Factors Influencing the Performance of Ball and Rolling Bearings

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Introduction

There are many factors that affect the performance of ball and roller bearings. Some are obvious and some are not very obvious. This course starts out explaining the performance characteristics of the various ball and roller bearings. It then deals with some of the aspects affecting performance such as; how different types of bearing loads can affect expected life calculations; how the material used and different refining and heat treatment methods can improve bearing performance; how oil lube film thickness affects expected life; and what the effect of misalignment and preloading have on a machine tool bearing application. This course is intended to enhance the understanding of all the above to ensure that bearing application engineering will be a more successful venture.

Performance Characteristics of Rolling Contact Bearings

Ball bearings are a common type of a rolling contact bearing. Radial ball bearings can support radial loads and a lesser amount of bi-directional thrust loads. Angular contact ball bearings can support both radial and thrust loads and are often used in pairs (See Figures 1, 2 and 3). Because of the much smaller contact between balls and rings, ball bearings cannot support loads as heavy as equal sized roller bearings; however, ball bearings can operate with lower torque and higher speed and precision than roller bearings. Radial ball bearings can be furnished prelubricated and sealed and can operate for life without maintenance. Ball and roller bearings can be furnished with snap rings installed in grooves in the outer ring outside for mounting purposes.

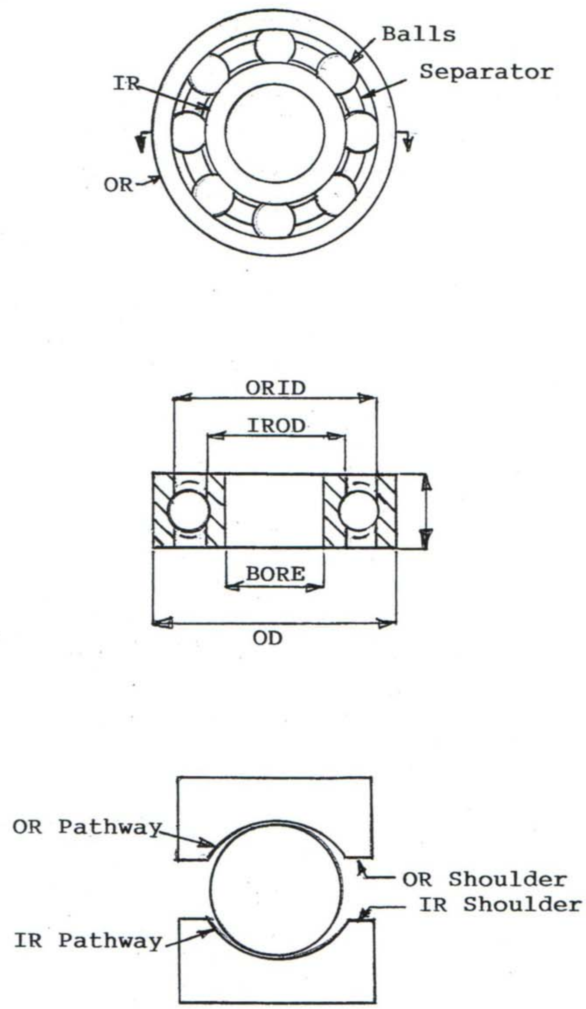
Roller bearings are also a common type of a rolling bearing. Cylindrical roller bearings can support higher radial loads than similar size ball bearings but lack the capacity to support substantial thrust loads. Tapered roller bearings can support high radial and high thrust loads and are often used in pairs (See Figures 4 and 5).

Following is a summary of Figure 6 which has a table of the characteristics of ball and roller bearings:

- Radial ball bearings have fair radial and thrust load carrying capability. They are excellent for high speed, high accuracy, low torque, and good for shaft misalignment. They can be used on both ends of a shaft. Angular contact ball bearings have good radial and thrust load carrying capability. They are excellent for high speed and high accuracy, fair for low torque, but poor for supporting shafts that are misaligned.
- Angular contact pairs are good for radial and thrust loads. They are good for high speed and accuracy and are poor for supporting shafts that are misaligned. They are commonly used on both ends of a shaft.
- Some forms of a cylindrical roller bearing have good radial load and fair thrust load carrying capacity. Others are excellent for high speed and accuracy. All are fair for shaft misalignment. Some forms are good for mounting on both ends of a shaft.
- Tapered roller bearings have excellent radial and good thrust load carrying capability. They are good for high speed and accuracy. Tapered roller bearings pairs are excellent for radial and thrust loads. They are good for accuracy and poor for misalignment. They too are commonly mounted on both ends of the same shaft.

