

## Chapter 9 Gears

### 9-1. General

*a.* Energy is transmitted from a power source to a terminal point, through gears that change speeds, directions, and torque. Gear lubricants are formulated and applied to prevent premature component failure, assure reliable operation, reduce operating cost, and increase service life. The important objectives accomplished by these lubricants include: reduction of friction and wear, corrosion prevention, reduction of operating noise, improvement in heat transfer, and removal of foreign or wear particles from the critical contact areas of the gear tooth surfaces.

*b.* Gears vary greatly in their design and in their lubrication requirements. Proper lubrication is important to prevent premature wear of gear tooth surfaces. When selecting a lubricant for any gear application the following issues must be considered: type and materials of gear; operating conditions, including rolling or sliding speed, type of steady load, and temperature; method of lubricant application; environment; and type of service. Enclosed gears -- those encased in an oil-tight housing -- usually require an oil with various additives, depending on the operating conditions. Rust, oxidation, and foam inhibitors are common. Extreme pressure (EP) additives are also used when loads are severe.

*c.* Worm gears are special because the action between the worm and the mating bull gear is sliding rather than the rolling action common in most gears. The sliding action allows fluid film lubrication to take place. Another significant difference is that worm gears are usually made of dissimilar materials, which reduces the chance of galling and reduces friction. EP additives usually are not required for worm gears and may actually be detrimental to a bronze worm gear. Lubrication can be improved by oiliness additives.

*d.* In open gear applications, the lubricant must resist being thrown off by centrifugal force or being scraped off by the action of the gear teeth. A highly adhesive lubricant is required for most open gear applications. Most open gear lubricants are heavy oils, asphalt-based compounds, or soft greases. Depending on the service conditions, oxidation inhibitors or EP additives may be added. Caution must be exercised when using adhesive lubricants because they may attract and retain dust and dirt, which can act as abrasives. To minimize damage, gears should be periodically cleaned.

### 9-2. Gear Types

*a. Spur gears.* Spur gears are the most common type used. Tooth contact is primarily rolling, with sliding occurring during engagement and disengagement. Some noise is normal, but it may become objectionable at high speeds.

*b. Rack and pinion.* Rack and pinion gears are essentially a variation of spur gears and have similar lubrication requirements.

*c. Helical.* Helical gears operate with less noise and vibration than spur gears. At any time, the load on helical gears is distributed over several teeth, resulting in reduced wear. Due to their angular cut, teeth meshing results in thrust loads along the gear shaft. This action requires thrust bearings to absorb the thrust load and maintain gear alignment.

*d. Herringbone.* Herringbone gears are essentially two side-by-side opposite-hand helical gears. This design eliminates thrust loads, but alignment is very critical to ensure correct teeth engagement.

*e. Bevel.* Bevel gears are used to transmit motion between shafts with intersecting center lines. The intersecting angle is normally 90 deg but may be as high as 180 deg. When the mating gears are equal in size and the shafts are positioned at 90 degrees to each other, they are referred to as miter gears. The teeth of bevel gears can also be cut in a curved manner to produce spiral bevel gears, which produce smoother and quieter operation than straight cut bevels.

*f. Worm.* Operation of worm gears is analogous to a screw. The relative motion between these gears is sliding rather than rolling. The uniform distribution of tooth pressures on these gears enables use of metals with inherently low coefficients of friction such as bronze wheel gears with hardened steel worm gears. These gears rely on full fluid film lubrication and require heavy oil compounded to enhance lubricity and film strength to prevent metal contact.

*g. Hypoid.* Hypoid gears are similar to spiral bevel gears except that the shaft center lines do not intersect. Hypoid gears combine the rolling action and high tooth pressure of spiral bevels with the sliding action of worm gears. This combination and the all-steel construction of the drive and driven gear result in a gear set with special lubrication requirements, including oiliness and antiweld additives to withstand the high tooth pressures and high rubbing speeds.

