Section 2
LUBRICANT MANUFACTURING

Definitions

Alkylation – the reaction of the double bond in an olefin with another molecule.

Aromatic hydrocarbon – a compound of hydrogen and carbon containing one or more benzene rings.

Base stock – the refined oil that is used to blend lubricants.

Catalyst – substance that causes or speeds up a reaction without changing itself.

Cracking – breaking large molecules into smaller ones in the presence of heat or catalyst. Examples are thermal cracking, catalytic cracking, or hydrocracking (cracking in the presence of hydrogen) High Temperatures.

Crude oil – a naturally occurring mixture of petroleum hydrocarbons, with small amounts of oxygen, nitrogen, sulfur and other impurities. It was formed by the action of bacteria, heat and pressure on ancient plant and animal remains and is usually found in layers of porous rock capped by a layer of shale or clay that traps the oil.

Detergent – additive that prevents contaminants from contacting metal surfaces. Detergents contain barium, calcium or magnesium, and other compounds and they may leave an ash residue if burned.

Dewaxing – a refining step that removes wax from crude oil fractions.

Dispersant – additive that suspends very small contaminant particles harmlessly in the oil. It prevents them from combining into large particles that could cause sludge, varnish and wear. Dispersants generally do not contain metals and are considered to be ashless when burned.

Distillation – a process where crude oil is heated so fractions start to boil; the fractions are collected as they condense.

Extreme pressure (EP) additive – additive that prevents sliding metal surfaces from seizing under conditions of extreme pressure. At high local temperatures it combines chemically with the metal to form a surface film. EP additives are commonly made of sulfur, phosphorus, chlorine or boron.

Foam inhibitor - in turbulent systems it helps combine small air bubbles into large bubbles which rise to the surface and burst. It spreads out on the bubble wall to thin it out so that it pops.

Hydrocarbon – a molecule predominantly made up of hydrogens and carbons.

Hydrocracking – a process that cracks molecules in the presence of hydrogen.

Hydrotreating – a process where oil streams are treated with hydrogen at elevated pressure and temperature in the presence of a catalyst to improve color and stability and reduce sulfur content.

Naphthene – also called a **cycloparaffin.** A hydrocarbon with the carbons arranged in one or more rings.

Olefin – a hydrocarbon with one or more double bonds.

Oxidation - the combination of a substance with oxygen. Some products of oxidation of oils include organic acids (which can cause corrosion), sludge and varnish.

Oxidation inhibitor – additive used to extend the life of lubricants. It can work in three ways (1) it combines with peroxides (the first chemicals created in the oxidation process) to make them harmless, (2) it decomposes the peroxides, or (3) it makes metal surfaces less able to promote oxidation.

Paraffin – a hydrocarbon where the carbons are arranged in a straight line or are branched off of each other.

Rust inhibitor – additive that prevents rust.

Saponification – process of converting certain chemicals into soaps, which are the metallic salts of organic acids. It is usually accomplished through the reaction of a fat, fatty acid, or ester with an alkali.

Saturated hydrocarbon – a compound of hydrogen and carbon with no double bonds.

Solvent extraction – a method of removing unstable components of a refining stream by dissolving them in solvent.

Synthetic base stock – fluid made by reacting specific chemical compounds to produce a produce with planned and predictable properties.

Vacuum distillation – separation of crude oil fractions by applying heat under a vacuum.

<u>Base Stock Refining</u>

Crude oil, as it comes from the ground, contains many substances other than gasoline, diesel fuel and lubricant base stocks. The natural gas that is used to power many city buses, or that heats burners can be dissolved in crude oil. You can find the building blocks for plastics and chemicals in its mixture of molecules. It is also a source of wax, asphalt, solvents, petroleum jelly and many other substances.

<u>Fuels are the principle products that come from crude oil.</u> Gasoline is the biggest component, followed by diesel fuel and jet fuel. Lubricants and waxes only constitute a little over 1% of the crude oil barrel.

Crude oil comes in many forms, depending upon its source. It can be as thin as gasoline, or it can be so thick that it needs to be heated or pressurized to flow. It can range from amber colored to pitch black.

The three major types of crude oil are paraffinic, naphthenic and asphaltic. Paraffinic crudes are the primary source of “neutral” base oils, while naphthenic crudes produce “coastal pale” oils. Asphaltic crudes are generally not acceptable for lubricant base stocks other than some open gear compounds, highly viscous lubricants or rust preventives.

Crude oil is sold by the barrel (42 gallons per barrel) by pipeline or in tanker ships. From there, it is transported by barge or pipeline to a refinery, where it is processed according to the steps described below. Lubricants are further processed in blending plants.

Crude oil is converted to lubricating oil through a series of refining steps including distillation, vacuum distillation, solvent extraction, hydrotreating, dewaxing and sometimes hydrocracking and alkylation. The yield of lubricating oil from a gallon of crude can be increased first through de-bottlenecking steps, second by a series of steps called cracking and alkylation.

When oil comes out of the ground, the first things that are released are gases. These include methane, ethane, propane and butane, as well as the mixture called natural gas. These gases can generally be captured without heating the oil.

Distillation towers, of which the atmospheric tower is the tallest in the refinery, work on the same principle as stills worked during Prohibition. Alcohol was made by fermenting grain or another substance and then heating it. Alcohol boils at a very low temperature, so it would start to boil, while the rest of the mash was left in the pot. The alcohol vapors would rise and get funneled into some coils, where they would cool and condense back into liquid.

Gasoline is a liquid at room temperature, but it evaporates very fast, and it boils at a very low temperature. In order to separate it from crude oil, the crude is heated until the gasoline starts to boil. The vapors above the boiling liquid are collected and sold as gasoline. Many of the solvents such as mineral spirits are collected at the same time before they are further refined.

Once the gasoline fractions are removed, the crude oil is heated further. Kerosene, jet fuel and diesel fuels are the next liquids that boil off. These fractions are also allowed to condense and are collected and sold.

After most of the light fuels have been removed from crude oil, you would think that they would just heat it up even more and boil off the lubricant fractions. But that is not energy efficient, and besides, if they had to heat up lubricants to 600°F to boil them off, they could destroy the lubricant.

Substances boil at a lower temperature if they are subject to a vacuum. Think of the vacuum as trying to pull the molecules out of the liquid. A lot less heat is needed to get them to boil. It is much more energy efficient to apply a vacuum to the oil to remove lubricant fractions, and it is much less harmful to the lubricant. Vacuum distillation prevents the cracking of lubricant fractions that would occur at higher temperatures.

Vacuum distillation separates lubricant fractions from crude oil**. Re-refining and reprocessing do not_require this step because their feedstock**, used lubricants, should contain minimal amounts of fuels, waxes or asphalt.

The lubricant stream that is separated from crude oil still contains many impurities and must be further refined. The next three refining steps, hydrotreating, solvent extraction, and dewaxing, can occur in any order, or may be optional depending upon the quality of the finished base oil.

