Lubrication for Life

Lubricant Selection is Often Overlooked in the Design Process

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Introduction

Lubrication plays a vital role in the performance and life of rolling element bearings, yet its significance is often underestimated. The most important task of the lubricant is to separate parts moving relative to one another (balls or rollers and raceways) in order to minimize friction and prevent wear. A lubricant that is designed for specific operating conditions will provide a load bearing wear protective film. The ideal condition is when this film separates the friction surfaces. In addition to providing this load bearing film, the lubricant should also allow for the dissipation of frictional heat to prevent overheating of the bearing and deterioration of the lubricant. The correct lubricant will also provide protection from corrosion, moisture, and the ingress of contaminants.

Lubricants used in rolling element bearings should have the following characteristics:

- Maintain a stable viscosity over a broad range of temperatures
- Good film strength that can support loads
- Stable structure that provides for long service life
- Non-corrosive and compatible with adjacent components
- Provide a barrier against contaminant and moisture that does not leak out of the bearing

Types of Lubricants

- **Oils**: Both petroleum based and synthetic oils are available. Examples of synthetic oils are silicone, diesters, PAO's, and fluorinated compounds. Bearings lubricated with oil exhibit less start up and running torque and have higher speed capability. However, because oils are subject to evaporative losses, their service life in a bearing is less than that of grease. Miniature and instrument bearings are often only lubricated once for the life of the bearing, making the choice of lubricant critical. Larger bearings are subject to re-lubrication as part of the machinery maintenance cycle. These bearings are often lubricated via oil recirculation systems that are designed into the machinery or equipment. Key characteristics to consider when selecting an oil include temperature range, viscosity, and evaporative rate.
- **Greases:** Greases consist of a base oil with a thickener added. These thickeners consist primarily of metal soaps (lithium, sodium, aluminum, and calcium), organic (ureas), or inorganic compounds. While these thickeners greatly influence the characteristics of the grease, the lubricating properties of the grease are attributable to its base oil. Additionally, grease can contain additives that improve its performance. Additive types include antioxidant, anticorrosion, anti-wear, fillers, fortifiers, and extreme pressure fortifiers. Temperature range, base oil viscosity, and stiffness or penetration level are key characteristics to consider when selecting a grease. Most greases used in rolling element bearings are NLGI grade 2.
- **Solid Films:** These are non-fluid coatings applied to the friction surfaces to prevent wear. They are used in harsh situations such as extreme temperatures, vacuum, or radiation where an oil or grease cannot survive and are typically selected as a last resort, or option. These coatings include graphite, MoS_2, silver, gold, or PTFE. Hard coatings include TiC or chrome. Solid films are engineered on a specific application-by-application basis.

The lubricant selected and amount used also impact the maximum operating speed and torque, both starting and running. In miniature bearings, the lubricant can impact the noise level. Filtered greases and oils are recommended for use with miniature or instrument bearings.

Selection Factors to Consider

Lubrication is one of the most critical specifications for the designer to consider. When selecting a lubricant, factors including temperature, loads, speed, environment, and desired life need to be examined. Additionally, there are many characteristics of greases and oils that should be considered such as oil separation, evaporative loss, dropping point, oxidation stability, channeling capability/stiffness, and others.

Grease is by far the most common lubricant selected for the radial ball bearings used in electric motors and gearboxes. Oils provide lower torque characteristics, but are subject to evaporative loss and migration and not always well suited for lifetime lubrication.

Grease Characteristics:

As previously mentioned, grease lubricants consist of a base oil, mineral or synthetic, combined with a thickener and typically other additives. The properties of a given grease are determined by these components, along with proper handling, storage of the raw materials, and good process control by the grease manufacturer.