*h. Annular.* Annular gears have the same tooth design as spur and helical gears, but unlike these gears, the annular gear has an internal configuration. The tooth action and lubrication requirements for annular gears are similar to spur and helical gears.

### **9-3. Gear Wear and Failure**

The most critical function provided by lubricants is to minimize friction and wear to extend equipment service life. Gear failures can be traced to mechanical problems or lubricant failure. Lubricant-related failures are usually traced to contamination, oil film collapse, additive depletion, and use of improper lubricant for the application. The most common failures are due to particle contamination of the lubricant. Dust particles are highly abrasive and can penetrate through the oil film, causing “plowing” wear or ridging on metal surfaces. Water contamination can cause rust on working surfaces and eventually destroy metal integrity. To prevent premature failure, gear selection requires careful consideration of the following: gear tooth geometry, tooth action, tooth pressures, construction materials and surface characteristics, lubricant characteristics, and operating environment. The first four items are related to design and application, and further discussion is beyond the scope of this manual. These items may be mentioned where necessary, but discussions are limited to those aspects directly related to and affected by lubrication, including wear, scuffing, and contact fatigue. Refer to ANSI/AGMA Standard 1010-E95, and ASM Handbook Volume 18, for photographs illustrating the wear modes described in the following discussion.

*a. Normal wear.* Normal wear occurs in new gears during the initial running-in period. The rolling and sliding action of the mating teeth create mild wear that appears as a smooth and polished surface.

*b. Fatigue.*

(1) Pitting. Pitting occurs when fatigue cracks are initiated on the tooth surface or just below the surface. Usually pits are the result of surface cracks caused by metal-to-metal contact of asperities or

defects due to low lubricant film thickness. High-speed gears with smooth surfaces and good film thickness may experience pitting due to subsurface cracks. These cracks may start at inclusions in the gear materials, which act as stress concentrators, and propagate below and parallel to the tooth surface. Pits are formed when these cracks break through the tooth surface and cause material separation. When several pits join, a larger pit (or spall) is formed. Another suspected cause of pitting is hydrogen embrittlement of metal due to water contamination of the lubricant. Pitting can also be caused by foreign particle contamination of lubricant. These particles create surface stress concentration points that reduce lubricant film thickness and promote pitting. The following guidelines should be observed to minimize the onset of pitting in gear units:

- ! Reduce contact stresses through load reduction or by optimizing gear geometry.
- ! Steel should be properly heat-treated to high hardness. Carburizing is preferable.
- ! Gear teeth should have smooth surfaces produced by grinding or honing.
- ! Use proper quantities of cool, clean, and dry lubricant with the required viscosity.

(2) Micropitting. Micropitting occurs on surface-hardened gears and is characterized by extremely small pits approximately 10  $\mu\text{m}$  (400  $\mu\text{-inches}$ ) deep. Micropitted metal has a frosted or a gray appearance. This condition generally appears on rough surfaces and is exacerbated by use of low-viscosity lubricants. Slow-speed gears are also prone to micropitting due to thin lubricant films. Micropitting may be sporadic and may stop when good lubrication conditions are restored following run-in. Maintaining adequate lubricant film thickness is the most important factor influencing the formation of micropitting. Higher-speed operation and smooth gear tooth surfaces also hinder formation of micropitting. The following guidelines should be observed to reduce the onset of micropitting in gear units:

- ! Use gears with smooth tooth surfaces produced by careful grinding or honing.
- ! Use the correct amount of cool, clean, and dry lubricant with the highest viscosity permissible for the application
- ! Use high speeds, if possible.
- ! Use carburized steel with proper carbon content in the surface layers.

c. *Wear.*

(1) Adhesion.

(a) New gears contain surface imperfections or roughness that are inherent to the manufacturing process. During the initial run-in period, these imperfections are reduced through wear. Smoothing of the gear surfaces is to be expected. Mild wear will occur even when adequate lubrication is provided, but this wear is limited to the oxide layer of the gear teeth. Mild wear is beneficial because it increases the contact areas and equalizes the load pressures on gear tooth surfaces. Furthermore, the smooth gear surfaces increase the film thickness and improve lubrication.