Hydrotreating essentially bombards the stream with hydrogen to remove sulfur and other impurities. It makes base stocks more stable. Treating base stock with hydrogen has the following advantages.

1. Minimizes use of solvents
2. Reduces solvent disposal
3. Increases yield
4. Permits use of different crude sources
5. May reduce processing temperatures
6. Produces base stocks with higher VI, which may increase fuel efficiency in engine oils
7. Produces bases tock with lower volatility – lower evaporative losses
8. Base oils that have been severely hydrotreated don't require a carcinogen label

Solvent extraction dissolves reactive components such as <u>aromatics</u> to improve the oil's oxidation stability, viscosity index and response to additives. <u>Sulfur</u> and <u>nitrogen</u>

compounds are also selectively extracted. The oil and the solvent are mixed in a tower, which results in two distinct liquid phases. The heavy components are dissolved in the solvent. The lighter phase, which contains the clean, high quality oil, is separated and the small amount of solvent is distilled off.

Solvent dewaxing removes wax, lowers the pour point, and improves the low-temperature properties of the oil. The solvent dissolves the wax and the mixture is chilled until the wax turns solid. The wax is filtered out and stripped of solvent and dried. The wax from this process can be used in crayons, candles, paper cups and fire logs.

Hydrodewaxing (catalytic dewaxing) accomplishes the same result, but by a different method. The oil is exposed to hydrogen at elevated temperature and pressure. This cracks the normal paraffins, which are converted to light compounds that can be used as building blocks for plastics and chemicals.

Finishing steps can include acid treating and clay filtration to remove trace impurities.

Refining severity is a compromise. Some of the more undesirable compounds, asphaltenes and unsaturates, which reduce oxidation resistance, also tend to improve boundary lubrication. An oil which has been only mildly refined may have poor oxidation resistance but relatively good boundary lubrication. On the other hand, severely refined oil has good oxidation resistance and a high viscosity index. The other required properties are then obtained by the use of additives.

A lubricant formulator can specify a base stock by type, i.e. paraffinic, naphthenic, synthetic, vegetable, and also by performance properties such as viscosity index, viscosity, pour point, flash point, color, or sulfur level. Paraffinic base stocks generally have higher viscosity index than naphthenics. Natural VI's of 90 to 105 are not uncommon for paraffinic oils, while naphthenic oils typically have VI's in the order of 30 to 65.

Base stocks also have varying natural resistance to oxidation. Here is a general guide for oxidation resistance of petroleum base stocks.

Paraffins	Most resistant
Naphthenes	↓
Aromatics	↓
Asphaltenes	↓
Unsaturates	Least resistant

As a rule, synthetic base stocks are designed to have better oxidation stability than petroleum oils, while vegetable oils have significantly lower resistance to oxidation.

Additives

Lubricants are comprised primarily of base oils and additives. Grease is comprised of base oils and additives along with thickeners.

The following is a brief description of lubricant additives and their functions.

Anti-wear additive – Zinc dialkyldithiophosphate (ZDDP) is the most common anti-wear additive, although there are many zinc-free additives based on sulfur and phosphorus that also impart antiwear properties. The zinc-sulfur-phosphorus end of the molecule is attracted to the metal surface allowing the long chains of carbons and hydrogens on the other end of the molecule to form a slippery carpet that prevents wear. Not a chemical reaction, rather a super-strong attraction.

Demulsifier – affects the interfacial tension of contaminants so they separate out from oil rapidly.

Dispersant – additive that suspends very small contaminant particles harmlessly in the oil. It prevents them from combining into large particles that could cause sludge, varnish and wear. Dispersants generally do not contain metals and are considered to be ashless when burned.

Dye – any oil-soluble dye can be added to oils for leak detection. Water-soluble dyes such as food coloring won't work because oil and water don't mix).

Emulsifier – added to some metalworking fluids, air tool oils and fire-resistance hydraulic fluids to allow them to mix with water.

Extreme pressure (EP) additive – additive that prevents sliding metal surfaces from seizing under conditions of extreme pressure. At high local temperatures it <u>combines chemically</u> with the metal to form a surface film. EP additives are commonly made of sulfur, phosphorus, or chlorine. They become reactive @ high temp. (170°+F) and will attack yellow surfaces. Generally, it is a good idea to stay away from extreme pressure additives if they are not needed but when in doubt always use EP gear oils. EP additives are generally pro-oxidants, in other words, they shorten the life of the oil. They also can be slightly corrosive to some metals, especially at elevated temperatures.

Foam inhibitor – in turbulent systems it helps combine small air bubbles into large bubbles which rise to the surface and burst. It decreases the surface tension of the bubble to thin and weaken it so that it pops.

Rust inhibitor – absorb onto metal surfaces to prevent attack by air and water.

Oxidation inhibitor – antioxidants act by interrupting the free radical chain reaction that results in oxidation. Essentially, as the oil starts to decompose in the presence of oxygen, these inhibitors interrupt the reaction. They also keep metal from speeding up the oxidation reaction by deactivating the metal.

Oiliness agent – fatty materials that have two benefits. They add extra lubricity at low to moderate temperatures, and they help prevent water from washing oil off of surfaces.

Pour depressant – disrupt the crystal structure of wax so that the oil will flow at lower temperatures.

Solid additives – graphite, moly and PTFE are added to some oil and grease formulations

Tackiness additive – polymer added to allow oils to adhere to metal surfaces.

Viscosity index improvers – polymers that change shape with temperature. At high temperatures they are somewhat bulky and prevent the oil from thinning down as much.

Grease Manufacturing

Lubricating grease is a solid or semisolid lubricant consisting of a thickening agent in a liquid lubricant. Greases generally contain additives to enhance properties such as oxidation stability and lubricity. Other ingredients imparting special properties may be included.

Greases that are thickened with soap can be made according to the following steps. The steps may vary according to manufacturing plant.

- Charge kettle with fatty material, complexing agent and metallic hydroxide
- Heat to dehydrate
- Cut back with mineral oil
- Quench and add additives
- Mill
- Deaerate
- Filter
- Package

Complexing agents are added to grease to increase their high temperature stability. These are very stable soaps generated by reacting an alkali with a high and low molecular weight fatty acid.

The reaction of a fatty acid and a base is very similar to the reaction of an acid and a base. The acid and base react to form salt and water. The fatty acid and base forms soap.

Acid + Base = Salt + Water

"Fatty Acid" + Base = Soap

Grease is typically made up of 75% to 96% percent oil. The oil is designed to separate from the thickener, so it is not uncommon to see some oil separation if the grease has been sitting. 12-hydroxy stearic acid is the most common type of fatty acid used in grease manufacture.

Grease Soaps and Thickeners

In addition to conventional and complex soaps, other materials may be used to thicken grease. Here is a partial list of thickeners.