Type of Base Oil:

Base oil viscosity is of primary consideration when evaluating a potential grease lubricant. Viscosity, the measure of "flowability", is the resistance to flow caused by internal friction between the lubricant molecules. This characteristic determines load carrying capacity, film thickness, and operating temperature. The higher the viscosity, the higher the film strength. Viscosity varies as a function of temperature. The higher the temperature, the lower the viscosity. Therefore, it is very important to select lubricants based on temperature ranges in operation. Specialty high temp greases, specialty low temp greases, and greases with very wide temperature ranges are available to address specific temperature specifications.

Stiffness:

Greases are classified by their consistency, or stiffness. The ASTM has developed a test method for determining the stiffness of grease utilizing a cone of a prescribed weight and dimensions that is dropped into the sample of grease. The cone is withdrawn after 5 seconds and the depth of penetration is measured in tenths of a millimeter. The higher the number, the deeper the penetration and the softer the grease. The grease sample is then placed in a machine that strokes it (think of a mixer or egg beater for baking) to simulate operating conditions. It is then retested. This result is referred to as the worked penetration and is the basis for classification. The National Lubricating Grease Institute (NLGI) classifications are listed in the following table.

Classification of Greases by NLGI Consistency Numbers

NLGI NUMBER	ASTM WORKED PENETRATION
000	445–475
00	400–430
0	355–385
1	310–340
2	265–295
3	220–250
4	175–205
5	130–160
6	85–115

The lower the NLGI number, the softer the grease. The lower the ASTM number, the stiffer the grease.

Thickeners

Greases consist of a solid soap such as calcium or lithium soap. In some cases, a fine clay is used that forms a structure in which base oil is held and dispersed. The thickener structure does not provide actual lubrication, but is a reservoir that releases lubricant to the contact area.

Thickeners, while not contributing much toward lubrication, impart unique properties to the grease affecting its applicability in certain applications or environments. Of these the lithium and lithium complex thickened greases are the most common.

- Lithium — Most common, easy to manufacture, easy to store, good pumpability, flowability permits dirt to flow out
- Calcium — Good water resistance, calcium soap aids lubrication
- Aluminum — Highest resistance to water, chemicals, acids
- Barium — High water resistance, but somewhat toxic
- Sodium — Fibrous, water-soluble

Another class of thickeners is the non-soap thickeners. These are often used in applications where high temperatures are causing other types of thickeners to experience thermal degradation. The organic polyurea thickener offers temperature range limits similar to the metal soaps, but also has antioxidation and antiwear properties that come from the thickener itself.

- Clays and Silica (Insoluble powders, silica or platelets of clay) — Chemically modified structures and surfaces are made usable as gelling agents for grease. These greases further increase the maximum usable temperature.
- Polyurea — Polyurea greases are called high performance greases due to their broad range of performance attributes.

Additives

Greases can be fortified to contain boundary and EP additives, as well as solid lubricants such as graphite and molybdenum disulfide.

- Corrosion and Rust Inhibitors — These are very common additives that prevent corrosion and rusting of metal parts in contact with the lubricant. These additives work by neutralizing acids and forming a chemical protective barrier to repel moisture from metal surfaces.
- Anti-wear (EP) — Anti-wear additives and/or extreme pressure additives are chemical additives that protect metal surfaces during boundary lubrication. They form a protective film on the wear surfaces and react chemically with metal surfaces to form a sacrificial surface film. They are activated at high loads and high contact temperatures.
- Anti-oxidants: Anti-oxidants are found in most greases and oils. They prolong the life of the base oil. Oxidation attacks the base oil. While oxidation occurs at all temperatures all of the time, it accelerates as the temperature increases and in the presence of water, wear metals, and other contaminants.
- Viscosity Index (VI): These additives reduce the rate of change of viscosity with temperature.
- Pour Point: Pour Point additives improve low temperature operating range.
- Tackifiers: These additives help the lubricant adhere to the metal surface during rotational movement.

