Gear Wear Caused By Contaminated Oils

Douglas Godfrey

Introduction

The diagnosis and prevention of gear tooth and bearing wear requires the discovery and understanding of the particular mechanism of wear, which in turn indicates the best method of prevention. Because a gearbox is a tribologically dependent mechanism, some understanding of gear and bearing tribology is essential for this process. ***Tribology*** is the general term for the study and practice of lubrication, friction and wear. If tribology is neglected or considered insignificant, poor reliability and short life will result.

One of the most common causes of practical industrial wear problems is contaminants in the oil. In this article the author shares his experience with the diagnosis and solution of such problems and their relationship to basic tribology.

Kinds of Lubrication Occurring in a Gearbox

All types of gears and their support bearings utilize the three kinds of lubrication.

Hydrodynamic Lubrication (HDL) exists when a gas or liquid film completely separates moving surfaces, preventing solid-to-solid contact. HDL is the most desirable regime of lubrication because friction is low and wear can be extremely low. In gears it occurs wherever the sliding of engaging teeth, especially just above or below the pitch line, allows for the formation of a wedge of oil that can completely separate the teeth. Journal bearings in the gearbox also operate in the HDL regime.

The primary HDL property of the oil is its viscosity. The oil film thickness must be greater than the sum of the surface roughnesses to minimize wear. A rule of thumb to apply here is that the oil film thickness is proportional to the square root of the viscosity. For example, if gear oil viscosity is increased from ISO 150 to ISO 320, film thickness will be increased 46% for a given load and sliding speed. It is important to note that in spur gears, HDL is discouraged by the automatic reversal of sliding direction on the addendum and dedendum.

Elastohydrodynamic Lubrication (EHL) implies that a full oil film is formed between moving surfaces that are elastically deformed. It occurs in concentrated contacts, such as rolling contact at the pitch line of the gears. The metals at the line of contact deform elastically, and the oil trapped between them is subjected to extremely high Hertzian pressures. The oil viscosity increases with high pressures by many orders of magnitude. For example, a mineral oil with a viscosity of 15 cSt at atmosphere pressure would be 100,000 cSt at 140,000 psi. The oil may be considered a solid for the short time it is at that pressure. The pressure-viscosity coefficent is a measure of change.

As a result of combined elastic deformation and high viscosity, an extremely thin film of oil completely separates the surfaces and prevents metal-to-metal contact. EHL also occurs between the rolling elements of rolling element bearings and their raceways. For EHL, oil viscosity at atmospheric pressures is still important for dragging the oil into the contact.

The EHL theory was developed by English tribologists Dowsen and Higgensen in order to understand zero tooth wear on a 30-year-old operating gearbox. They developed an equation for the calculation of minimum oil film thickness of engaging gear teeth (See Table 1).

Boundary Lubrication (BL) occurs when HDL and EHL fail, and metal-to-metal contact occurs, such as when the tip of a spur gear tooth slides near the root of the opposing tooth. BL also occurs during

Table 1 — Equation for the Calculation of Minimum Film Thickness in the Elastohydrodynamic Lubrication Regime. *

$$h_{min} = \frac{1.63\alpha^{0.54}(\mu_o V_e)^{0.7} \cdot \rho n^{0.43}}{(X_r W_{Nr})^{0.3} Er^{0.13}}$$

The specific film thickness is given by

$$\lambda = \frac{h_{min}}{\sigma}$$

where

σ = composite surface roughness

$\sigma = (\sigma_1^2 + \sigma_2^2)^{1/2}$

σ_1, σ_2 = surface roughness, rms (pinion, gear)

μ_o = absolute viscosity, Reyns (lb sec/in^2)

α = pressure-viscosity coefficient, (in^2/lb). The pressure-viscosity coefficient ranges from α=0.5 x 10^{-4} to α=2 x 10^{-4} for typical gear lubricants.

Er = reduced modulus of elasticity given by

$$Er = 2\left(\frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2}\right)^{-1}$$

where

υ_1, υ_2 = Poisson's ratio (pinion, gear)

E_1, E_2 = modulus of elasticity (pinion, gear)

ρn = normal relative radius of curvature

$$\rho n = \frac{\rho_1 \rho_2}{(\rho_2 \pm \rho_1)\cos\Psi_b}$$

ρ_1, ρ_2 = transverse radius of curvature (pinon, gear)

Ψ_b = base helix angle

V_e = entraining velocity given by

$V_e = Vr_1 + Vr_2$

where

Vr_1, Vr_2 = rolling velocities given by

$Vr_1 = \omega_1 \rho_1$

$Vr_2 = \omega_2 \rho_2$

ω_1, ω_2 = angular velocities (pinion, gear)

W_{Nr} = normal unit load given by

$$W_{Nr} = \frac{W_{Nr}}{L_{min}}$$

where

W_{Nr} = normal operating load

L_{min} = minimum contact length

* These equations are taken from Reference 2, Errichello, "Lubrication of Gears."

start-up, shut down, at high loads and high temperatures and in worm gears. The important oil property for BL is the soluble anti-wear and anti-scuff additives in the oil, which react with the metal surfaces to form a thin, tough film that reduces metal-to-metal contact.

