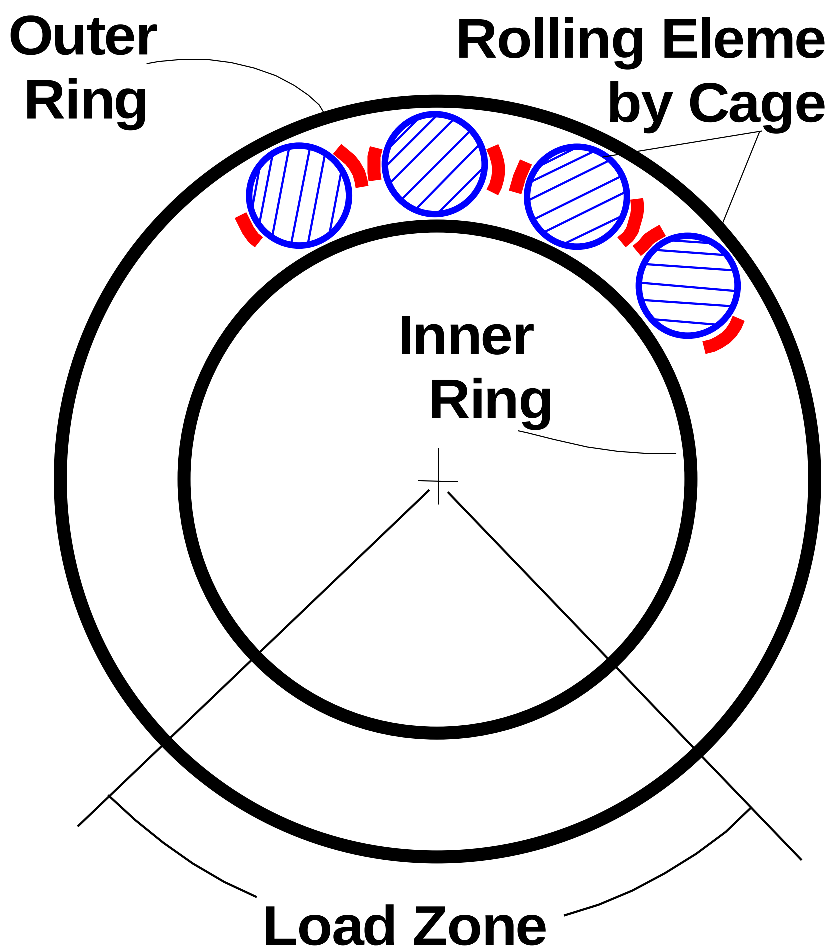
So, let's go back to that motor bearing that was poorly installed and is now expected to live for 2.7 years instead of 5.7.

If the lubricant is contaminated with water, that L_{act} life will drop to 7 months!

AND machines have more than one bearing, so we have to look at L_{act} x L_{act} x … = reality!

To understand why this happens, we’ll look a little more in detail about what goes on inside a “rolling element” bearing during operation.

As the bearing rotates…



One of the rings rotates and the balls roll between the two rings.

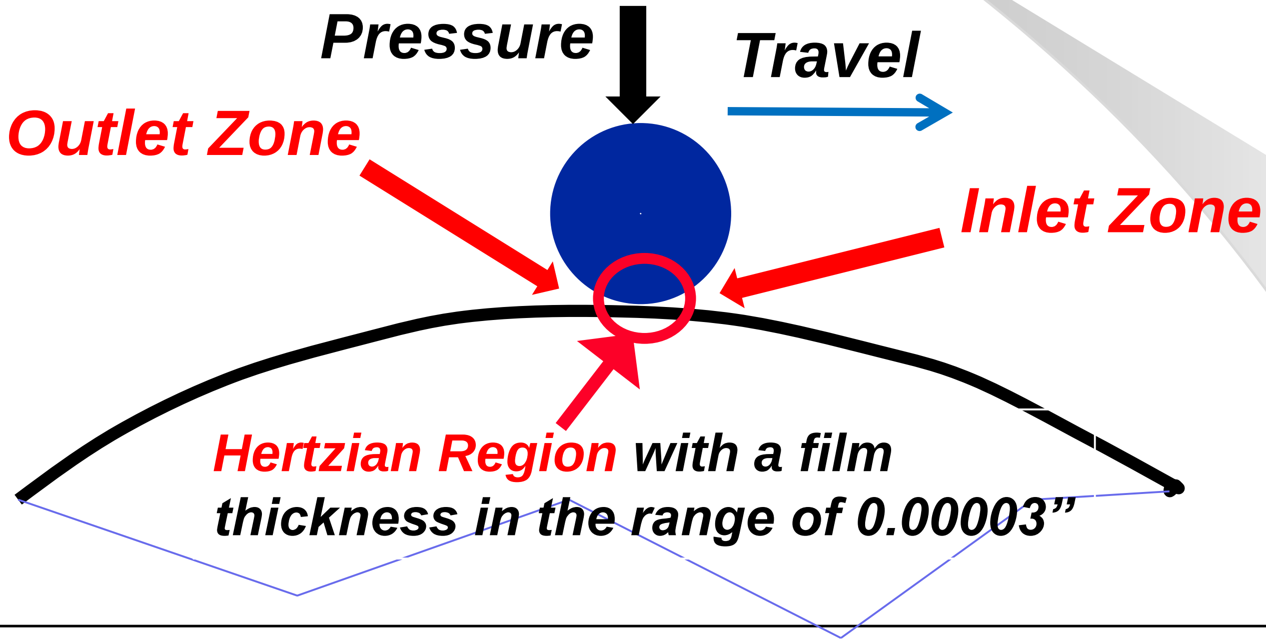
The "load zone" is the area where the balls are trapped between the two rings. (In this area the balls drive the cage.)

Lubrication is critical for two reasons as the rolling elements go in and out of the load zone.