Figure 1

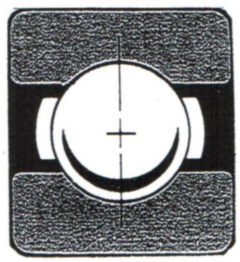
Ball Bearing Terminology



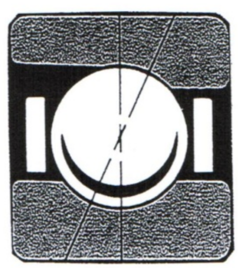
(Exaggerated View)

Figure 2

Ball Bearing Types



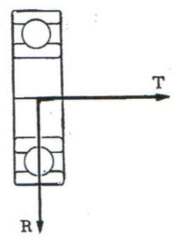
Radial Ball Bearing



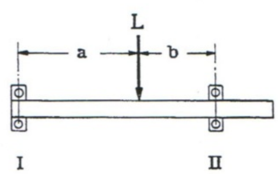
Angular Contact Ball Bearing

Figure 3

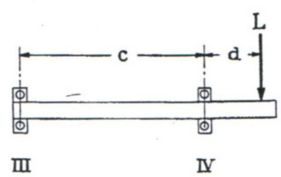
Bearing Loads



Bearing Load



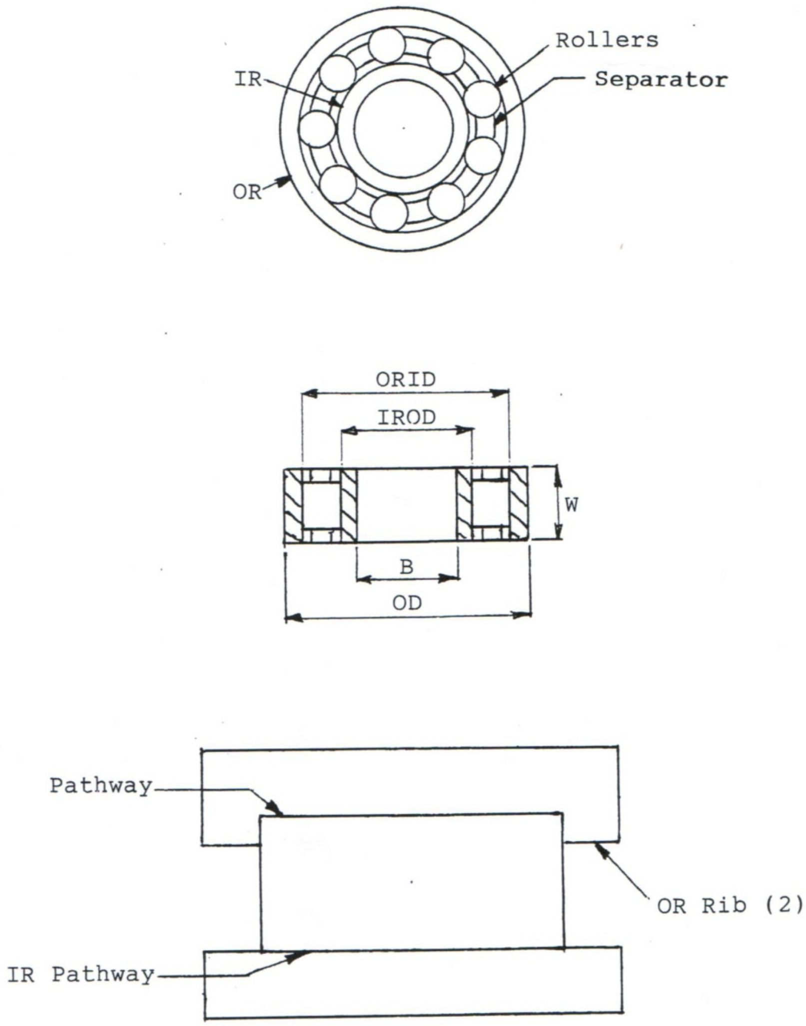
Bearing Location



Bearing Location

Figure 4

Cylindrical Roller Bearing



(Enlarged Section)