(b) The amount of wear that is acceptable depends on the expected life, noise, and vibration of the gear units. Excessive wear is characterized by loss of tooth profile, which results in high loading, and loss of tooth thickness, which may cause bending fatigue.

(c) Wear cannot be completely eliminated. Speed, lubricant viscosity, and temperature impose practical limits on gear operating conditions. Gears that are highly loaded, operate at slow speeds, i.e., less than 30 m/min (100 ft/min), and rely on boundary lubrication are particularly subject to excessive wear. Slow-speed adhesive wear is highly dependent upon lubricant viscosity. Higher lubricant viscosities provide significant wear reduction, but viscosities must be carefully selected to prevent overheating.

(d) The following guidelines should be observed to minimize the onset of adhesive wear in gear units:

- ! Gear teeth should have smooth surfaces.
- ! If possible, the run-in period for new gear units should be restricted to one-half load for the first hours of operation.
- ! Use the highest speeds possible. High-load, slow-speed gears are boundary lubricated and are especially prone to excessive wear. For these applications, nitrided gears should be specified.
- ! Avoid using lubricants with sulfur-phosphorus additives for very slow-speed gears (less than 3 m/min, or 10 ft/min).
- ! Use the required quantity of cool, clean, and dry lubricant at the highest viscosity permissible.

(2) Abrasion. Abrasive wear is caused by particle contaminants in the lubricant. Particles may originate internally due to poor quality control during the manufacturing process. Particles also may be introduced from the outside during servicing or through inadequate filters, breathers, or seals. Internally generated particles are particularly destructive because they may become work-hardened during compression between the gear teeth. The following guidelines should be observed to prevent abrasive wear in gear units:

- ! Remove internal contamination from new gearboxes. Drain and flush the lubricant before initial start-up and again after 50 hours of operation. Refill with the manufacturer's recommended lubricant. Install new filters or breathers.
- ! Use surface-hardened gear teeth, smooth tooth surfaces, and high-viscosity lubricants.
- ! Maintain oil-tight seals and use filtered breather vents, preferably located in clean, nonpressurized areas.
- ! Use good housekeeping procedures.
- ! Use fine filtration for circulating-oil systems. Filtration to 3  $\mu\text{m}$  (120  $\mu\text{-in.}$ ) has proven effective in prolonging gear life.
- ! Unless otherwise recommended by the gear manufacturer, change the lubricant in oil-bath systems at least every 2500 hours or every 6 months.

- ! When warranted by the nature of the application, conduct laboratory analysis of lubricants. Analysis may include spectrographic, ferrographic, acid number, viscosity, and water content.

(3) Polishing. Polishing wear is characterized by a mirror-like finish of the gear teeth. Polishing is caused by antiscuff additives that are too chemically reactive. An excessive reaction rate, coupled with continuous removal of surface films by very fine abrasive particles in the lubricant, may result in excessive polishing wear. The following guidelines should be observed to prevent polishing wear in gearsets:

- ! Use less chemically active antiscuff additives such as borate.
- ! Remove abrasives from the lubricant by using fine filtration or by frequent oil changes.

d. *Scuffing.*

(1) General. The terms scuffing and scoring are frequently interchanged. The following definitions are provided to assist in correctly ascertaining the type of damage observed. The ASM Handbook Vol 18 defines scuffing as localized damage caused by the occurrence of solid-phase welding between sliding surfaces. It defines scoring as the formation of severe scratches in the direction of sliding. The handbook also stipulates that scoring may be caused by local solid-phase welding or abrasion, but suggests that minor scoring be considered as scratching. Gear scuffing is characterized by material transfer between sliding tooth surfaces. Generally this condition occurs when inadequate lubrication film thickness permits metal-to-metal contact between gear teeth. Without lubrication, direct metal contact removes the protective oxide layer on the gear metal, and the excessive heat generated by friction welds the surfaces at the contact points. As the gears separate, metal is torn and transferred between the teeth. Scuffing is most likely to occur in new gear sets during the running-in period because the gear teeth have not sufficient operating time to develop smooth surfaces.