Soap Base

- Aluminum
- Aluminum complex
- Barium
- Barium complex
- Calcium
- Calcium-complex
- Lithium
- Lithium complex
- Sodium
- Sodium complex
- Mixed soap such as sodium calcium

Non-soap Base

- Polyurea
- Modified bentonite and other clays
- Colloidal silica
- Organic compounds
- Fluorinated compounds

Grease Additives

The additives used in greases are very similar to those used in lubricating oils, which are listed in Section 2C. Some additives that you would expect to find in grease include:

- Antioxidants or oxidation inhibitors
- Corrosion inhibitors

Color stabilizers
Dyes
EP or film-strength agents
Metal deactivators
Rust inhibitors
Stringiness additives
Structure modifiers for soap-oil systems

Grease Fillers

In addition to soap, base oil and additives, solid fillers can be added to grease to enhance its lubricity and load carrying ability. Some of the fillers used in lubricating greases are listed below:

- Graphite:
  - Colloidal
  - Flake
  - Powdered
- Lead powder
- Red lead
- Zinc oxide
- Zinc dust
- Molybdenum disulfide
- Lead powder
- Copper flake

Section 3
BEARINGS

(Sect. 3A) Definitions

Anti-friction bearing – ball or roller bearing

Axial load – load in the direction of the axis. In the case of most rolling contact bearings, it will be the load in the direction of the shaft.

Bearing – A device that is positioned between two moving parts to reduce friction, aid in alignment and support load.

Bore diameter – the inside diameter of a bearing.

Cage – the element of a rolling contact bearing that separates the balls or rollers.

Elastohydrodynamic lubrication – found in rolling contact bearings where the rolling elements deform since they are more elastic than the fluid.

Hydrodynamic lubrication – commonly found in plain bearings, it is a full fluid film that develops between moving surfaces.

Hydrogen embrittlement – cracks that occur when water molecules pass through the load zone on a bearing. High temperatures break the water down to hydrogen and oxygen. Hydrogen ions are forced into micro cracks in bearing surfaces, which expands subsurface cracks.

Hydrostatic lubrication – occurs when lubricant is applied to a bearing under pressure, generally where a full fluid film cannot be maintained by the motion of the surfaces alone.

Inclusions – contaminants that enter steel during the manufacturing process.

Interference fit – a shaft diameter that is slightly larger than the bore diameter of the bearing, resulting in a tight fit.

Journal bearing – a plain bearing that fits around a journal, or shaft. An example would be the bearing around the crankshaft in an automobile.

Race – the inner and outer rings of a rolling contact bearing that have grooves for balls or rollers.

Radial load – load that is perpendicular to the axis, i.e. weight of a shaft pressing on a bearing.

Rated life – the number of revolutions, at a given constant speed, that 90% of identical bearings will complete before the first evidence of fatigue.

Shield – a metal disc fitted to the bearing outer ring with a small clearance with the inner ring. It prevents ingress of gross contaminants and may help retain lubricant.

Spalling – propagation of destructive pitting. It results from excessive loads coupled with the rolling forces that remove metal from the bearing service. It is the cracking or flaking of metal caused by repeated stress.

Thrust load – Generally, load in the axial direction.

Tolerance – the amount of variation from the absolute exact measurement that is permitted during manufacture.

Slider bearing – Only has linear motion, not circular like a journal bearing.

Bearing Types

Bearings are generally categorized into two main groups, plain (or sliding), and anti-friction (rolling contact).

Advantages of plain bearings are that they are easy to install, carry high loads, are less expensive, repairable, and are less sensitive to particle and water contamination. Anti-friction bearings may be sealed for life, can be used for high speeds, can accommodate misalignment, and use less energy than plain bearings.

Plain bearings can be divided into two main types based on how the lubricant film is maintained in the bearing:

Hydrodynamic bearings run on a full fluid film. The shape and relative motion of the sliding surfaces generate film pressures large enough to support the load. As a general rule for these bearings, the higher the load, the lower the film-thickness.

Hydrostatic bearings depend upon the lubricant being supplied from an external source such as pump.

Plain bearings are further classified according to function as journal, slider (guide), and thrust bearings.

Slider bearings are used to prevent wear where there is linear (or back-and-forth) motion. The simplest and most basic form of hydrodynamic bearing is the fixed-pad slider bearing. More complex plain bearings have tilting pads. Guide bearings guide and hold in proper position the reciprocating part of a machine.

Journal bearings are so named because they support or operate against a rotating shaft. The shaft that is surrounded by the bearing is known as the journal. Hydrostatic journal bearings have the following advantages: extremely low friction, ability to support a load with no shaft rotation, ability to sustain appreciable loads with low-viscosity fluids (such as water, liquid metals, etc.), and ability to control stiffness by varying the fluid pressure. Journal bearings cannot carry thrust loads.

Journal bearings can be further categorized by their configuration.

> **Solid bearings**, also referred to as a sleeve or a bushing are, as their name implies, solid.
>
> **Split bearings** are divided lengthwise into two pieces. They can be replaced on a shaft more easily than a solid bearing because it is not necessary to slide them on from the end.
>
> **Half bearings** encircle only one half of the journal, leaving the other half exposed. It is used when the load is carried on the top of a shaft.
>
> **Multi-part bearings** usually consist of four separate parts, or quarters. These bearings are found on the crankshafts of such machines as air compressors and steam engines. The four-piece construction permits these bearings to be readjusted to the crank-pin to take up slack when wear takes place.
>
> **Thrust bearings** prevent a shaft from moving endwise, or for an axial load to creep down the shaft.
>
> **A Kingsbury thrust bearing** is a bearing with tilted shoes that form an oil wedge between the shoe and collar.

Components of a plain bearing can include the following: overlay (babbitt), oil holes, oil grooves, and housing.

Plain bearings are usually made from bronze, babbitt, or some other softer-than-steel material so that wear will be on the bearing rather than on the steel part rubbing against it. Bearings are sacrificial since they are easier and cheaper to replace than shafts. The following chart shows that babbitts are generally softer than many other metallic coatings.

Materials used in Sliding Bearings

Bearing Material	Hardness, Room Temp, Brinnell
Tin-base babbitt	20-30
Lead-base babbitt	15-20
Alkali-hardened lead	22-26
Cadmium base	30-40
Copper-lead	20-30
Tin bronze	60-80
Lead bronze	40-70
Phosphor bronze	---
Aluminum alloy	45-50
Silver (over plated)	25
Three-component bearings	
Babbitt surfaced	---

All babbitts are inherently weak, and high temperatures reduce their strength even further. Therefore, babbitts are usually bonded to a stronger backing material such as bronze or mild steel.