A. It separates the balls from the rings.

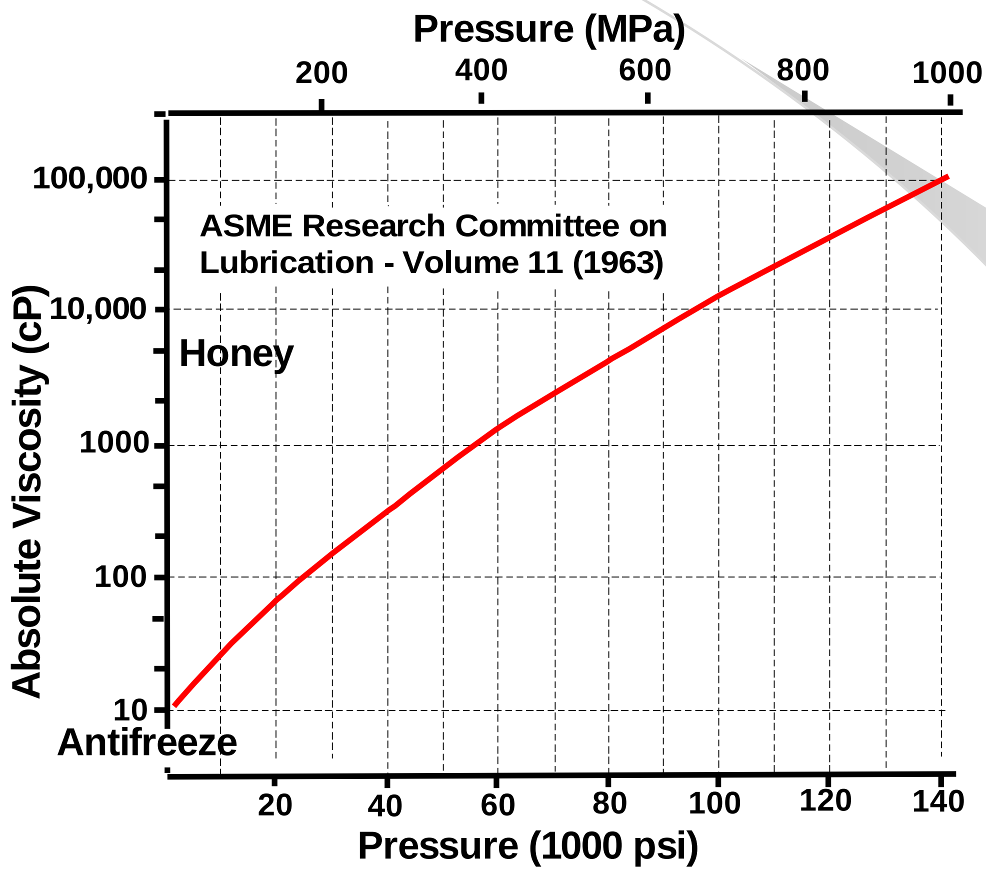
B. It cushions between the balls and the cage – because the cage drives the balls through the unloaded area.

Elastohydrodynamic (EHD) Lubrication and Viscosity Transformation



As the ball moves, the lubricant gets trapped between the ball and ring and is subjected to pressures of more than 300,000 psi (2 GPa). When This happens, the oil viscosity increases tremendously during ***“viscosity transformation”,*** and separates the two elastically deformed steel pieces.

Pressure and Viscosity



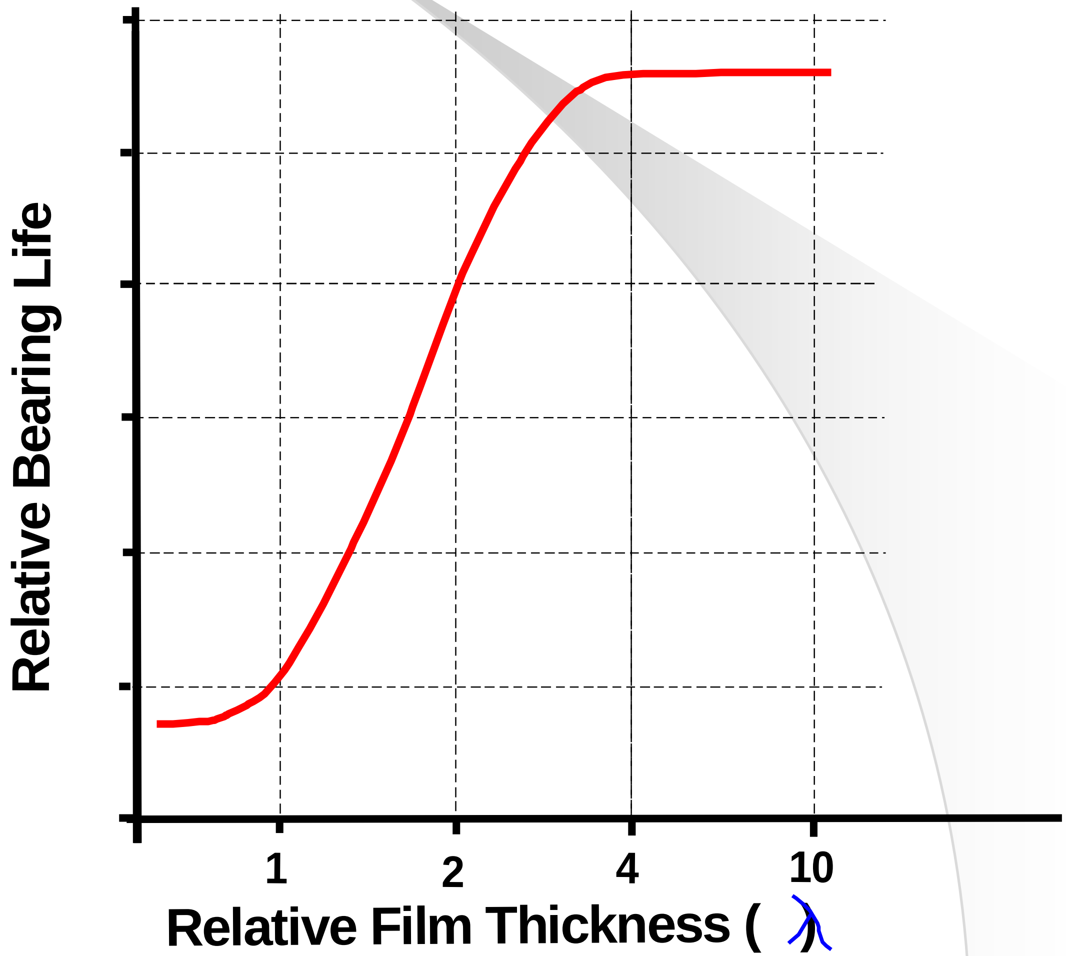
This chart was developed over 50 years ago. Some modern research shows the viscosity goes up by another 10^5.

Pressure and Viscosity

What do you think that water does when it's subjected to those pressures?

Film Thickness effect on Bearing Life

λ (lambda) is the symbol used to show ratio between the asperities on two mating parts and the lubricant film separating them.



We know the lubricant functions include separating and cushioning between the moving pieces,

and it is also important for heat transfer.

Temperature Effects on Lubricants

- Increased temperature reduces the lubricant viscosity and the actual film thickness.
- Increased temperature increases the rate of additive deterioration (Arrhenius' Rule).