(2) Critical scuffing temperature.

(a) Research has shown that for a given mineral oil without antiscuffing or extreme pressure additives, there is a critical scuffing temperature that is constant regardless of operating conditions. Evidence indicates that beyond the critical temperature, scuffing will occur. Therefore, the critical temperature concept provides a useful method for predicting the onset of scuffing. The critical scuffing temperature is a function of the gear bulk temperature and the flash temperature and is expressed as:

$$T_c = T_b + T_f \quad (9-1)$$

where the bulk temperature  $T_b$  is the equilibrium temperature of the gears before meshing and the flash temperature  $T_f$  is the instantaneous temperature rise caused by the local frictional heat at the gear teeth meshing point. The critical scuffing temperature for mineral oils without antiscuffing or extreme pressure additives increases directly with viscosity and varies from 150 to 300 °C (300 to 570 °F). However, this increased scuffing resistance appears to be directly attributed to differences in chemical composition and only indirectly to the beneficial effects of increased film thickness associated with higher viscosity. Examination of the critical temperature equation indicates that scuffing can be controlled by lowering either of the two contributing factors. The bulk temperature can be controlled by selecting gear geometry and design for the intended application. The flash temperature can be controlled indirectly by gear tooth smoothness and through lubricant viscosity. Smooth gear tooth surfaces produce less friction and heat while increased viscosity provides greater film thickness, which also reduces frictional heat and results in a

lower flash temperature. Furthermore, judicious application of lubricant can cool the gears by removing heat.

(b) For synthetics and lubricants containing antiscuff additives, the critical temperature depends on the operating conditions and must be determined experimentally for each case. Antiscuff additives commonly used are iron sulfide and iron phosphate. These additives react chemically with the protected metal gear surface to form very strong solid films that prevent metal contact under extreme pressure and temperature conditions. As previously noted in the discussions of oil additives, the beneficial effects of extreme pressure additives are enhanced as the temperature increases.

(c) The following guidelines should be observed to prevent scuffing in gear units:

- ! Specify smooth tooth surfaces produced by careful grinding or honing.
- ! Protect gear teeth during the running-in period by coating them with iron-manganese phosphate or plating them with copper or silver. During the first ten hours of run-in, new gears should be operated at one-half load.
- ! Use high-viscosity lubricants with antiscuff additives such as sulfur, phosphorus, or borate.
- ! Make sure the gear teeth are cooled by supplying adequate amount of cool lubricant. For circulating-oil systems, use a heat exchanger to cool the lubricant.
- ! Optimize the gear tooth geometry. Use small teeth, addendum modification, and profile modification.
- ! Use accurate gear teeth, rigid gear mountings, and good helix alignment.
- ! Use nitrided steels for maximum scuffing resistance. Do not use stainless steel or aluminum for gears if there is a risk of scuffing.

#### **9-4. Gear Lubrication**

*a. Lubricant characteristics.* Gear lubricant must possess the following characteristics:

(1) General. The following characteristics are applicable to all gear lubricants. The lubrication requirements for specific gears follow this general discussion:

(a) Viscosity. Good viscosity is essential to ensure cushioning and quiet operation. An oil viscosity that is too high will result in excess friction and degradation of oil properties associated with high oil operating temperature. In cold climates gear lubricants should flow easily at low temperature. Gear oils should have a minimum pour point of 5 °C (9 °F) lower than the lowest expected temperature. The pour point for mineral gear oil is typically -7 °C (20 °F). When lower pour points are required, synthetic gear oils with pour points of -40 °C (-40 °F) may be necessary. The following equation from the ASM Handbook provides a method for verifying the required viscosity for a specific gear based on the operating velocity:

$$v_{40} = \frac{7000}{V^{0.5}} \quad (9-2)$$

where

$v_{40}$  = lubricant kinematic viscosity at 40°C (105°F) (cSt)

$V$  = pitch line velocity (ft/min) given by :

$$V = 0.262nd \quad (9-3)$$

where  $n$  is the pinion speed in rev/min and  $d$  is the pitch diameter (inches).