(Sect. 3C) Plain Bearing Lubrication

Lubricants for plain bearings in industrial applications should be selected on the basis of bearing load, sliding speed of the bearing and viscosity of the lubricant at operating temperature. They must be viscous enough to maintain a full fluid film, be thin enough to prevent excessive internal friction, conduct heat, remain stable under severe operation conditions, and be reasonably economical. There are charts available from bearing manufacturers or oil supplier that recommend oils and greases based on load, speed and temperature.

In a plain bearing fluid friction is used to carry the lubricant into the load zone of the bearing. When the machine is started and the journal begins to rotate, a wedge-shaped film of oil develops under the journal. This wedge of oil actually lifts the journal away from contact with the bearing. This film of oil allows the machine to run easily by reducing friction and also guards the bearing and journal against wear. By this mechanism, lubrication of journal bearings is accomplished by hydrodynamic lubrication, i.e., the establishment of a full-fluid film between the sliding surfaces.

To distribute a lubricant through a bearing, shallow grooves or holes and channels are often provided in the bearing surface. To properly locate a lubricating groove, it is first necessary to determine what part of the bearing is to be under high pressure. The orientation of oil grooves in fluid-film journal bearings falls into two main categories, circumferential and axial. Usually, oil grooves and holes should be placed parallel to the shaft axis 90º to 120º ahead of the load zone.

There should be no holes or grooves in the areas of highest load. The wedge of oil that is formed under high pressure prevents metal-to-metal contact and should not be broken by grooves.

Chamfered grooves prevent oil from being scraped off the shaft, promote cooling, greater flow and better distribution of oil, and reduce foaming.

Journal bearings are often lubricated with a ring, which rides around a journal or shaft. It picks up oil from the sump and distributes it to the bearing as it rolls around the shaft.

Plain bearings are either oil-lubricated or grease-lubricated, depending on their design. Grease-lubricated plain bearings are usually found on slow-moving machinery and where inadequate seals or other conditions are such that oil would be unsuitable.

Gas lubricated bearings, like their liquid lubricated counterparts, fall into the categories of hydrodynamic bearings and hydrostatic bearings. They are used in applications involving small shaft diameters, high speeds, high or low temperatures, and light loads. The primary disadvantage of hydrostatic bearings is that a pressure source is required.

Hydrostatic bearings can often be made to support greater loads than hydrodynamic bearings. Other advantages include no contact and very low friction at starting and stopping. Precise spacing of two surfaces is possible with hydrostatic bearings, thus making them very attractive for instruments and machine tools.

Plain Bearing Failures

Some of the reasons why plain bearings fail are lack of lubricant, excessive load, fatigue, misalignment, high heat, contamination, vibration, improper fit, improper grooving, and inadequate bonding of Babbitt to sleeve or corrosion.

Anti-friction bearings

An anti-friction bearing is one in which a series of rollers or balls separates two moving parts. These rollers or balls are usually, but not necessarily, mounted in a cage or separator and enclosed between rings known as races. The races are supported in a housing. The dimensions of a rolling contact bearing are the inner diameter, outer diameter, radial clearance, pitch diameter and width.

Some types of rolling contact bearings include needle, cylindrical roller, spherical roller, thrust or tapered roller, ball, angular contact, and deep groove Conrad bearings.

The **ball bearing** is probably most widely known. **Ball bearings can be used at higher speeds than roller_bearings and may be less expensive than roller bearings**. Single row ball bearings should be considered for moderate radial loads, while double row ball bearings should be considered for heavy radial loads. The ball thrust bearing is used to prevent a shaft from moving endwise.

When the balls of a ball bearing are elongated into a cylinder or barrel shape, they are called rollers. If the axis of each roller is parallel to the axis of the bearing it is a **straight roller**. Cylindrical roller bearings with axially fixed inner and outer rings are not suitable for thrust loads.

A **thrust bearing** is defined as a bearing that prevents the lengthwise motion of a shaft. Three types of thrust bearings are <u>tapered roller</u> bearing, <u>angular contact</u> ball bearings and <u>spherical roller</u> thrust bearing.

The rollers in a **tapered roller** bearing are somewhat cone-shaped to that it can carry axial load as well as radial load. A tapered roller bearing is used to support a rotating shaft and also to prevent the shaft from moving endwise. In this respect, it acts as a thrust bearing. It can carry higher loads than ball bearings

The **needle bearing** differs from the others in that it generally **has no inner race and no separator or cage,** and its small rollers or needles are just slightly separated by the lubricant. The name comes from the fact that the length of each roller is so much greater than its thickness. It offers the largest capacity and the smallest cross section obtainable for a given shaft size.

When there are two anti-friction bearings on a shaft, one should be fixed (or held) and the other should be floating (or loose). The most common mounting for a roller bearing is interference fit against a shoulder. In general, **rolling bearings handle dirt better than ball bearings** because there is more area supporting the load, so the pressure at any one point is less concentrated.

Limiting Speed

The limiting speed for rolling contact bearings is a function of the bearing design, the load applied, the lubricating system, and the ambient conditions. Speed is usually limited by the rate at which the heat of friction of the bearing can be dissipated.

Bearing Type	Limiting speed, rpm
Radial ball bearings	
Normal operation	3,500
Under very light load	15,000
Angular contact bearings	3,500
Cylindrical roller	3,000
Tapered roller	2,500
Spherical roller	2,500
Thrust bearings	1,500

The operating or dynamic clearance of a bearing depends upon the speed, load and lubricant viscosity. Under a constant load, the life of a bearing is inversely proportional to speed.

Most anti-friction bearings have an operating temperature limit of 250°F.

Surface Roughness

Rolling contact bearings can have fluid films of ten- to twenty-millionths of an inch thick, depending on speed and lubricant viscosity. If the surface roughness of rolling elements and races is less than half the film thickness, no actual solid contact occurs during operation except for starting and stopping. Bearing manufacturers can specify surface roughness. If a bearing manufacturer specifies a bearing specification of 2μ, RMS, it means that the average of the distance between the peaks and valleys of asperities is no more than 2 millionths of an inch. RMS stands for Root Mean Square, or average surface roughness. The centerline average is the average of the height of the peaks and depth of the valleys.

Friction and Wear

Approximate 90% of bearings fail prematurely. Some common causes of bearing failure are improper type and viscosity of the lubricant, inadequate lubrication, installation, contaminants, improper selection, maintenance practices, fatigue, overload, misalignment, and unbalance. Most bearings in commercial applications do not fail from fatigue. Poor lubrication, faulty mounting, and misapplication are sole or contributory causes of the failure.

Eventually, a properly installed and well-maintained bearing will fail of fatigue. The fatigue failure, which usually commences as a small crack below the rolling surface at a point of high shear stress, is observed as a spall or pit formed in the surface.

Spalling (destructive pitting) results when normal loading is combined with sliding. It occurs when large wear particles are generated from cracks that are propagated from surface defects.