Why do roller bearings need higher viscosity lubricants than ball bearings?

The contact points of balls and rollers are very different and the line contact of rollers requires a thicker lubricant film to ensure sufficient clearance.

Then, with roller thrust bearings, there is a huge difference in contact point velocities as the radius becomes smaller.

Table 8.6 – Suggested minimum viscosities at operating temperatures for typical industrial machinery

Minimum Viscosity (mm/sec)	Equipment
13	Ball bearings, hydraulic systems
23	Spherical, tapered, cylindrical roller bearings, lightly loaded gears
35	Roller thrust bearings
40	General spur and helical gears
70	Worm reducers

Low speed changes the lubricant viscosity requirements

The general rule for ball bearings is that a minimum viscosity of 13 cSt should be adequate, but at low speeds there isn't enough velocity to create the viscosity transformation – so a heavier oil and/or EP additives are needed.

Looking at a 6209, at 10 rpm, instead of 13 cSt, the AFBMA calculations show a 1000 cSt oil should be used.

In a mine hoist application we worked on, the manufacturer spec'd the lube based on the high speed travel. They didn't recognize that the bearing saw many revolutions at a relatively low speed at the start and end of every trip. The bearings only lasted a little more than a year!

Rolling element bearings are designed to fail from Hertzian fatigue, but surface fatigue is the most common failure cause!

… UNFORTUNATELY,

what often happens is that we force them into position, feed them contaminants, neglect good fits, put water in their lubricants, and Hertzian Fatigue never gets involved.

Both water (because it destroys the lubricant film) and dirt (because it increases the Hertzian stresses) will have huge effects on bearing life.

In the next few slides, we’ll look at a series of failed bearings, talk some more about how and why precise fits are critical, and see how these bearings didn’t last long enough to see Hertzian fatigue

Conducting the Failure Analysis

Look carefully at the bearing, chart the symptoms (clues), then find out where they came from

Usual Steps in the Analysis

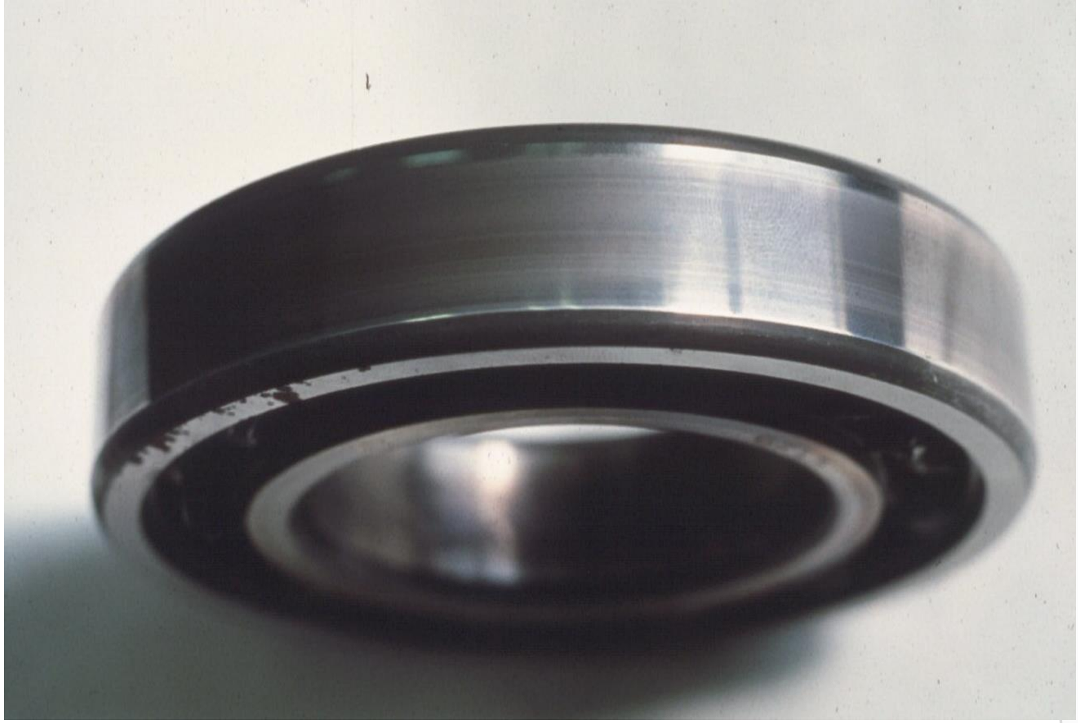
1. Look at the exterior - Inspect the external surfaces, the seals, shields, external and internal bores (***Most bearing failure causes can be found in this step – and going further adds little!)***
2. Look at the ball or roller paths
    1. Geometry
    2. Surface conditions
3. Cut the cage and look for wear patterns
4. Look at the ball surfaces

Step #1

Examine the Shaft and Housing Fits

1. How does heat get out of the bearing?
2. Loose fits cause additional vibration.

This outer ring should have a machine ground surface - but what does this bearing show?

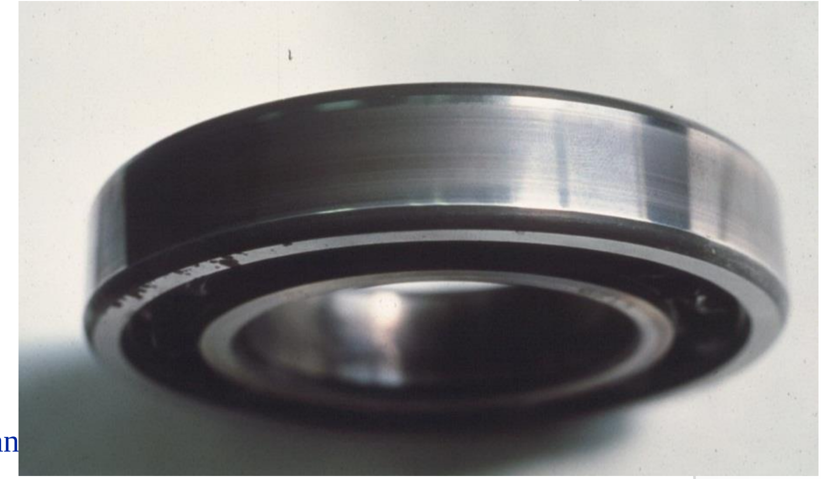


Step #1

Why Shaft and Housing Fits are So Important – High Speed

In high speed bearings a loose fit reduces heat transfer. As a result:

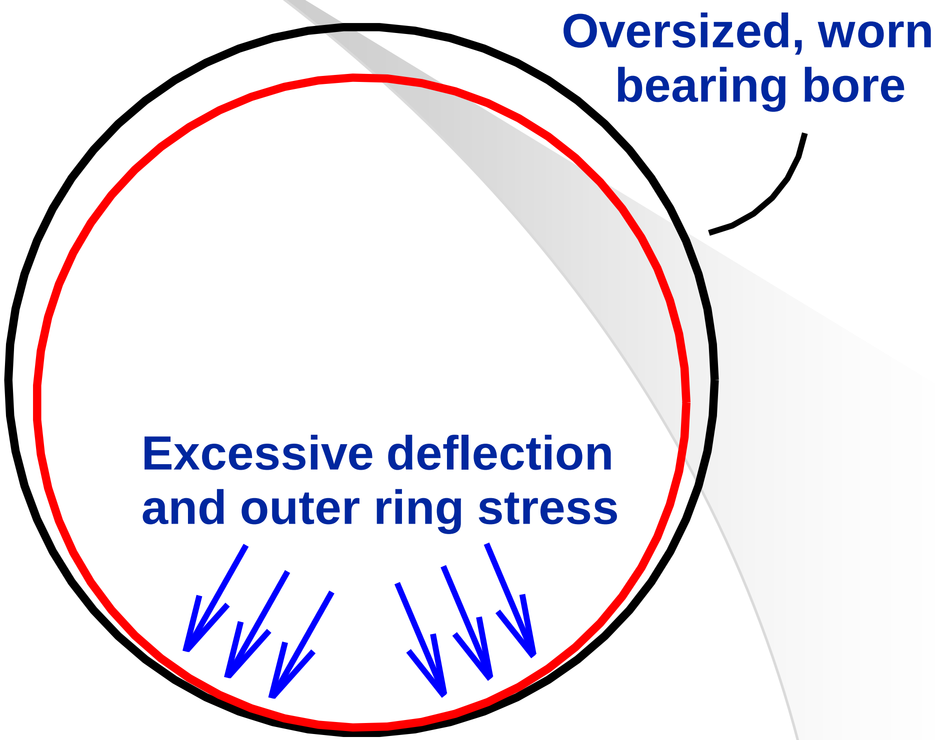
1. Internal clearances are decreased and fatigue stresses increase.
2. As the temperature goes up:
    1. The lubricant film goes down – and bearing life decreases.
    2. Nearby seal life is decreased.



Step #1

Why Housing Fits are So Important – Low Speed

A poor fit increases fatigue stresses with all ball and roller bearings.



The reason why this is particularly damaging on low speed bearings (and frequently leads to cracked rings) is because fatigue is a physical mechanism.

Look at this Ring Surface!

The installation was designed with the bearing only half way into the bore. Look at how the outer ring surface was polished where it was loose in the bore.

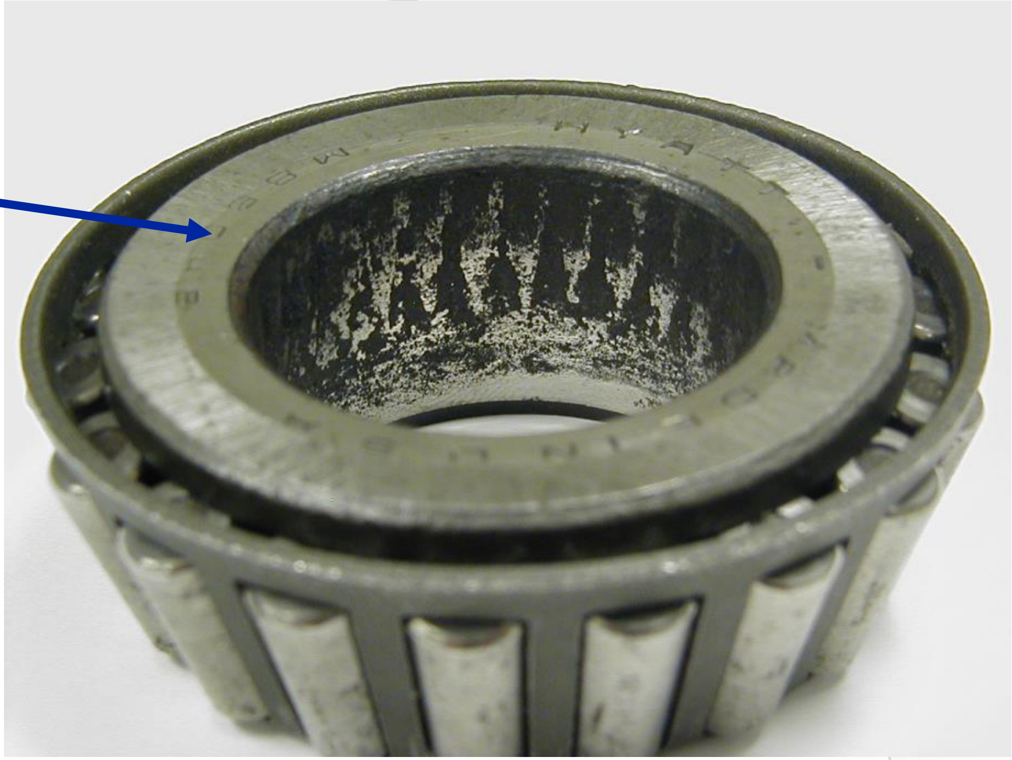
Fretting

Fretting is a wear and corrosion mechanism that results from tiny movements between the bearing and the housing (or shaft) causing wear, followed by oxidation of the wear particles.

How does this affect heat transfer?

Inner Ring Fit Clues

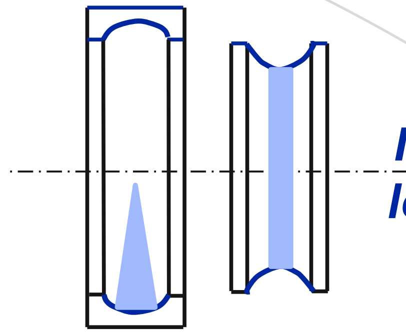
Loose inner ring fit with fretting and mirroring of the grinding pattern. (Note polishing on the thrust face of the inner ring.)