(b) Film strength. Good film strength helps prevent metal contact and scoring between the gear teeth.

(c) Lubricity (oiliness). Lubricity is necessary to reduce friction.

(d) Adhesion. Helps prevent loss of lubrication due to throw-off associated with gravity or centrifugal force especially at high speeds.

(e) Gear speed. The now superseded Industrial Gear Lubrication Standards, AGMA 250.04, used center distance as the primary criterion for gear lubricant selection. The new version of this standard, designated AGMA 9005-D94 Industrial Gear Lubrication, has adopted pitch line velocity as the primary selection criterion. As noted above, gear speed is a factor in the selection of proper oil viscosity. The pitch line velocity determines the contact time between gear teeth. High velocities are generally associated with light loads and very short contact times. For these applications, low-viscosity oils are usually adequate. In contrast, low speeds are associated with high loads and long contact times. These conditions require higher-viscosity oils. EP additives may be required if the loads are very high.

(f) Temperature. Ambient and operating temperatures also determine the selection of gear lubricants. Normal gear oil operating temperature ranges from 50 to 55 °C (90 to 100 °F) above ambient. Oils operating at high temperature require good viscosity and high resistance to oxidation and foaming. Caution should be exercised whenever abnormally high temperatures are experienced. High operating temperatures are indicative of oils that are too viscous for the application, excess oil in the housing, or an overloaded condition. All of these conditions should be investigated to determine the cause and correct the condition. Oil for gears operating at low ambient temperatures must be able to flow easily and provide adequate viscosity. Therefore these gear oils must possess high viscosity indices and low pour points.

(2) Open gears. In addition to the general requirements, lubrication for open gears must meet the following requirements:

(a) Drip resistance. Prevents loss of lubricant, especially at high temperatures which reduce viscosity.

(b) Brittle resistance. Lubricant must be capable of resisting embrittlement, especially at very low temperatures.

(3) Enclosed gears. In addition to the general requirements, lubrication for enclosed gears must meet the following requirements:

(a) Chemical stability and oxidation resistance. Prevents thickening and formation of varnish or sludge. This requirement is especially significant in high-speed gears because the oil is subjected to high operating oil and air temperatures.

(b) Extreme pressure protection. Provides additional galling and welding protection for heavily loaded gears when the lubricant film thickness fails. Extreme pressure lubricants are available for mild and severe (hypoid) lubricant applications.

*b. Types of gear lubricants*

(1) Oil. Refer to AGMA 9005-D94 for the specifications for the following lubricants.

(a) Rust and oxidation oils. These petroleum-based oils are frequently referred to as RO gear oils. RO oils are the most common gear lubricants and have been formulated to include chemical additives that enhance their performance qualities. RO lubricating oils have easy application properties for gear and bearings, good lubrication qualities, and adequate cooling qualities and they are economical to use. Disadvantages include restriction to enclosed gear applications to prevent contamination.

(b) Compounded gear lubricants. These oils are a blend of petroleum-based oils with 3 to 10 percent fatty or synthetic fatty oils. They are particularly useful in worm gear drives. Except as noted in the AGMA applicable specifications, compounded oils should comply with the same specifications as RO oils.

(c) Extreme pressure lubricants. These gear lubricants, commonly referred to as EP lubricants, are petroleum-based and specially formulated to include chemical additives such as sulfur-phosphorus or other similar materials capable of producing a film that provides extreme pressure and antiscuffing protection.

(d) Synthetic oils. Synthetic oils have the advantage of stable application over wide temperature range, good oxidation stability at high temperatures, high viscosity indices, and low volatility. Because gear oils must be changed periodically, the main disadvantage of synthetics is high cost, which can only be justified for applications at high temperature extremes where other lubricants fail. Another disadvantage of synthetics is possible incompatibility with seals and other lubricants. The equipment manufacturer should be consulted before using synthetic oils to ensure that exposed materials will not be damaged or warranties voided. Gear units should be flushed of all mineral oils before the filling with the final synthetic oil.