Brinelling and false brinelling are two other mechanisms of failure. Brinelling occurs when a bearing race is marred by balls or rollers due to shock impact, often caused during handling and installation. Care must be taken during installation. Bearings should not be hammered onto or off of a shaft. The recommended method of removing a bearing from a shaft without damaging it is to use an arbor press or hydraulic bearing puller. The evidence of false brinelling can be seen by the grooves in a race that are formed by vibration, for example, when bearings jiggle back and forth in a case while they're transported by train or over the road.

Fretting corrosion occurs when there is relative movement between the bearing bore and shaft or the bearing OD and the housing. Its appearance looks much like marbleized patches of rust. This type of corrosion is caused by insufficient interference fit. This produces rust-type material that causes wear in the bearing itself and increases internal clearances.
.
Sometimes it is possible to diagnose bearing failures by listening to them. A low-pitched noise can indicate misalignment. A high pitched whine is a symptom of overload. Rattles can occur as a result of inadequate interference fit. And a low rumble may be caused by poor surface finish. The most pronounced noise that can come from a bearing sounds like marbles rolling around. This is almost always an indication of cavitation.

Rating Life

If a group of apparently identical rolling bearings is operated at identical speeds under identical loads, all bearings will not fail simultaneously but will be distributed according to a statistically predictable pattern. The L_{10} life is the fatigue life in millions of revolutions (or hours) at a given operating speed which 90 percent of a group of substantially identical rolling bearings will survive under a given load. The L_{10} life is frequently called the "rating life." Some manufacturers base their ratings on the median life, i.e., the life which 50 per cent of the bearings will survive. Considerable endurance testing has demonstrated that L_{50} is approximately five times L_{10}.

Rolling Contact Bearing Lubrication

When choosing a bearing lubricant, it is important to know the speed, load, environment (including temperature, exposure to water or chemicals), type of bearing, size, and how the lubricant is applied. The right choice of lubricant depends on the type of bearing, and how and where it is used.

Lubricants in rolling element bearing have four basic functions. First, they reduce the friction that increases temperature and promotes wear. Second, lubricants dissipate some of the heat that is generated in the action of the bearing. Third, the coating action of the lubricant helps prevent corrosion on bearing components. Fourth, greases, in particular, seal out contaminants.

Relubrication intervals for bearings depend upon the speed, size, temperature and load. Bearing manufacturers will generally issue charts that give relubrication intervals based on these criteria.
A rolling-contact (anti-friction) bearing has highly finished surfaces and, as a rule, does not require large amounts of lubricants or frequent replenishing. Consequently, lubricant quality is especially important, and only the best oils and greases should be used. Remember: Don't wash the original lubricant from a new bearing.

Oil bath lubrication is widely used method in the case of low or medium speeds. The oil should be at the center of the lowest rolling element. It is desirable to provide a sight gauge so the proper oil level may be maintained.

The constant level method maintains oil supply by having a reservoir in which a small quantity of oil is always trying to work its way into the lower portion of the outer raceway of the bearing. This is good for slow speed, horizontal applications in immobile units. The oil level must be constant to avoid problems.

The regulated drip method is used often, but there can be problems controlling the drip. Other problems can be plugging the orifice, oil waste, messiness, and a loss of supply.

Splash systems are based on oil splashing from adjacent machine elements finding its way into the bearing. This system is practical for many relatively high-speed applications with large reservoirs of oil. An example is in auto transmissions.

Channels, holes, grooves, rings, collars, and discs can be incorporated into bearing assemblies to assure adequate lubrication. Lubrication chains are also used to pick up lubricant from the sump and deposit it on the bearing as they rotate around the shaft.

Circulating oil systems are complicated but also practical. The most common types are wick feed and circulating pump feed. Circulating lubrication is commonly used for high speed operation requiring bearing cooling and for bearings used at high temperatures. Oil is supplied at the top of the bearing. It travels through a pump and a filter and then through the bearing. The oil discharge pipe should be larger than the supply pipe so that an excessive amount of oil will not back up in the housing.

In the wick feed system, oil is fed from a reservoir through the wick to a smooth rotating disc, which feeds the oil into the bearings. Oil leaving the disc is generally in the form of fine droplets. This method uses capillary action to move the oil.

Oil mist systems are generally purchased commercially and installed into high-speed applications. The unit atomizes drops of oil and forces it into the bearings with low-pressure dry air, supplied from an external source. The oil supplied to the bearing is finely atomized, so very little interference is encountered. Surplus air creates positive pressure in the spindle, preventing dirt from entering the unit. The airflow helps cool the bearings and also can apply a positive pressure to the cavity and can prevent ingress of contamination.

Jet lubrication is often used for ultra high speed lubrication such as bearings in jet engines with a dmN value (dm is the pitch diameter of rolling element set in mm; N is the rotational speed in rpm) exceeding one million. Lubricating oil is sprayed under pressure from one or more nozzles directly into the bearing.

If you don't know the right viscosity of a bearing lubricant, it would be better to err on the side of viscosity that is too high rather than too low. A high viscosity lubricant causes energy loss, viscous drag, overheating and oil oxidation. Viscosity that is too low may cause metal-to-metal contact, wear, and eventual failure.

Sintered brass or bronze are excellent materials for oil impregnated bearings. There are spaces in the metallic lattice that retains the oil. A sintered (also called porous or impregnated) metal bearing can contain up to 35% liquid lubricant impregnated between the metal pores.

Rolling bearings are lubricated with grease or oil. Grease is generally preferred, as it is easier to retain in the housing, provides a better barrier to contaminants and is less likely to drain away from the bearing surfaces, therefore providing more reliable lubrication. It also requires less frequent re-lubrication. The lubricant stays in place. It can be used in sealed-for-life applications.

Bearing Greases

Whether hand packed or applied by grease gun, the primary recommendation for rolling contact bearings is NLGI 2 or 3 grease. NLGI 0 or 1 is used where temperatures are low or if dispensed through a centralized system. Channeling soap greases are generally the first choice for high speed rolling element bearings. Complex soap greases are recommended for high temperatures.

The procedure for changing out grease in a bearing is:

1. Purge out old grease by adding new grease until old grease appears at vent.
2. Rotate bearing and add grease until new grease appears.
3. Rotate bearing and vent grease for about 20 min. to prevent over greasing.

There are several methods for determining the correct amount of grease for roller bearings. One method for calculating the amount of grease to be used in rolling contact bearings is to use the formula.

(1) $G = 0.005\ DB$
(2) $G = 0.114\ DB$

(1) G = Grease quantity (grams), D = Bearing outside diameter (mm), B = Bearing width (mm)

(2) G = Grease quantity (ounces), D = Bearing outside diameter (inches), B = Bearing width (inches)

Fill the available space in the bearing and housing between one third and two thirds full, depending upon the speed of the bearing. The higher the speed, the less grease is necessary.