Other Considerations

- Amount: The lubricant amount selected also impacts the maximum operating speed and torque, both starting and running. Too much grease will often cause a bearing to run hot. Generally, as rotational speed increases the fill amount is reduced. Also, as loads increase, the fill amount is normally increased as well.
- Cleanliness: In miniature, or smaller, bearings the lubricant can impact the noise level. Filtered greases and oils are recommended for use with miniature or instrument bearings. Particle sizes larger than the lubricant film thickness will also lead to EHD film breakdown and generate wear debris. This can trigger a progressive process that leads to premature failure.

Figure 1 Diagram of grease composition (oil, thickener additive).

Shelf Life

Shelf life is the period following the lubricant's manufacture during which it is deemed suitable for use without re-testing its physical characteristics. Synthetic oils are inherently stable materials. Generally, they are not expected to oxidize, polymerize or volatilize at room temperature for 10 years or more. Ester oils, where the ester linkage may be subject to a minute degree of hydrolysis in the presence of moisture, could become more acidic if moisture is present. Fluorinated oils and silicones are not likely to be affected by simple aging.

Greases can "age" in more complicated ways. Grease quality could be affected by a change in the gel structure. If the gel contracts, significant oil bleed would be evident and the remaining grease would stiffen. The gel structure may also become softer over a period of time.

High quality lubricants are essential to ensure optimum bearing performance and many are qualified to military or other specifications. When the designer does not specify the type and quantity of lubricant, bearings are lubricated to conform to industry standards.

Manufacturers state that the shelf life applies only if oils and greases are properly stored in their original, unopened containers.

Lubrication Regimes

The thickness of the fluid film determines the lubrication regime, or the type of lubrication. The basic regimes of fluid film lubrication are:

Hydrodynamic Lubrication — Two surfaces are separated by a fluid film.

- Elasto-Hydrodynamic Lubrication (EHL) — Two surfaces are separated by a very thin fluid film.
- Mixed Lubrication — Two surfaces are partly separated, partly in contact.
- Boundary Lubrication — Two surfaces mostly are in contact with each other even though a fluid is present.

In addition to fluid film lubrication, there is solid film lubrication, in which a thin solid film separates two surfaces.