Figure 5

Tapered Roller Bearing

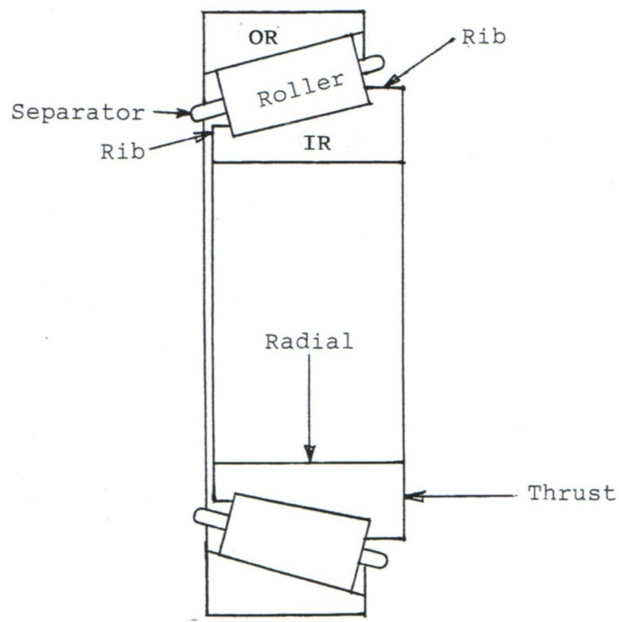


Figure 6

Bearing Characteristics

	Radial Ball Brg	Ang Contact Ball Brg	Cylindrical Roller Brg	Tapered Roller Brg	Double Row Ang Contact	Double Row Taper Roller
Radial Load)	Fair	Good	Good	Good	Good	Excellent
Thrust Load)	Fair	Good	Fair	Good	Good	Good
Combined Load)	Fair	Good	Fair	Good	Good	Excellent
High Speed)	Excellent	Excellent	Excellent	Good	Good	Good
High Accuracy)	Excellent	Excellent	Excellent	Good	Good	Good
Low Torque)	Excellent	Fair	Good	Fair	Fair	Fair
Misalignment)	Good	Poor	Fair	Fair	Poor	Poor

*The above ratings may vary somewhat for some forms of some of the bearings.

Bearing Life Calculation Factors

The equation for calculating the life of a rolling contact bearing is as follows:

$$L_{10}=3000(C/P)^{n}(500/S)$$

- **L_{10}** is the life in hours that 90% of the bearings are expected to endure. This is the standard equation for all ball and roller bearings.
- **C** is the capacity of the bearing in pounds and is found in industry catalogs. Capacity is largely dependent on the number and diameter of the rolling elements and the bearing material.
- P is the load in pounds that the bearing is expected to support. Radial loads act perpendicular to the bearing axis of rotation while thrust loads act parallel to the bearing axis of rotation. When both types of loads act on the same bearing, industry catalogs will give an equivalent radial load to be used in the equation. In most applications, the load is stationary. When the load rotates with the inner ring, a factor of 1.25 is applied to the load in the equation because of an increase of stress on the inner ring. When the load rotates with the outer ring, no factor is needed. If the load oscillates over 45^{o}, multiply the load times 1.25. Oscillation less than 45^{o} should be avoided because a condition called "false brinelling" can occur resulting in damage to the bearing rings.
- **n** is 3 for ball bearings and 10/3 for roller bearings.
- **S** is the speed of rotation of the bearing in revolutions per minute (rpm). In most applications, the inner ring rotates while the outer ring is stationary. When the outer ring rotates and the inner ring is stationary, a factor of 1.25 is applied to the load because of the additional stress put on the inner ring.

When there are a variety of load and speed conditions for a given application, the following equation is used:

$$L_{10}=1/(t_1/L_1+t_2/L_2+t_3/L_3+etc.)$$

- **L_{10}** is the B10 life of a bearing operating under a number of different load and speed conditions.
- **t_1** is the percent time operating under B10 life condition L_1, t_2 is the percent time spent under B10 life condition L_2, t_3 is the time spend under B10 life condition L_3, etc.