Never fill bearing housings completely full of grease. When a bearing rotates, it is lubricated by a thin film of grease. Excess grease is moved into the cavities of the bearing and housing. If these cavities are already filled with grease, the excess has nowhere to go and remains in the bearing where it is "churned". This causes overheating so the grease liquefies and can run out, starving the bearing of lubricant.

When a properly packed bearing starts up, there will be an initial rise in the temperature while the grease disperses throughout the bearing and housing, before falling off to a steady operating temperature. If the temperature does not lower then there is too much grease in the bearing, or there is a problem with the bearing fit.

Greasing electric motors

The bearings are the most critical lubrication points on electric motors. They are typically lubricated with high-quality NLG1 grade 2 non-EP grease that is made with a polyurea or lithium complex thickener. These motors may be lubricated for life. Some electric motors bearing run in a bath of oil, typically with a viscosity of ISO 68 when running at1800 rpm and ISO 32 at 3600 rpm

Care and Handling of Bearings

Cleanliness

New bearings must be protected against foreign bodies and condensation. Keep new bearings in their original wrappings as long as possible, and store them away from moisture where the temperature can be kept reasonably constant. To prevent contamination, do not flush the original lubricant from a new bearing.

Anything that may come into contact with bearings should be kept clean, including workers' hands, benches, tools, solvents, and cloths. Perspiration, condensation – any type of moisture should also be kept away from bearings. Handle bearings with clean, lintless cloths. Protect bearings with an oil film and make every effort not to break that film.

In general, roller bearings handle dirt better than ball bearings because there is more area supporting the load, so the pressure at any one point is less concentrated.

Use extreme caution when using compressed air around bearings. Compressed air is a source of moisture, which can cause corrosion in bearings.

Make every effort to avoid nicking bearings, which can be caused by striking them with hardened steel tools or sharp objects. Even though bearings are heat-treated, surfaces are brittle and fractures can easily occur. Nicks on the exposed surfaces can cause bearings to be improperly mounted, which will reduce bearing life.

Proper mounting techniques

A major load should never be applied through the ball complement when mounting bearings. Bearings should never be struck any blows with hardened steel implements. Use a hydraulic bearing puller or arbor press to install or remove bearings.

Caution should be used to prevent loose particles from falling into bearings while being mounted. This danger might occur on an arbor press or while using the drift tube technique.

In heating bearings for easier mounting, it is best to heat the bearing in an oven with circulating heat or use a hot oil bath or induction heating. Heating temperatures should, in general, not exceed 200°F.

Section 4
GEARS

Types of Gears

Gears serve to transmit motion from one shaft to another or from a rotating shaft to a reciprocating element, and to vary turning speeds. Gears are better at transmitting power than belts and ropes because they are more efficient, there is less slippage, and they last longer and are able to carry higher loads. The basic types of gears include spur, helical, herringbone, rack and pinion, bevel, spiral bevel, worm and hypoid.

A spur gear is a toothed wheel whose teeth are parallel the shaft or axle. It is the classic gear shape for transmitting motion from one shaft to another that is parallel to it. If one gear is small, and the other larger, the small gear is usually called the pinion and it usually has the fewest teeth.

Spur gears can have external teeth around the outside of cylindrical gear or internal teeth on the inside of a ring. When the teeth are on a straight bar, and are driven by a classic cylindrical gear, the gear set is called a rack and pinion. The toothed bar is called the rack and the small gear is the pinion.

Elliptical gears are used to convert the uniform rotary motion of a driving shaft to a rhythmic, pulsating rotation of the driven shaft.

An **equalizer gear** and **eccentric pinion** are sometimes used to drive large chain conveyors in order to prevent the changes of conveyor speed that would occur when the long bar links pass around the sprockets at the driving end. The eccentric driving pinion revolves at a constant speed, but imparts an irregular motion to the equalizer gear that is calculated to provide a smooth, unvarying speed to the chains. This type of drive reduces what otherwise might be excessive shock on the chains.

Planetary gears usually have three sets of gears. The innermost gear is called the sun gear and had teeth around its outside circumference. Meshing with the sun gear are one or more planetary gears. They rotate around the sun gear just as planets would rotate. Holding the set together is an outside ring gear. The teeth of the planetary gears mesh with the teeth on the outside of the sun gear. They also mesh with teeth that are on the inside circumference of the ring gear.

What makes planetary gears so useful is that speed and motion can be varied depending upon which gear is held stationary. Automatic transmissions work on the principle of planetary gears.

Helical gears are similar in shape to spur gears, but their teeth are placed at an angle on the face of the gear, so they appear to be curved. In meshing helical gears, more teeth are in contact at one time than in the case of spur gears. Helical gears run smoother than spur gears. Like spur gears, they transmit motion between parallel shafts. Even though they run smoother, the angled teeth of helical gears cause thrust.

Herringbone gears have the appearance of two helical gears side by side with teeth inclined in opposing directions. They are used when it is desired to obtain smooth operation and to eliminate the end thrust on a shaft that would be present if only a helical gear were used.

A rack and pinion combination is a spur gear meshing with a straight element. It is used to produce reciprocating motion from rotating motion.

Bevel gears are used to transmit motion between shafts that are at an angle to each other. The straight bevel gear has straight teeth on a slanted or beveled working surface. The spiral bevel gear has spiral teeth and gives smoother operation than does the straight bevel gear.

In **worm gear** sets, the small element, called the worm, usually drives the large element known as the wheel or gear, the shaft of the worm being perpendicular to the shaft of the wheel. The worm is expensive to machine, so the sacrificial gear, the driven gear, is often made of a softer metal like brass or bronze.

Worm gears have advantages over conventional gear sets. They have a high capacity to accept shock loads, can transmit energy along right angles, have a high turn down ratio, and are smooth and quiet. Conversely, worm gears are not very energy efficient, are fairly expensive for the horsepower output and develop high thrust loads.

Worm gears require lubricants with higher viscosity than spur or helical gears because a worm gear has a higher degree of sliding motion and requires oil with greater lubricity. Worm gear lubricants may also contain fatty materials (called compounding) that form a molecular carpet on the metal that resists being stripped off by the sliding motion of the worm.

Screw and nut combinations may be considered a type of gear since the threads in the nut transmit motion.

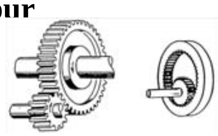
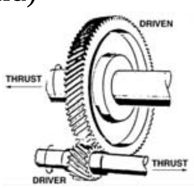
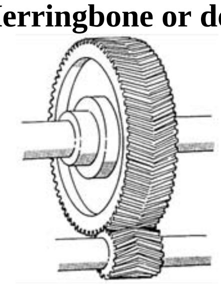
Hypoid gears are found in the transmission of many standard shift automobiles. They are similar to spiral bevel gears, but the shafts are offset. They were designed to eliminate the hump that ran down the middle of a car.