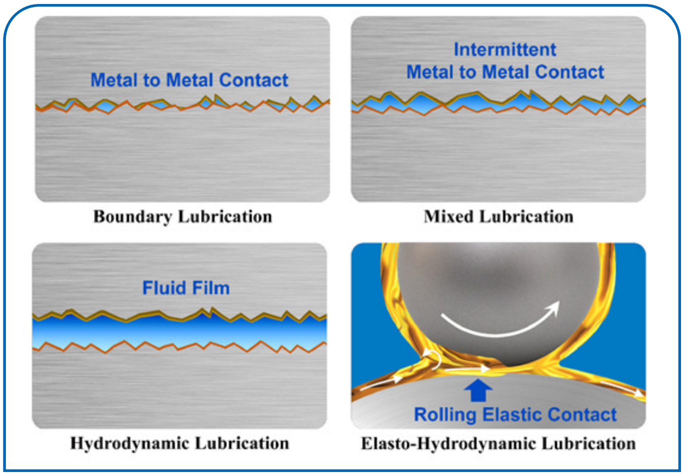
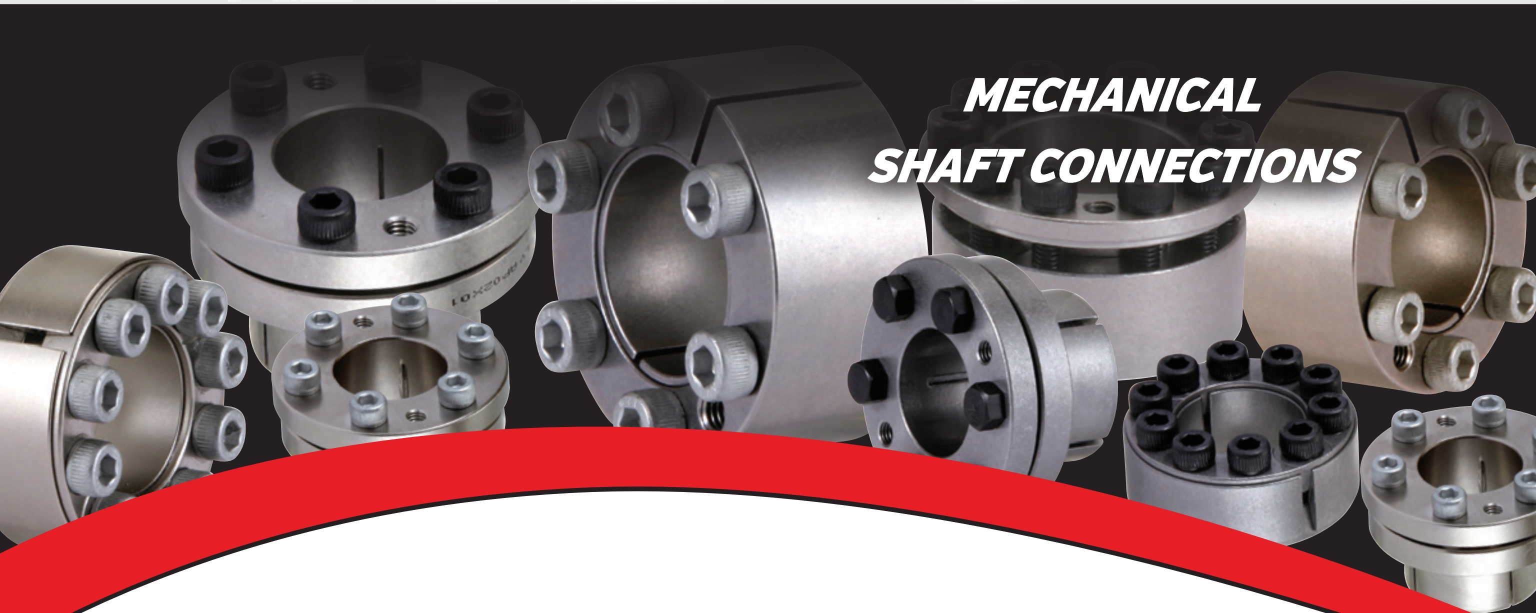


Figure 2 Diagram of the lubrication regimes.



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Lubricating Film: A Must for Long Life in Ball Bearings

Long bearing life is predicated upon proper lubrication—a lubricating film present and separating the metal surfaces. In the case of radial ball bearings operating in electric motors or other devices running at similar speeds, proper lubrication means the presence of an EHD (Elastohydrodynamic) film. Bearing life calculations assume the presence of this film.

The ABMA (American Bearing Manufacturers Association) standard 9 is used to calculate the basic rating life for ball bearings. The method includes adjustment factors for reliability, special bearing properties, and operating conditions. The adjustment factor a_3 would be used for operating conditions and would be less than 1 if the kinematic viscosity of the lubricant drops below 13 cSt or if the rotational speed is very slow (meaning no EHD film formation). The adjusted rating life could be 20% to 50% that of the basic rating life calculated.

Film Formation and the Stribeck Curve

The fluid viscosity, the load that is carried by the two surfaces, and the speed that the two surfaces move relative to each other all combine to determine the thickness of the fluid film. This, in turn, determines the lubrication regime. How these factors all affect the friction losses and how they correspond to the different regimes is shown on the Stribeck curve. Engineers use this tool to evaluate lubricants, to design bearings and to understand lubrication regimes (Fig. 3).