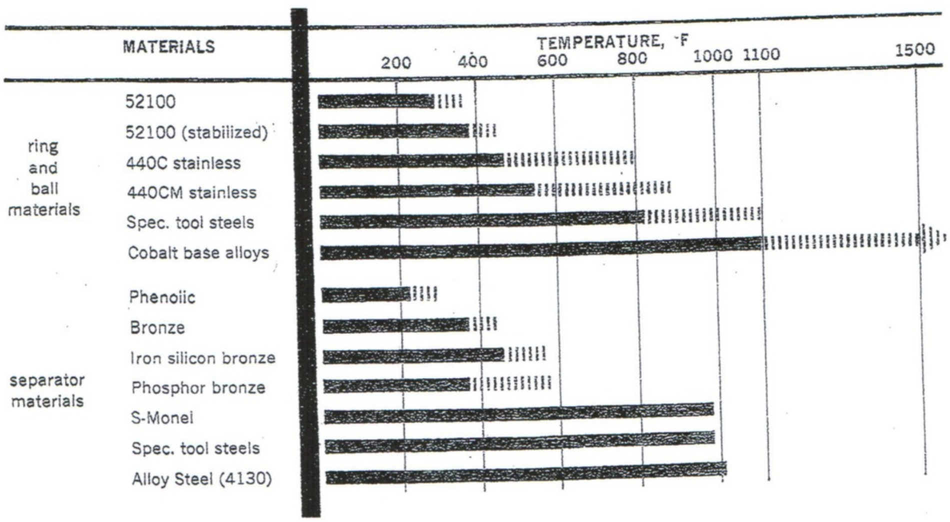
Material and Heat Treatment

The composition, cleanliness and condition of the material used to fabricate rolling contact bearings have a distinct effect on performance. The material used for most ball bearings is thru-hardened AISI 52100 alloy steel. The primary alloying elements are carbon, manganese and chrome. The high carbon content of 1.04% gives the steel responsiveness to heat treatment with corresponding very high strength and hardness. The manganese content of .35% acts as a deoxidizer (purifier) and also imparts strength and responsiveness to heat treatment. The chrome content of 1.45% increases response to heat treatment and depth of hardness penetration. An important part of steel is not only chemical composition, but its cleanliness or freedom from voids and impurities that come from the iron ore refining process. In bearing service, steel must withstand compressive stresses up to 500,000 psi. Impurities and voids in the steel, especially if they are found in the load zone of a bearing, can cause an early failure. Many bearing manufacturers use AISI 52100 “vacuum degassed”. This process improves steel cleanliness over “air melt” grades eliminating voids and reducing the chance of an early failure. For extremely critical applications such as aircraft and aerospace bearings, “consumable electrode vacuum melt steel” is used for even more improved cleanliness and bearing life

The material used for roller bearings is case-hardened AISI 8620. The primary alloying elements are .20% carbon, .80% manganese, .55% nickel, .50% chrome and .20% molybdenum. Nickel increases strength and toughness while molybdenum adds to the penetration of hardness and increases toughness. Case hardening involves heating the steel in a carbon rich atmosphere and quenching it producing a hard outer case and softer inner core. Roller bearings have a much higher spring rate than ball bearings. The hard outer case provides support of high compressive stresses while the softer inner core protects against shock loads. Tests have shown that case-hardened steels perform as well as thru-hardened steels. In the past, life improvements factors of 2 for AISI 52100 and 3 for AISI 8620 have been recommended because of improvements in steel cleanliness. Figure 7 shows the temperature limitation of some common bearing materials.

Figure 7

Ball Bearing Material



Ball Bearing Ring, Ball, and Separator

Material Temperature Limitation

Manufacturing Processes

Ball bearing rings are processed as follows:

- They are machined from tubing that is of a special size to reduce cycle time.
- They are heat treated to a high hardness throughout.
- Every surface is fine ground.
- The pathways are honed to an even finer surface finish.

Ball bearing balls are processed as follows:

- Blanks are cut from steel wire.
- The blanks are cold formed into a spherical shape and heat treated.
- The spheres are ground to a fine finish.
- The spheres are then honed to a very fine super finish.
- The finished balls are separated into different diameter class sizes.

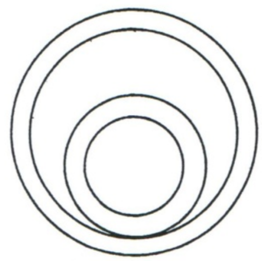
Ball bearings are assembled as follows:

- The inner and outer ring pathway diameters are measured.
- A compliment of balls is selected to obtain the correct internal clearance.
- Radial ball bearings are assembled according to the Conrad method whereby the inner ring is placed off center inside the outer ring, the balls loaded in the crescent space, the rings centered, the balls spaced, and the separator assembled (See Figure 8).

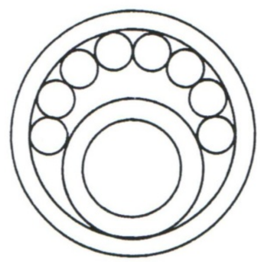
It has been found that grain flow can have an effect on bearing life. The raw tubing for rings is extruded which positions the grain parallel to the tubing central axis. When machining the pathways, end grain is exposed on the surface of the pathway especially higher up the shoulder. It has been found that balls running on end grain have a greater propensity to fail the ring than balls running on the grain itself. This is particularly true for angular contact ball bearings where the balls run higher up the pathway shoulder where end grain is more prevalent than at the center of the pathway where radial bearings run. Forging or roll forming ring blanks prior to further processing has been found to minimize exposed end grain resulting in improved bearing performance.

Figure 8

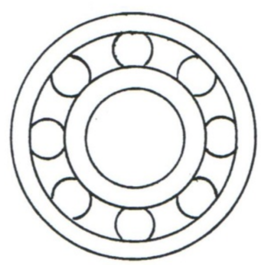
Ball Bearing Assembly



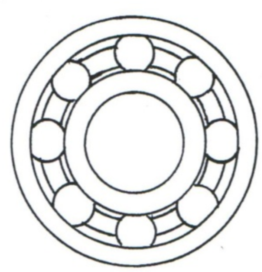
The IR is placed off-center inside the OR.