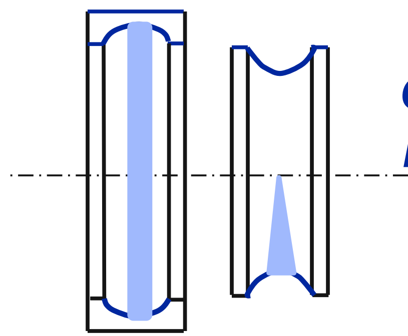
Step #2

Typical Normal Load Zones

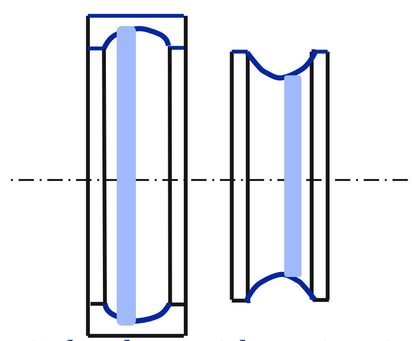
Looking at the Ball Paths (Traces)



Inner ring rotating with pure radial load – i.e., drive end motor bearing



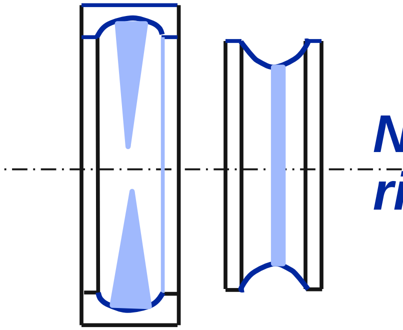
Could be either outer ring rotating, i.e., a trunnion bearing, or the load could be rotating with the inner ring (unbalance).



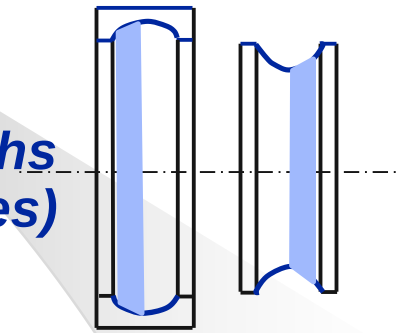
Typical of axial loading

Typical Abnormal Ball Paths

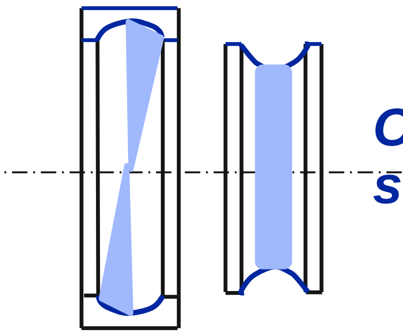
Indicating Parasitic Loads



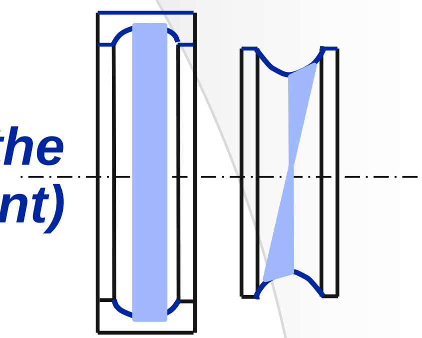
Normal inner ring path, outer ring is out–of-round



Excessive thrust load (paths high off center lines)



Outer ring not square to the shaft (ring misalignment)



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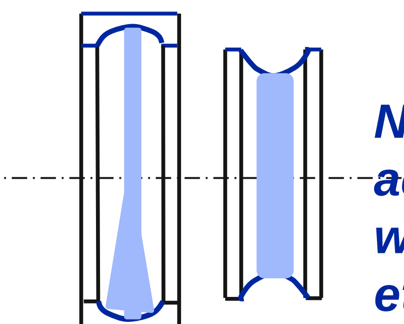


Normal inner ring path combined with additional preload resulting in excessively wide paths, i.e. possible shaft fit problem, etc.

Looking at the Ball Paths

A double row, self-aligning ball bearing with VERY unequal loading on the paths.

Another Ball Path

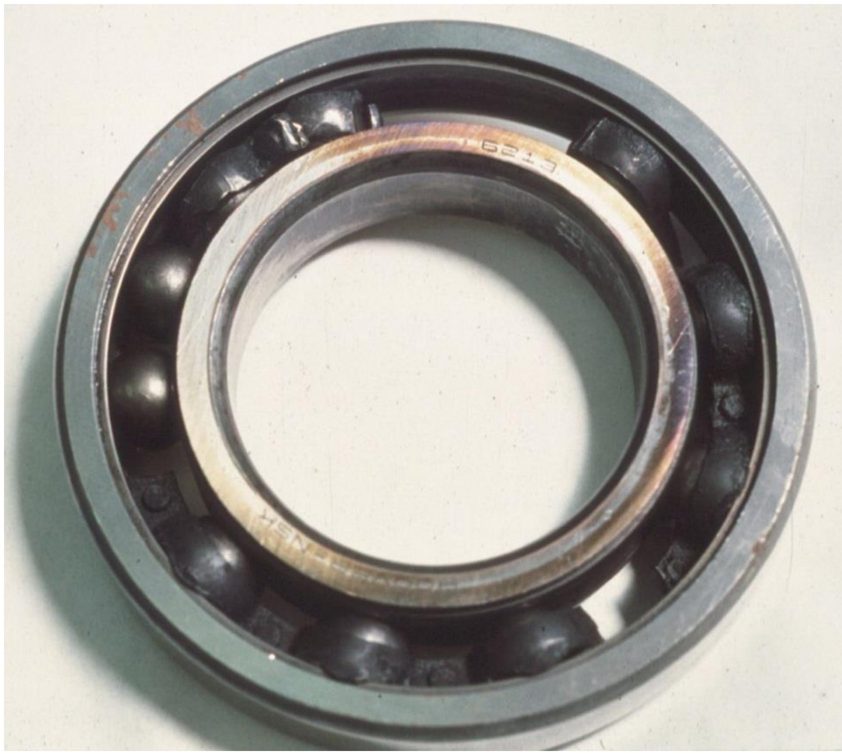
This ball path has been hot and is typical of a bearing without enough internal clearance.