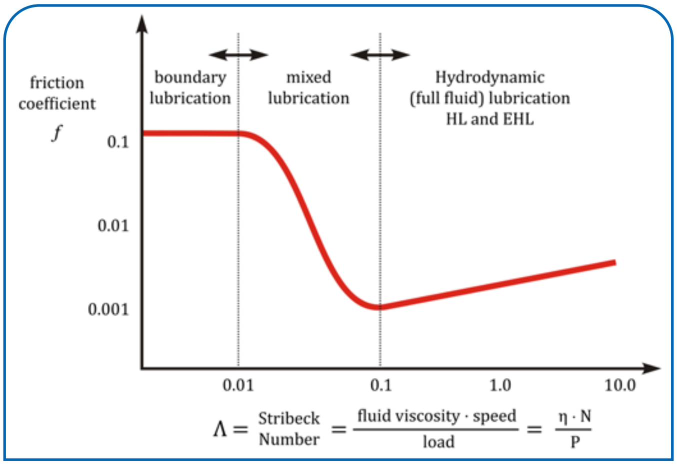

Figure 3 Diagram of a Stribeck curve.

The combination of low fluid viscosity, low speed, and high load will produce boundary lubrication. Boundary lubrication is characterized by little fluid in the interface and large surface contact. We can see on the Stribeck curve that this results in very high friction (Fig. 4).

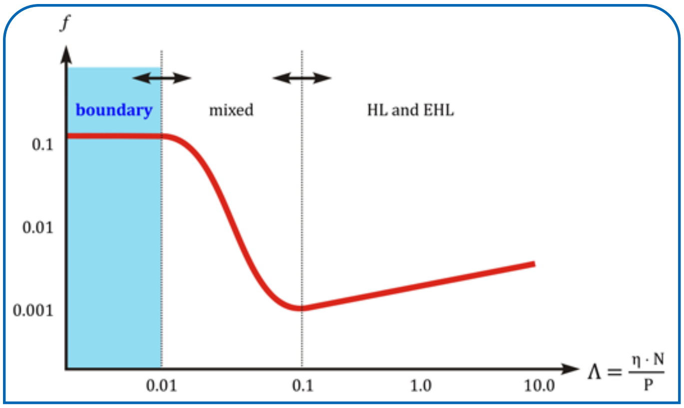

Figure 4 Diagram of a "boundary" Stribeck curve.

As the fluid viscosity and speed increase, and/or as the load decreases, the surfaces will begin to separate, and a fluid film begins to form. The film is still very thin, but acts to support more and more of the load. Mixed lubrication is the result, and is easily seen on the Stribeck curve as a sharp drop in friction coefficient. The drop in friction is a result of decreasing surface contact and more fluid lubrication (Fig. 5).

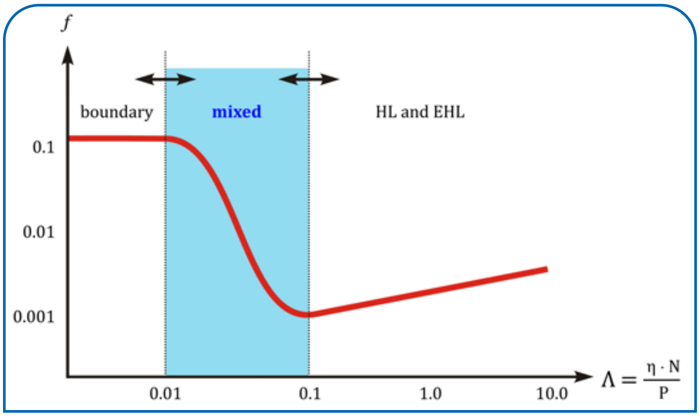

Figure 5 Diagram of a "mixed" Stribeck curve.

The surfaces will continue to separate as the speed or viscosity increase until there is a full fluid film and no surface contact. The friction coefficient will reach its minimum and there is a transition to hydrodynamic lubrication. At this point, the load on the interface is entirely supported by the fluid film. There is low friction and no wear in hydrodynamic lubrication since there is a full fluid film and no solid-solid contact (Fig. 6).