The balls are placed in the open space.



The IR is centered and the balls spaced.



The separator is installed.

Lubrication

For normal conditions, the best lubricant to use is mineral oil which is refined from petroleum. Synthetics have been developed that have good high temperature and good anti-oxidation properties for special applications but they don't form elastohydrodynamic (EHD) films as well as mineral oils. EHD refers to the film of oil that builds up in the load zone between the rolling element and the rings of rolling contact bearings. It has been found through lab testing that there are several factors that influence the thickness of the film that builds up between the rolling elements and rings. Oil films that are too thin compared to bearing surface finishes can result in performance less than predicted, while films that are thicker result in bearing life that exceeds calculated values.

The following equation is one that can be used to calculate bearing oil film:

$$T=B(OS)^{m}L^{-n}$$

- **T** is a measure of oil film thickness.
- **B** is a bearing factor which takes into account the physical properties of bearings that influence oil film thickness. B is largely dependent on bearing size with larger diameter bearings developing thicker oil films. The kind of bearing used plays a more minor role with standard design ball and roller bearings falling into the middle of the category.
- **O** is an oil factor which is influenced primarily by oil viscosity at bearing operating temperature. The type of oil used plays a more minor role with napthenic being the best, paraffinic lying in the middle, and synthetic being the worst.
- **S** is a speed factor which shows that higher speeds produce thicker oil films.
- **L** is a load factor showing that higher loads result in thinner oil films.

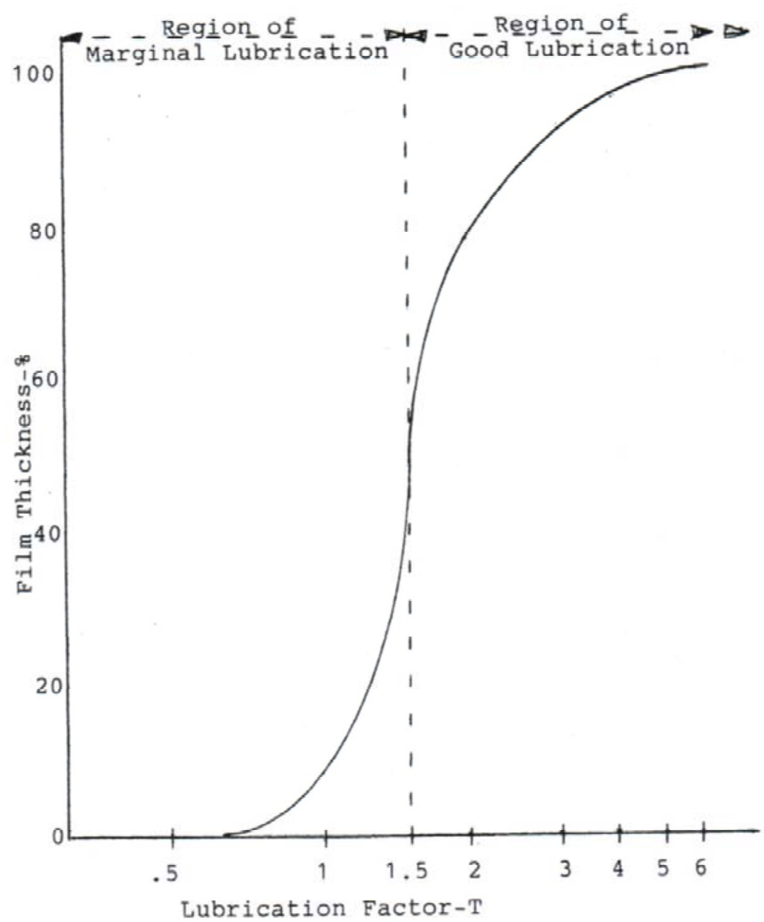
Graphs of all the above factors have been developed which make it easy to calculate oil film thickness and its effect on bearing life. Use of the graphs simplified the equation down to the following:

$$T=BOSL$$

Figure 9 has a graph of oil film thickness vs. T which shows that T values below 1.5 result in marginal lubrication and above 1.5 result in good lubrication.

Figure 9

Elastohydrodynamic Lubrication



Misalignment and Mounting

Misalignment refers to the angle made by the center line of the inner ring with respect to the centerline of the outer ring in a bearing. When the two centerlines are collinear, the misalignment is 0^o. Normally, ball bearings can tolerate more misalignment than roller bearings because there is less chance of a ball contact pattern moving over the top of the race shoulder than a roller contact moving over the edge the roller. When contact patterns move over an edge, there is a high amount of stress concentration which can lead to early failure. A feature called “crowning” is applied to rollers and rings to reduce edge loading under misalignment operation (See Figures 10 and 11). Normally, cylindrical and tapered roller bearings can tolerate approximately 4 minutes of misalignment while ball bearings can tolerate 16 minutes of misalignment before serious life reduction occurs.