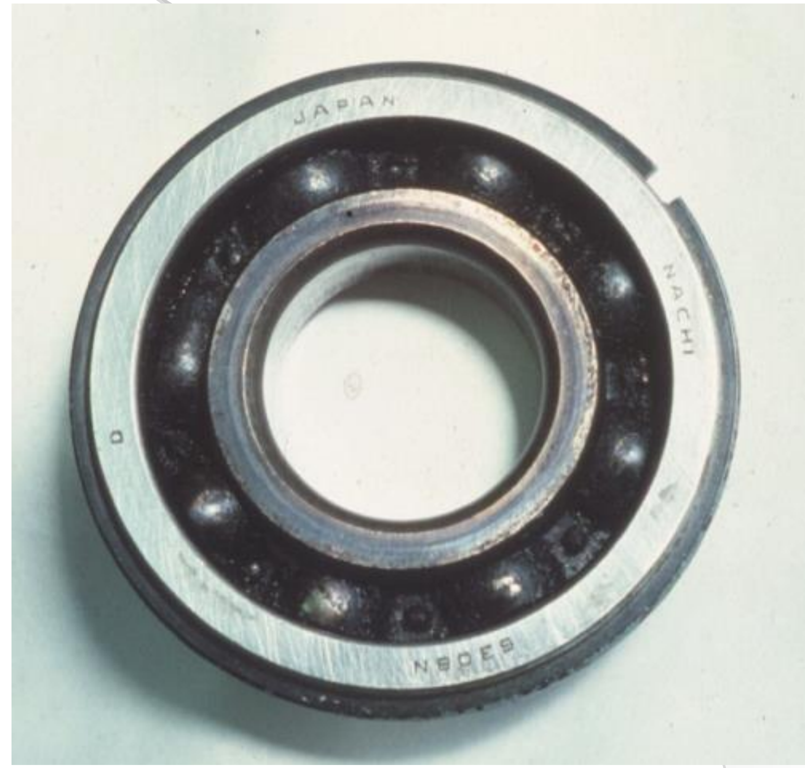
How hot has it been? (500^{0}F!)

Looking at two Roller Paths

Why is this double-row spherical roller bearing badly worn on one path?

Two Classic "Inadequate Lubrication" Failures - With VERY Different Causes



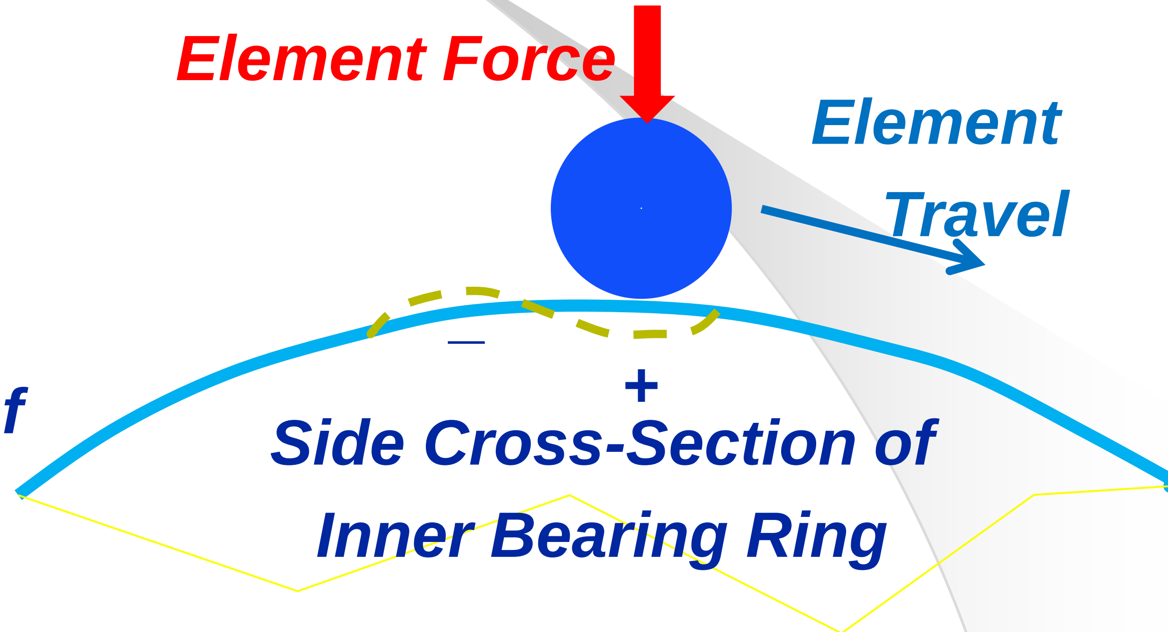


Horrible shaft and housing fits caused elevated temperatures

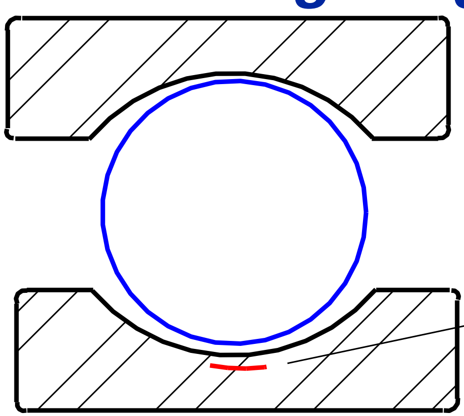
Installation crew forgot to grease new pump bearing

But the result was the same!