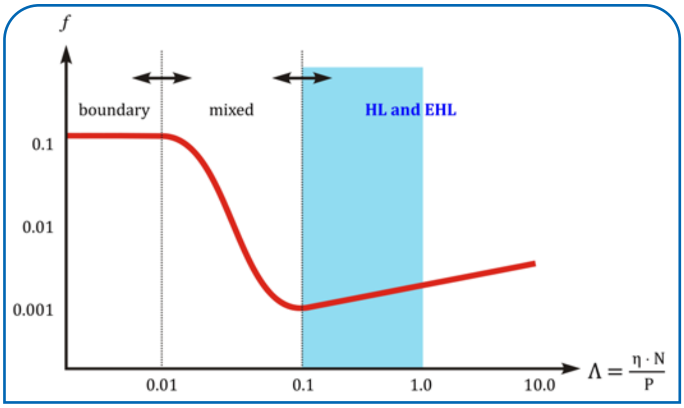

Figure 6 Diagram of a "hydrodynamic" Stribeck curve.

The Stribeck curve shows the friction increasing in the hydrodynamic region. This is due to fluid drag (friction produced by the fluid) — higher speed may result in thicker fluid film, but it also increases the fluid drag on the moving surfaces. Also, a higher viscosity will increase the fluid film thickness, but it will also increase the drag.

Machinery will typically see boundary lubrication at start-up and shutdown (low speeds and thin film), before transition to hydrodynamic lubrication at normal operating conditions (high speeds and thick film). A review of the Stribeck curve shows us that a motor or machine sees the most friction and wear during start-up and shutdown (Fig. 7).

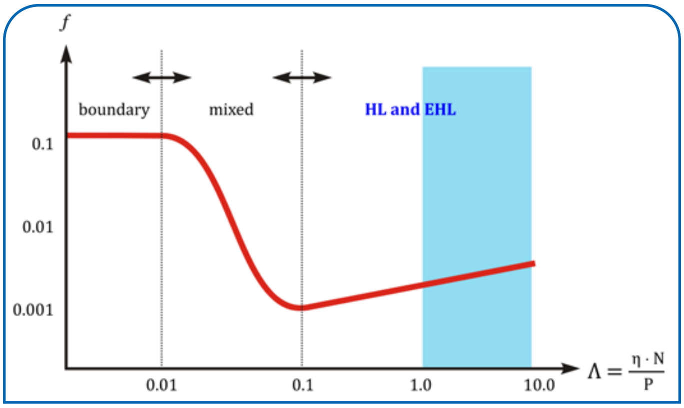

Figure 7 Diagram of an "EHL" Stribeck curve.

Hydrodynamic lubrication gets its name because the fluid film is produced by relative motion of the solid surfaces and the fluid pressure increases that result. The surfaces will have tiny asperities (peaks) and direct contact should be avoided. If one surface slides over the other, then friction increases, the asperities would break off and the surfaces will wear. In hydrodynamic lubrication, the fluid film separates the surfaces, preventing wear and reducing friction.

The hydrodynamic film is formed when the geometry, surface motion, and fluid viscosity combine to increase the fluid pressure enough to support the load. The increased pressure forces the surfaces apart and prevents surface contact. Therefore, in hydrodynamic lubrication, one surface floats over the other surface. The increase in fluid pressure that forces the surfaces apart is hydrodynamic lift.

Examples of Applications

Typical environments include factory and industrial sites, dirt and contaminants, humidity, and wash down areas. Typical properties of a grease that is suitable for the majority of motor applications:

- NLGI Grade 2
- Mineral or Synthetic base oil
- Thickener formulation that provides durability against mechanical shear forces
- Low noise properties
- Corrosion resistance
- Operating Temperature Range of around -20°F to +350°F

High speed operation — The DN value, bearing bore diameter in mm × rpm, can be used to determine if the bearing is operating at high speed. DN values over 1.5 million warrant a high speed lubricant. Or, a safe rule of thumb is — if the bearing operates at over 70% of permissible speed value listed in the catalog, a lubricant for high speed should be selected. High speed greases typically have base oils with lower kinematic viscosity. At high speeds, higher viscosities lead to excess heat generation. Also, the stiffness of the grease should be considered. A grease that has channeling properties is often desirable. Channeling greases are more easily pushed out of the way by the rolling element as the bearing rotates, and stays out of the way. This results in less churning and less temperature gain. Greases that are non-channeling, or slumping, flow back into the ball path and can result in the generation of excess heat.