Figure 12 has several different mounting arrangements for ball bearings. The top sketch has the left bearing fixed in the housing and the right bearing free to float. This type of mounting accommodates manufacturing tolerances and shaft thermal expansion without putting unwanted thrust load on the bearings. The middle sketch has both bearings free to float when shaft end play is not critical. The lower sketch has radial ball bearings with loading grooves which are used to load extra balls in the bearing for added capacity.

The top sketch of Figure 13 illustrates how two angular contact ball bearings mounted “back-to-back” can be used to resist shaft misalignment and overturning moments. The middle sketch has two angular contact ball bearings mounted “face-to-face” to accommodate shaft misalignment. The lower sketch illustrates how two angular contact ball bearings can be mounted in “tandem” to accommodate high one direction thrust loads.

Figure 14 has cylindrical roller bearings supporting a spur gearset. The two right bearings are mounted differently above and below the centerline. Above the centerline, the bearings are mounted in the housing cover which necessitates machining the housing bores separately. Below the centerline, the bearings are mounted in a separate cap which allows the housing bores to be machined in one setup providing for better bearing and gear alignment. Figure 15 has tapered roller bearings supporting bevel gears in an automotive drive axle. The two smaller bearings are nut preloaded while the two larger bearings are shim preloaded to provide stiff support for the gears.

Figure 10

Roller Bearing Crowning

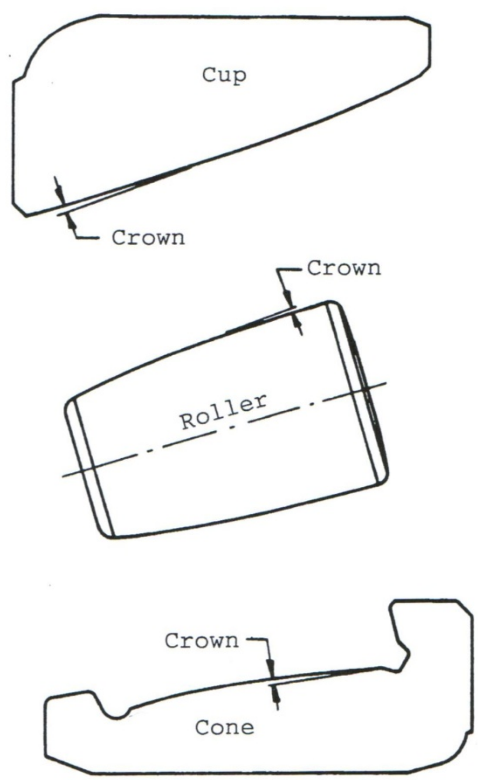
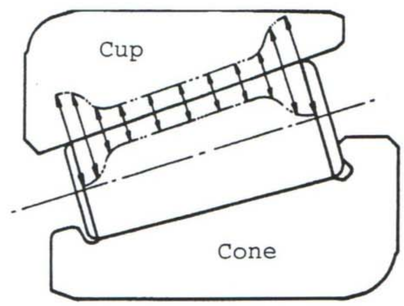
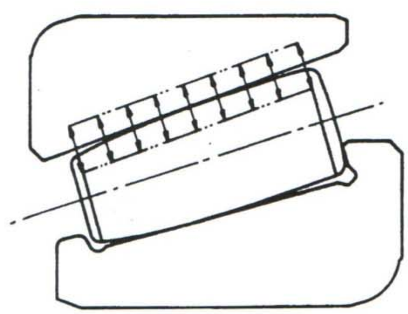


Figure 11

Roller Bearing Stress



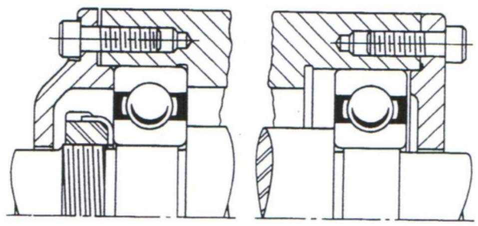
Stress Distribution With
Non-Crowned components.



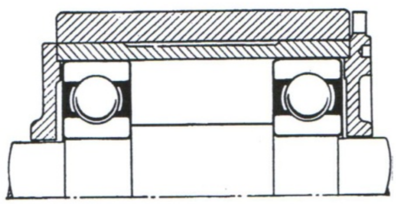
Ideal Stress Distribution
With Crowned Components.