(e) Residual compounds. These are higher-viscosity straight mineral or EP lubricants that are mixed with a diluent to facilitate application. Viscosities range from 400 to 2000 mm<sup>2</sup>/s at 100 °C (mm sq/sec cST at 100 °C) without diluent. Once applied, the diluent evaporates and leaves a heavy residual lubricant coating on the treated surface.

(2) Special compounds and greases. These lubricants include special greases formulated for boundary lubricating conditions such as low-speed, low-load applications where high film strength is required. These lubricants usually contain a base oil, a thickener, and a solid lubricant such as molybdenum disulfide (MoS<sub>2</sub>) or graphite. The gear manufacturer should be consulted before using grease. The primary disadvantage of using grease is that it accumulates foreign particles such as metal, dirt, and other loose materials that can cause significant damage if adequate maintenance is not provided.



Grease also has a tendency to be squeezed out of the gear tooth meshing zone, and it does not provide satisfactory cooling.

(3) Open-gear lubricants. Open-gear lubricants are generally reserved for slow-speed low-load boundary lubricating conditions. Due to the open configuration, the lubricants must be viscous and adhesive to resist being thrown off the gear teeth surfaces. The disadvantages of these lubricants are similar to those noted above for grease.

(4) Solid lubricants. The solid lubricants most commonly used in gear trains are molybdenum disulfide, graphite, polytetrafluoroethylene (PTFE), and tungsten disulfide ( $WoS_2$ ). Because they are expensive to apply, use of these lubricants is reserved for special applications such as high and low temperature extremes where other lubricants fail to perform adequately.

*c. Applications.*

(1) Spur, helical, bevel, and hypoid gears. Spur, helical, and bevel gears have similar load and speed characteristics, and similar requirements for antiscuffing and viscosity.

(a) Spur and helical gears. Spur and helical gears usually require mineral oils with RO inhibitors. Low-viscosity RO oils, such as turbine oils, are commonly used in high-speed, low-load gear units. For high-speed, low-load gear applications, mineral oils without antiscuff/extreme pressure agents can be used successfully provided the oil viscosity is capable of maintaining the required film thickness. However, low-speed gears are usually heavily loaded so antiscuff/extreme pressure agents are necessary to ensure adequate protection.

(b) Hypoid gears. Hypoid gears combine the rolling action and high tooth pressure of spiral bevel gears with the sliding action of worm gears. These severe operating conditions result in high load, high sliding speeds, and high friction. Therefore, hypoid gears are very susceptible to scuffing. Mineral oils for this application must have high lubricity and high concentrations of antiscuffing/extreme pressure additives.

(2) Worm gears. Worm gears operate under high sliding velocity and moderate loads. The sliding action produces friction that produces higher operating temperatures than those that occur in other gear sets. Normal operating temperature for worm gears may rise to 93° C (200° F) and is not a cause for concern. Lubricants for worm gears must resist the thinning due to high temperatures and the wiping effect of sliding action, and they must provide adequate cooling. Mineral oils compounded with lubricity additives are recommended. Extreme pressure additives are usually not required for worm gears. However, when EP protection is required, the additive should be selected with caution to prevent damaging the bronze worm wheel.

(3) Gear combinations. Many applications use different gears in the same gear housing. For these applications the lubricant must be suitable for the gears with the most demanding requirements. Generally, the other gears will operate satisfactorily with such high-performance lubricants.

(4) Gear shaft bearings. Gear shaft bearings are frequently lubricated by gear oil. In most instances this condition is acceptable. Bearings in high-speed, low-load applications may operate satisfactorily with the gear oil. However, low-speed, heavily loaded gears usually require a heavy oil. For these conditions a low-viscosity EP oil may provide adequate lubrication for the gears and bearings. The low-viscosity oil

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will adequately lubricate the bearings while the EP additive will protect the gear teeth from the effects of using a low-viscosity oil.