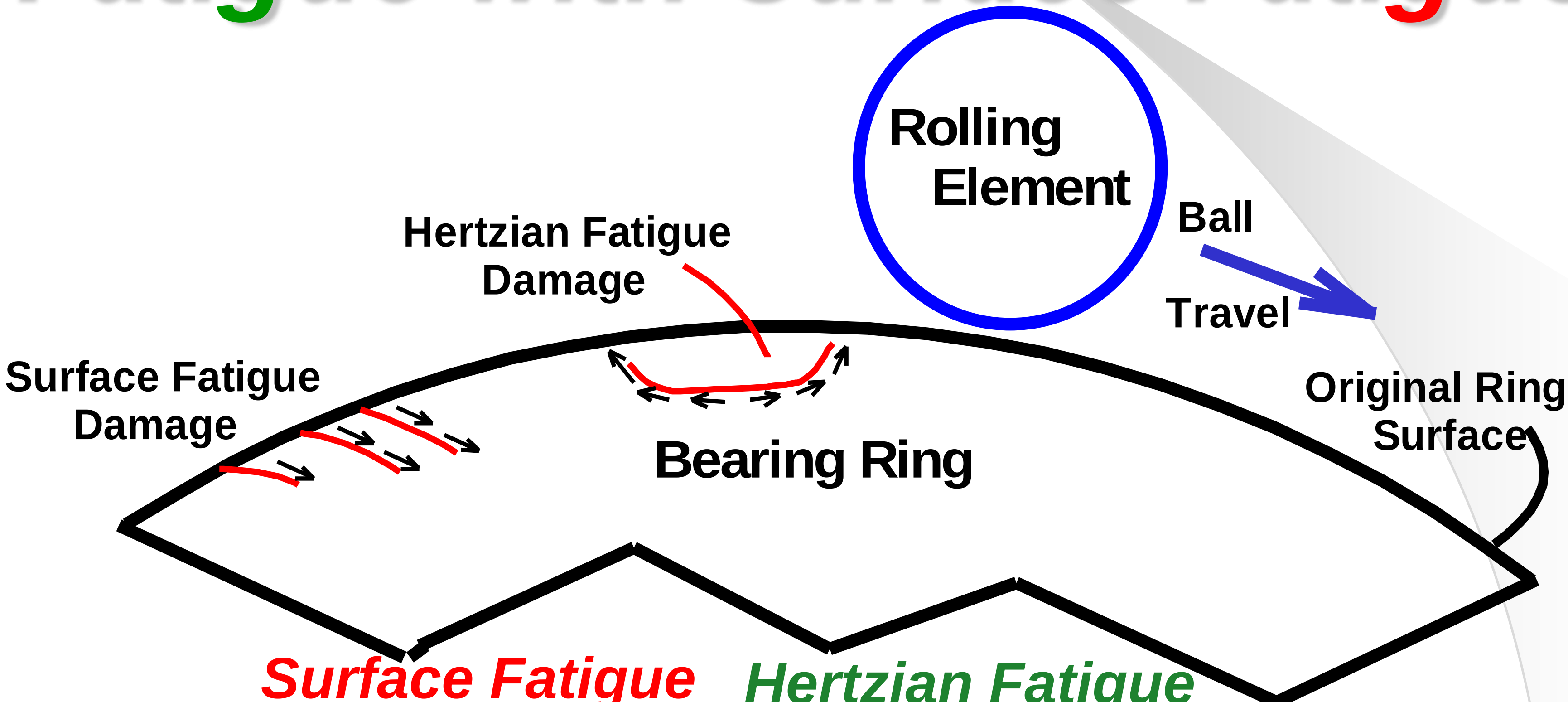
Design is based on Failure by Hertzian Fatigue



Radial Cross-Section of Ball Bearing Rings



Comparing Hertzian (Design) Fatigue with Surface Fatigue



Surface Fatigue

Starts on the surface, then grows inward

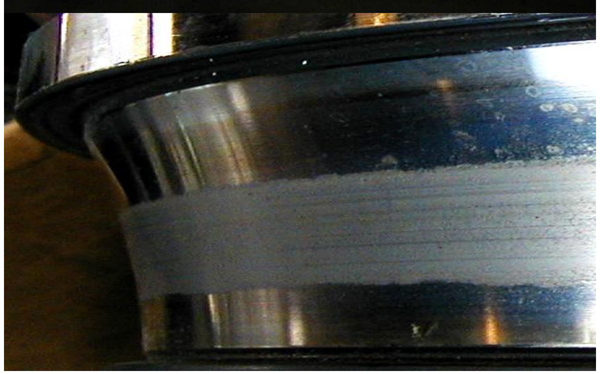
Hertzian Fatigue

Starts inside the ring and grows outward

Comparing the Causes

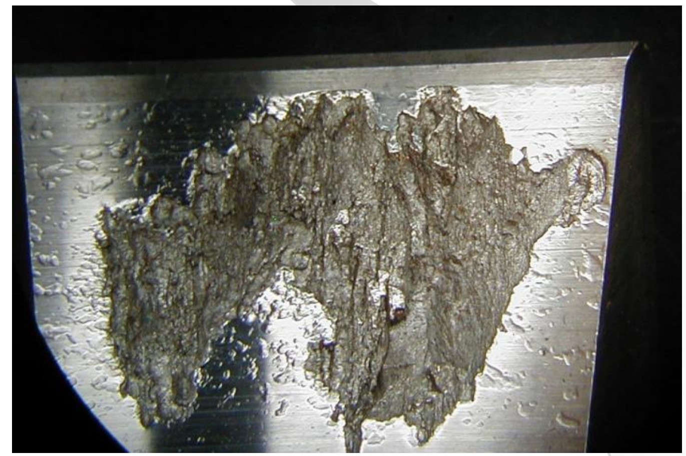
Early death caused by lack of lubricant film from excessive load, dirt, or water in the lubricant