Figure 12

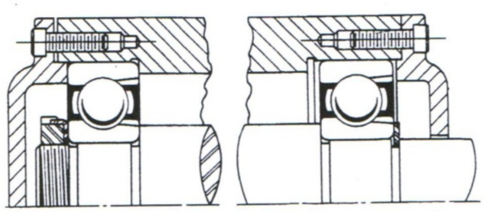
Ball Bearing Mounting



The bearing on the left is clamped to the housing and the shaft. The bearing on the right is free to accomodate shaft thermal expansion and tolerance build-up.



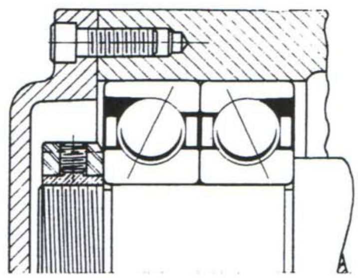
Both bearings can be made to float in the housing if shaft end play is not critical.



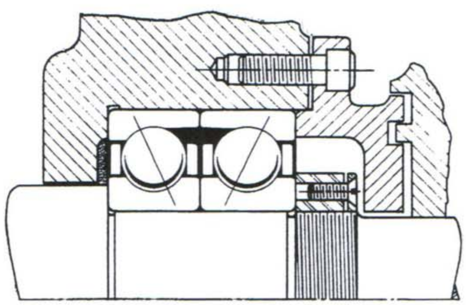
When thrust loads are low, loading groove bearings can be used to take heavy radial loads.

Figure 13

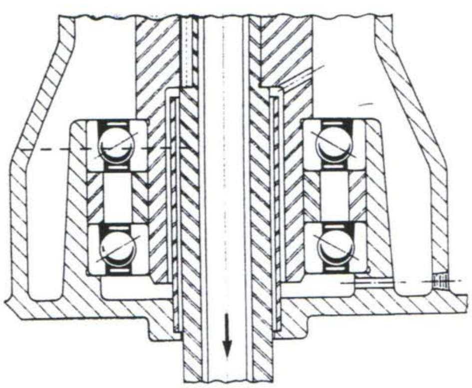
Angular Contact Ball Bearings



Maximum resistance to high moment loading is obtained by using two angular contact ball bearings mounted back-to-back.



Compliance to high shaft misalignment is accomodated by using two angular contact ball bearings mounted face-to-face.



Support of high one-direction thrust loading is accomplished by using two angular contact ball bearings mounted in tandem. The thrust is downward on the shaft.

Figure 14

Cylindrical Roller Bearing Mounting

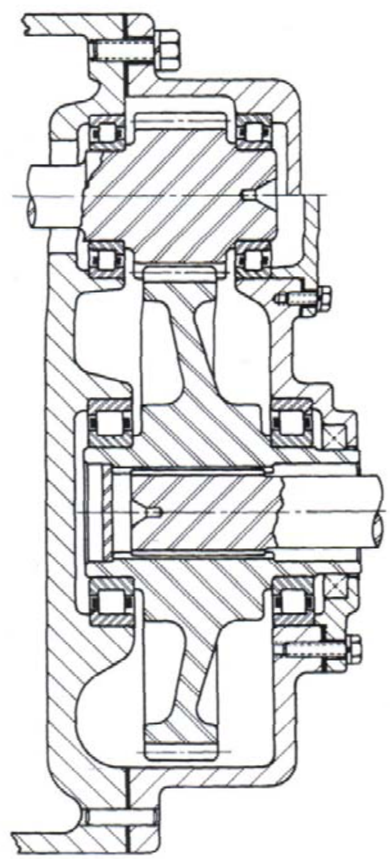
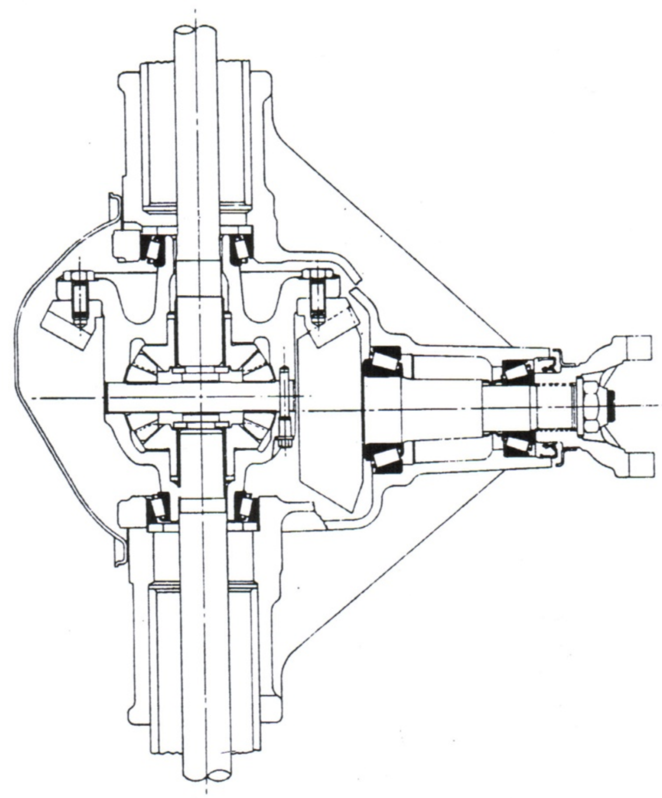