High Temperature — A high temperature grease should be considered for bearings that continually operate at temperatures above 300-350°F. At higher temperatures the lubricant is subject to thermal degradation. This may be the most challenging situation for lubrication engineers. There are many options that include a variety of base oil and thickener formulations. Oxidation and thermal properties of the grease components — base oil, thickener, additives — must be taken into consideration. However, always remember the base oil is the component of the grease that is primarily responsible for lubrication. The correct base oil viscosity is the factor that determines if there is an EHD film.

Extreme Environments can include marine use, salt water, aerospace with exposure to fuel and the hard vacuum of space. In vacuum applications, outgassing is often a consideration. PFPE, or perfluoropolyether, oils and greases are often the solution. They have low vapor pressure and many are formulated with a thickener and additive package that is highly resistant to chemicals. These are often selected for use in aerospace and aviation applications. This family of products can be very expensive.

Regulatory Environments such as food processing, medical, and pharmaceutical may require the use of lubricants that have been approved for use applications.

The United States Department of Agriculture (USDA) created the original food-grade designations H1, H2 and H3. The approval of a new lubricant and its registration in one of these categories depends on the list of the ingredients.

H1 lubricants are food-grade lubricants used in food-processing environments where there is the possibility of incidental food contact.

H2 lubricants are food-grade lubricants used on equipment and machine parts in locations where there is no possibility of contact.

H3 lubricants are food-grade lubricants, typically edible oils, used to prevent rust on hooks, trolleys and similar equipment.

Deciding whether there is a possibility of contact is tough, and many have erred on the side of safety with respect to selecting H1 over H2.Since September 30, 1998, the National Sanitation Foundation (NSF) took over for the USDA as the USA organization issuing registration of food-grade lubricants.

Failure Modes / Improper Selection

Engineers often fail to consider the three important factors of temperature, speed, and loads and don't realize the impact these factors have on the lubricant. If they have not properly analyzed the operating conditions, they can realize too late that they have exceeded the operational characteristics of the grease. Equipment operated in environments the lubricant was not designed for can result in equipment failure, and in an attempt to determine why it failed, the OEM discovers that a different grease will not only have solved the problem but also expand the usefulness of the equipment.

One of the most common mistakes is not knowing that a grease engineered for certain conditions can greatly increase life. Designer simply selects a bearing with a standard factory supplied lubricant. Although these lubricants are a good choice for most applications, they may not be suited for certain environments.

In addition to temperature, speed, and loads, designers must consider other operating factors and environmental conditions that may impact lubricant performance and life. These include oscillatory movement, vibration, and shaft orientation (vertical versus horizontal). Environmental conditions include extreme temperatures, moisture and humidity, or the hard vacuum of space. Water entry and particulate contaminants can also affect the efficacy of the lubricant.

Bearing failure is generally the result of wear from the ball/raceway contacts. If the lubricant fails, the load bearing EHD film that prevents contact between the metal surfaces breaks down. When this happens, the high asperities of the raceways and balls come in contact and break off and metal particles enter the lubricant. As wear progresses, the lubricant becomes a mixture of metal wear particles and degraded lubricant. This leads to deterioration of the components and ultimately bearing failure.

Summary

Selection of the right lubrication is essential for peak performance and extending the life of rolling element bearings in electric motors and gearboxes. Engineers who consider all the lubrication selection factors discussed here will maximize the life of their bearings and machinery, therefore saving money, time, and manpower and make operations more efficient and more reliable. **PTE**

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