Flexible couplings are not considered gears, but the American Gear Manufacturer's Association (AGMA) sets specifications for them just like they do for gears. A flexible coupling is a device that connects two shafts in such a way that the rotation of one results in the synchronized rotation of the other. It compensates for misalignments or shifts in position of the machinery. An example would be the connection between an electric motor and gear box were the shafts of the two were not exactly aligned.

Grid couplings are all-metal couplings, which combine sliding (like chain couplings) and flexing (like rubber tire designs). The grid, a piece of zigzag tempered steel wire, fits between radial slots in the hubs. Flexible-disc couplings transmit torque through a stack of thin, high carbon steel or stainless wafers acting as leaf springs.

Combinations of gears are often used in place of simple gear pairs to reduce load on gear teeth and to minimize thrust load. Power can be transmitted from one gear, to another, then to another. Triple and quadruple reductions are not uncommon.

Parallel Shaft Gears

Types	**Advantages / Disadvantages**
Spur 	Transmits power on parallel shafts Lower load carrying ability Economical Moderate to low speeds No thrust induced 10 – 1 ratio limit No axial alignment problems
Helical (Similar to spur gear except teeth at angle, one is right hand and mate is left hand) 	Transmits power to parallel to shafts More costly than spur gears Greater load carrying capacity than spur gears Produces axial thrust Runs better at high speeds due to tooth overlap 10 – 1 ratio limit No axial alignment problems
Herringbone or double helical (has both right and left-hand helix) 	Transmits power on parallel shafts Expensive Greater load carrying capacity than spur gears Requires careful axial alignment Runs better at high speeds due to tooth overlap Transmits no thrust 10:1 ratio limit

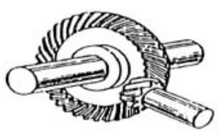
Right Angle Shaft Gears

Types | **Advantages** **Disadvantages**

Straight Bevel

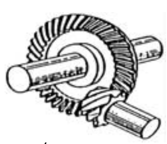
Easy to manufacture
Low load carrying ability
Economical
Relatively low speed
Low thrust
Careful mounting
6:1 ratio limit

Spiral Bevel



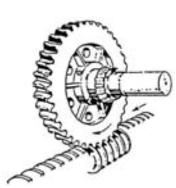
Greater load capacity than straight bevel
Produces axial thrust
Capable of higher speeds due to tooth overlap
Runs smoother and quieter
Careful mounting
6:1 ratio limit

Hypoid Gears



Greater load capacity than straight bevels
Low efficiency
Ratio’s as high as 100 – 1
Supporting shafts can pass each other making it compact

Worm Gears



High shock capacity
Low efficiency and run hot
Smooth and quiet
High thrust
Ratios as high as 100 – 1
High price per HP
High availability
Supporting shafts can pass each other

Lubrication methods

Enclosed gears can be lubricated by a variety of methods including bath/splash, circulating system, spray, mist or drip. AGMA recommends changing gear lubricants every 2,500 hours or six months, whichever comes first.

A bath system is not generally recommended for low or high speeds in gearboxes. Under low speeds, a low viscosity lubricant drips off the lower gear before it can be distributed to upper gears. At high speeds, the lubricant may be slung off.

Be careful to maintain an adequate level in the bath. Under filling a gearbox sump obviously can cause lack of lubrication. But overfilling may be equally destructive. It can cause the oil to overheat, produce foam and air entrainment, and the fluid may overflow. Eventually, higher temperatures and increased exposure to air can cause the oil to oxidize, which causes sludge, varnish and corrosive by-products.

Many gear manufacturers recommend breaking in gear sets for a set amount of time before adding the operating charge of lubricant. Break-in oils can be lapping compounds or light viscosity oils with small amount of an anti-wear additive like tricresyl phosphate.

Lubricants

When selecting a gear lubricant it is important to consider the load, speed, temperature, gear type and finish, and application method. In general, higher viscosity fluids are needed for higher loads and temperatures, lower speeds, rougher finishes, and for worm gears. Extreme pressure additives should be used for heavy loads and moderate temperatures, but are not effective with yellow metals such as bronze or brass.

Synthetic oils such as polyalphaolefins (PAO) and glycols can extend the life of the gear and oils, reduce temperatures, save energy and can be used over wider ranges of temperature. They are frequently recommended when consolidating lubricants. Because of their naturally high viscosity indices and exceptional lubricity, synthetic oils can often be substituted for petroleum oils that are one ISO viscosity grade higher or lower. For example, after checking with the equipment manufacturer, many plants will substitute a PAO based EP 220 viscosity grade where ISO 150, 220 or 320 oils are used. Worm gears that normally take an ISO 680-petroleum oilcan often use an ISO 460 PAO synthetic.

Gear oils contain many of the same additives as bearing lubricants such as rust inhibitors; oxidation inhibitors and foam inhibitors but they also contain extra lubricity additives for heavily loaded applications. Extreme pressure additives can be formulated from sulfur, phosphorus, chlorine or boron, although it is rare to find gear oil with chlorine because of environmental disposal concerns.

There are several tests that determine the load carrying ability of gear oils. These include the Timken OK load test, the Falex test, the FZG test and the 4-ball EP test. The presence of a fatty material can be determined by the saponification number test.

Determine the right viscosity to use by following the guidelines established by AGMA for viscosity grades. There are charts available from gear manufacturers and from oil suppliers that can determine the proper viscosity based on the speed, size or load, and temperature of the application. Choosing too low of a viscosity can accelerate wear, and cause an increase in noise, vibration and temperature due to lack of film strength. Too high of a viscosity can contribute to overheating and rapid oil oxidation.

If, because of consolidation, you have the choice of using a lubricant with a viscosity lower than what is recommended or one that is more viscous than optimum, choose the higher viscosity. The more viscous oil will provide more load carrying ability and maintain better film strength. A lighter oil may contribute to adhesive wear, low load carrying ability and tooth damage. Ensure that the oil is not so viscous that it cannot be distributed properly through the gear case.

Although AGMA has established standards for several levels of gear oils based on viscosity, base oils and additives, they are being phased out. However, because they are still printed on equipment tags that will be in service for years to come, it is still good to know them. The AGMA viscosity grades range from 0 to 15R. Rust and oxidation oils fall into grades 0 to 13, which correspond to ISO grades 32 to 1500. Extreme pressure gear oils use grades 2 EP to 13 EP, which are ISO grades 68 through 1500. Synthetic oils have their own category with grades from OS to 13S.

Oils with fatty materials fall into the compounded category; their grades range from 7 comp to 8A comp, which are ISO 460 to 1000. There is a special category for residual gear oils normally recommended for open gears, 14R and 15R.