Figure 15

Tapered Roller Bearing Mounting



Drive Axle Bearing and Gear Arrangement

Preloading

Preloading is a method of mounting bearings on a shaft, whereby one is thrust loaded against the other. On manufacturing machines, preloading is done to secure the shaft more rigidly so that the tool attached to it will machine production parts more accurately.

Figure 16 has a drawing of a machine tool spindle (small shaft) supported by two angular contact ball bearings. The inner rings of the two bearings are clamped tightly against the shaft shoulder. Each outer ring is mounted in its own sleeve. Torquing the nut N puts an axial load on the right hand bearing through sleeve B. This load is then transferred through the clamped inner rings to the left bearing; preloading the bearings and putting the shaft in tension.

Let us assume that the nut N is torqued so that a preload of 3000 pounds is put on the bearings and shaft. Then a work force of 2500 pounds is applied to the right on the front left end of the shaft. This additional force increases the load on the front bearing while decreasing the preload (tension) on the shaft and decreasing the load on the rear bearing. The front bearing is now supporting less than the preload and the additional work load (3000+2500=5500 lbs) and the rear bearing is supporting less than the 3000 pound preload.

An analysis will show that the final load on the front bearing is 4500 pounds and the final load on the rear bearing is 2000 pounds. Both bearings are now operating above the steepest part of their load vs. deflection curve and are giving the shaft greater support. Without preload, the 2500 pound work load would have produced a shaft deflection of .003 inch while with preload, the deflection is down to .001 inch which is a big gain considering that some ball bearing components have manufacturing machining tolerances less than .0001 inch.

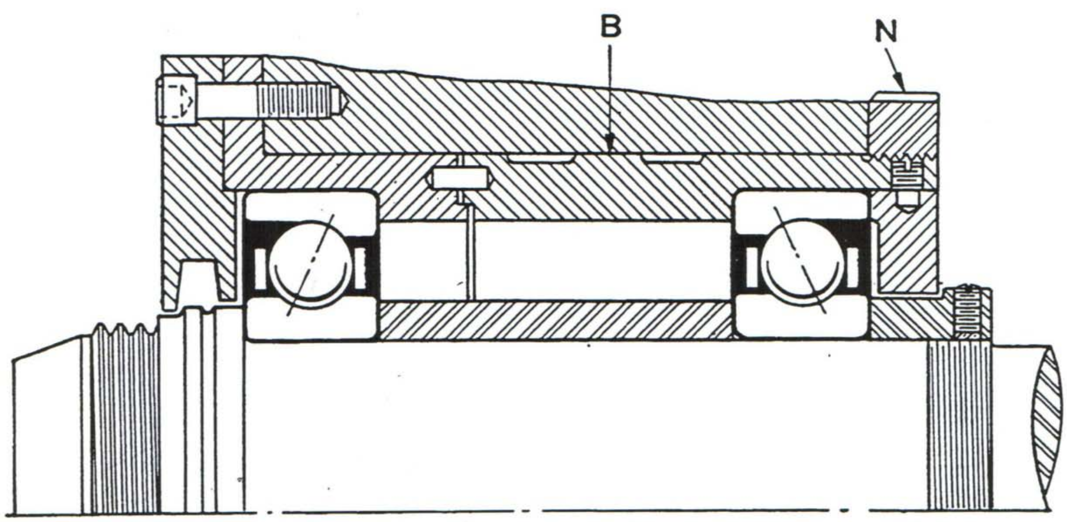
The calculated life of the left bearing with a 2.1654 inch bore and 4650 pound capacity under a 4500 pound thrust load equals:

$$L_{10}=3000(4650/3136)^{10/3}(500/1000)=5575 \text{ hours}$$

The 3136 pound equivalent radial load was obtained from an industry catalog. The life of 5575 B10 hours is equivalent to operating the machine for 2.68 years at 40 hours per week. Angular contact ball bearings are an excellent choice for supporting machine tool spindles and shafts.

Figure 16

Angular Contact Ball Bearing
Preloading



Machine Tool Spindle