Shallow, Surface origin

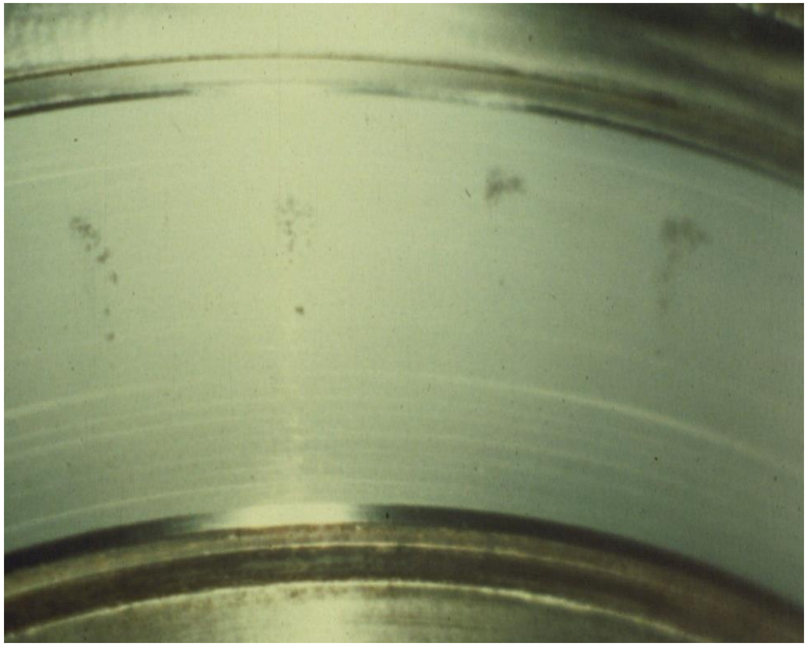


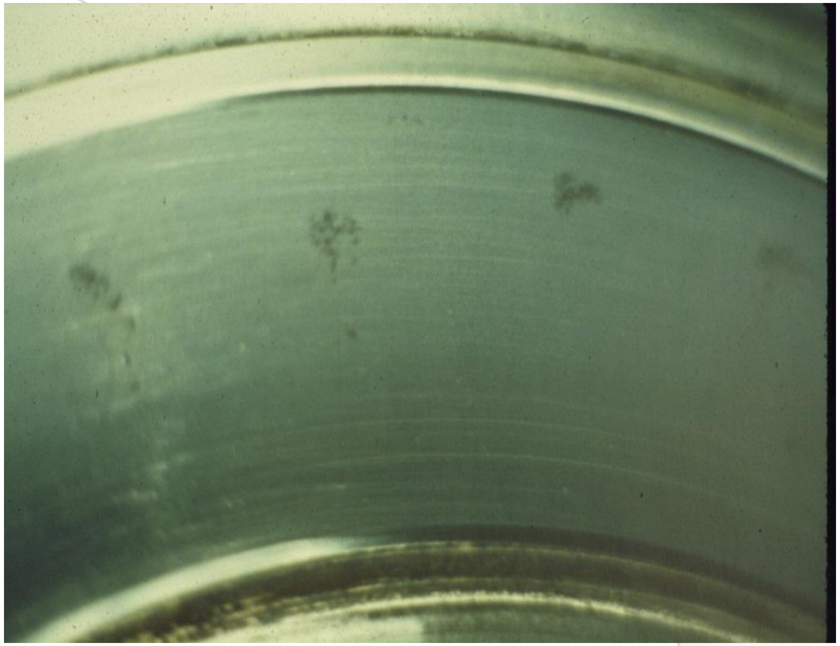
End of life from Hertzian fatigue caused by heavy repeated loads

Deep, Subsurface Origin



Water Marks (Corrosion)





These black stains are the result of corrosion. However, the real damage is from hydrogen liberated by the corrosion reaction. Hydrogen atoms enter the steel and cause microcracks (underneath the black stains) that significantly reduce the bearing life.

More Water Damage and Corrosion

Corrosion pits in the ring above are the result of a contaminated EP lubricant that became acidic (***in the differential of our car!!!***).

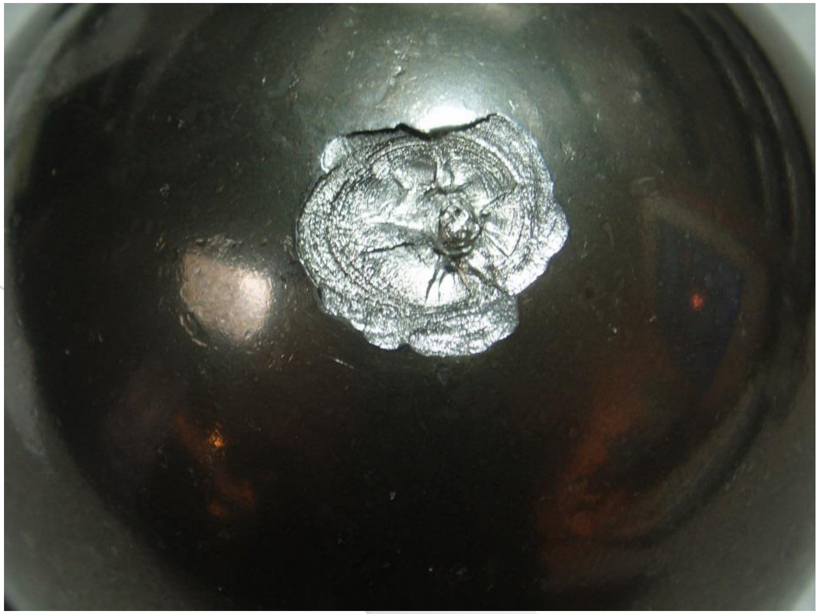
The black marks on the ring to the left are the effect of water that was in the bearing during a shutdown period.

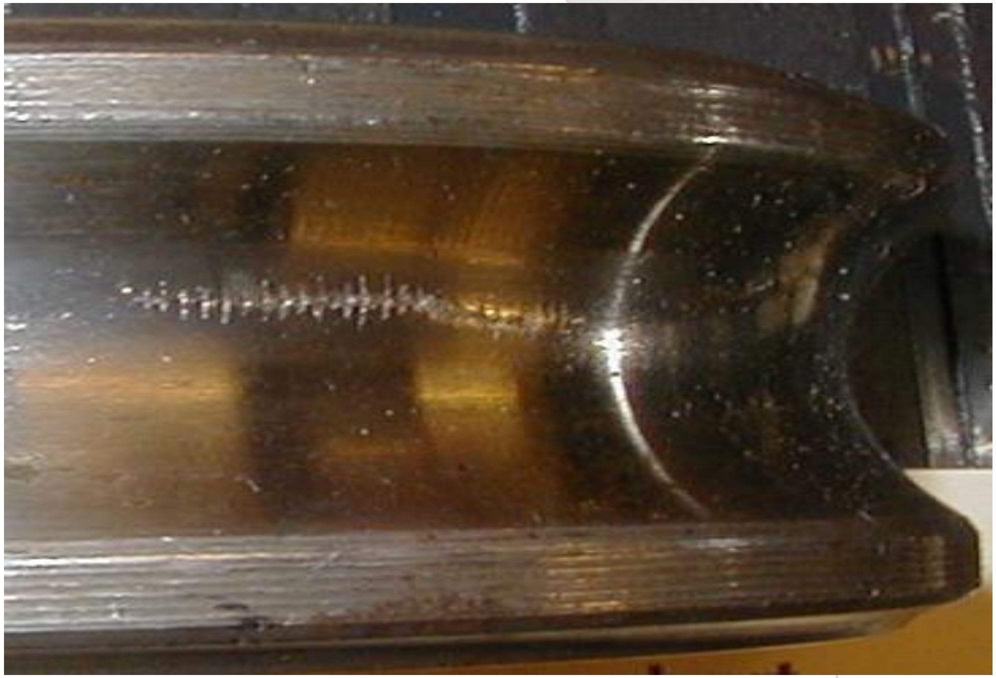
Electrical Fluting

This example came from a variable speed electric motor. This is becoming a common failure mode.

Arcing Damage
(from welding)

Ball from a stopped machine





Inner ring damage that resulted when a welding current arced through the bearing while the machine was running.

How to determine why it failed prematurely:

- Look at the surrounding conditions
- Get the operating history
- Talk to the operators and maintenance people
- Look at the bearing components and chart every symptom.
- From that, then determine the parasitic loads and lubricant condition.
- Then look back at the human and latent roots to that allowed the failure to happen, ***and change the way you do things.***

Some questions

1. What is the most common metallurgy for rolling element bearings?
2. Where are ceramic components used? Why?
3. With rolling element bearings, why is a VERY SLIGHT internal interference a good idea?
4. What is the mechanism that allows the typical lubricating oil to separate the rolling elements from the bearing rings?
5. How flat should a typical machine base be?

Thank you for listening!

Any questions about bearings you want to talk about?

Please don’t hesitate to call or email if you have questions later:

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email nevsachseng@gmail.com