A typical recommendation for a worm gear is an AGMA 7 comp lubricant, which would be ISO 460 oil with about 3 – 10% of a fatty additive. Sulfur phosphorus extreme pressure additives are not very effective in worm gear applications because the localized temperatures of a ferrous metal contacting brass or bronze does not get hot enough to activate the EP additive to form the slippery metallic soap. Extreme pressure additives are also not recommended because they can be corrosive to yellow metals at elevated temperatures.

A better recommendation for worm gears is an AGMA 7S lubricant. Synthetic PAO and glycol-based lubricants have both demonstrated energy savings in worm gear applications. Some studies have shown energy savings up to 10% with PAO's in some applications.

Hypoid gears in automotive use gears require a high level of extreme pressure additive, both because of the sliding motion, and because automotive gear oils are not changed regularly. The American Petroleum Institute set standards for hypoid gear lubricants in automotive use. The most current standard is GL-5.

Open gear lubricants are frequently made of residual materials such as asphalt that help the lubricant stick to the gears. They may be cut back with a solvent to make application a little easier. Once the solvent has evaporated, the lubricant left behind is more viscous and has a higher pour point and flash point than a fluid lubricant. Extra tacky greases are also used to lubricate open gears. They often contain solid fillers such as molybdenum and /or graphite.

Roller chains are another method of transmitting motion, and have the advantage over gears in that they are flexible. Pin links and roller links require oil, grease or a residual product. To lubricate a chain, apply the lubricant to the lower strand before the sprocket/gear. Lubricant can be applied using a brush, oil can, bath, spray, slinger, or by using drip or mist lubrication.

Gear Failure Modes

A number of factors affect gear life, including **load, environment, temperature, speed and contamination**. Each gearbox should be given a thermal rating by the manufacturer. It is given in terms of the recommended maximum speed, reduction ratio and horsepower. If the gearbox is used above this value, it will overheat.

AGMA (American Gear Manufacturers Association) lists the following gear failure modes: Tooth breakage, surface fatigue (spalling), wear and scoring (galling), plastic flow (deformation). Also, wiping, scuffing, abrasive wear, overload, Hertzian fatigue, brittle fracture, ductile fracture, rolling, bruising, peeling, pitting, scratching, cutting, gouging, denting, seizing, flaking, feather edging, brinelling, rippling, fish scaling, ridging, tip-to-root interference, adhesion, corrosion, fretting, cavitation, electrical discharge damage, polishing, burnishing, welding, smearing.

AGMA considers the four major causes of gear failure to be surface **fatigue, wear plastic flow and tooth breakage.** Misalignment, overloading and soft gear metal can lead to plastic flow of gear material. Clearly tooth breakage is one of the most catastrophic of failures, but seizing, galling, and degrees of several of the other failure modes can be equally destructive.

Most gear tooth failures occur through the process of surface fatigue. The result is pitting of tooth surfaces. The severity of this type of failure follows the progression of initial pitting, destructive pitting, and sometimes, spalling and usually occurs in the dedendum or lower half of the gear tooth.

Initial pitting – Asperities on the tooth surfaces of new gears can weld and break off under high load leaving small pits. When the surface roughness is at some distance from the pitch line, where there is sliding as well as rolling action, they may be worn smooth during run-in before fatigue and pitting can occur. On the other hand, initial pitting frequently occurs near the pitch line where there is rolling but little or no sliding action. This is often referred to as "pitch-line pitting".

Teeth surfaces which are rough usually require higher viscosity oil.

The gear tooth dedendum (below the pitch line) will normally show initial wear and pitting. Gear manufacturers will increase the hardness of the gear, increase its face width, increase the pinion pitch diameter or improve the geometry of the gear in order to decrease pitting.

Beam strength and Hertzian strength refer to the ability of a gear tooth to withstand repeated loadings. Fatigue occurs when a gear is pushed beyond its design capacity.

Destructive pitting – In progressive or destructive pitting, pits continue to form and enlarge as edges crumble or as pits break into each other. Eventually, tooth shape may be destroyed, the gears may become noisy and rough running, and if the condition progresses far enough, one or more teeth may fracture.

Destructive pitting is sometimes termed spalling, especially where large chips of metal "spall" out or where small pits merge into each other and form large ones.

Spalling may also describe the surface damage that occurs when large chips flake off near tooth tips or ends. This type of damage may be the result of subsurface defects or of excessive internal stresses due to heat treatment. The type of spalling may occur after a relatively few cycles of operation.

Scoring (sometimes called galling) is a form of wear in which gross damage to tooth surfaces occurs. Scuffing is a mild form of scoring. The actions that take place under boundary film conditions (shearing, deformation, plowing, welding) result in the development of high temperatures in the minute contact areas. These local temperatures are of short duration and are known as flash temperatures. Under heavy loads and high sliding speeds, the number of contacts in a given area may be so great that the heat developed cannot be dissipated and the surfaces run hot. Extensive welding, tearing and flow of metal surfaces may occur. The resulting damage is called scoring or galling, or in its mildest form, scuffing.

The term **plastic flow** refers to deformation of gear tooth surface metal as a result of heavy loading, especially impact loading. This form of failure usually occurs with soft, ductile metal, but may also occur on gear teeth that are case-hardened.

Tooth breakage is relatively uncommon. When it does occur, however, it is more serious than other forms of failure, as it usually makes the gears unsuitable for further operation. Tooth breakage can be classified as (1) fatigue breakage or (2) over-load breakage.

Fatigue breakage – This form of breakage is the result of many repetitions of bending stresses that are above the endurance limit of the material.

Overload breakage – Breaks of this type occur suddenly as a result of shock overloads. Gear wear can lead to failure. The three stages of gear wear are normal (slow loss of material), moderate (not destructive but life may be shortened and noise develops), and destructive (deterioration and change in tooth shape).

Two design features that can affect lubricant efficiency are backlash and clearance. Clearance is the distance between the top of one tooth to the base of the tooth on the other gear. It is a function of the height of the tooth. In gear terms, it is the amount by which the dedendum in a given gear exceeds the addendum of its mating gear.

Backlash is the distance between the back of one tooth and the front of the next mating tooth. It is a function of the width of the teeth. If there is not enough backlash, lubricant may not coat the teeth properly, and that can lead to overheating, noise, tooth wear and failure.

The basic causes of gear failure are common to other machine elements and are covered in other sections. These include:

1. Original surface roughness
2. Foreign matter in the lubricant
3. Mechanical damage
4. Metal failure
5. Lubrication failure

Checking gear tooth contact

Parallel shaft helical gear tooth contact can be checked two ways. Soft machinist blue or transfer blue can be applied to the teeth of one gear and that gear can then be rolled by hand through mesh with its mating gear. The transfer of the blue from one gear to the other gear is read as the contact. Another method is to paint the gear teeth with hard blue or layout blue (paint) and run the gear unit. Then observe the pattern or the “wear-off” of the bluing.

Look for evidence of even load across much of the gear tooth, both flank and face width. The contact between gear teeth is line contact; therefore, the alignment between rotating elements is critical.