In worm gears, which resemble a screw thread with continuous sliding, lubricity additives are required to reduce friction. Lubricity is defined as that property of a lubricant that reduces friction. Oil with good lubricity also improves gearbox efficiency.

Mixed Lubrication. HDL, EHL and BL may not occur ideally and isolated in gears, but in a mixed condition. During one tooth engagement all three lubrication mechanisms may occur consecutively or simultaneously. Unfortunately, ideal lubrication mechanisms frequently fail and allow high wear.

Many articles such as Refs. 1 and 2 provide information on gear lubrication.

Kinds of Gear Wear

The AGMA booklet (Ref. 3) and other literature describe the numerous kinds of gear tooth failures. Table 2 shows a list of the most common wear mechanisms related to contaminated lubricants.

Table 2 — Common Kinds of Gear and Bearing Wear

Gears		
	Abrasion	
	Scuffing	
	Contact Fatigue and Spalling	
	Polishing Wear	
	Pitting	
Bearings		
	Rolling Element	
		Nicks and Dents
		Contact Fatigue
		Abrasion
		Fretting Corrosion
	Journal	
		Wiping of Babbitt
		Excessive Embedment

Wear Caused by Contaminated Gear Oil

In the author's experience, contamination of the lubricant accounts for about 80% of gear tooth wear and bearing distress. *Therefore for reliability and long life, keep the oil clean and dry.* Contaminants in lubricated machines may come from the fresh oil or the new machine, be generated by the system while running or ingested from external sources. These issues are discussed in detail in Ref. 4.

Following are the major kinds of oil contamination and the types of gear tooth and bearing wear they cause.

- Ingested dirt
  - Any solids interfere with oil film formation.
  - Hard particles cause abrasion.
  - Fine particles cause polishing wear.
  - Dirt makes dents in rolling element bearings, leading to fatigue failure.
- Water
  - Interferes with oil film formation.
  - Causes rust.
  - Degrades the oil by acting as a catalyst for oxidation.
- Manufacturing debris
  - Same as ingested dirt, plus metal chips bridge the oil film and initiate scuffing.
- Chemicals
  - Cause corrosion and oil degradation.
- Wear debris
  - The accumulation of gear wear debris promotes oil degradation.

- Wear debris embeds in babbitt bearings and destroys the surface.
- Wrong oil
  - If viscosity is too low, oil film is too thin.
  - If viscosity is too high, gearbox efficiency decreases.
  - If additives are too chemically active, corrosion and polishing wear result.
  - If additives are not chemically active enough, the risk of scuffing increases.

Abrasion

Hard particles in the oil are the most frequent cause of gear tooth wear. Abrasion is the cutting of metal by hard particles or a rough surface. Abrasion is readily recognized by parallel furrows in the direction of sliding. If the abrasion is caused by hard particles, such as sand or grinding grit in the oil, it is called three-body abrasion. Prevention is obvious—remove the hard particles. If abrasion is caused by one tooth cutting the opposing one, such as when a hard, sharp gear tooth tip slides against a softer root, two-body abrasion occurs. The result is the same as filing. Smoother surfaces and chamfered tips will prevent this type of abrasion.

Rolling element support bearings suffer when solid particles and water contaminate the oil. The hard particles cause nicks and dents on the raceway and the rolling elements and abrade the sliding areas, such as between the cage and the rolling element bearings. The dents shorten life and start contact fatigue failure. Water in the oil accelerates crack growth, thus shortening fatigue life. Ideally, the rolling element bearings would be less stressed if they had their own clean and separate oil supply and didn't have to run on the oil contaminated with gear wear particles.

Other well-known tribology problems are caused by improper metallurgy, excessive loads, speeds and temperatures and misalignment.

Detection of Contaminated Gear Oil

The degree of contamination and the type of contaminants are usually determined by an oil analysis laboratory. However, a rough idea of contamination can be obtained on site using a simple process.

Collect some oil in a clean, tall, narrow glass bottle, (a 2-oz. olive bottle is about right). Look at the oil with a bright light. If it is hazy, it is probably contaminated with water. Smell the oil. If it has a bad odor compared to fresh oil, it is probably oxidized. Now set the bottle aside for at least two days and allow the dense contaminants to settle; then examine the material in the bottom. Metal wear fragments will be present and if ferrous, they will move with a magnet. Water will be a clear layer; sand and clay will also be on the bottom, but will not move with a magnet. To get a better look, carefully pour off most of the oil above the contaminants, add clean paint thinner, shake up and allow the contaminants to settle again. *Any* visible magnetic fragments, sand or water is bad news.

Reducing Contamination

Contamination can be reduced and oil cleaned by following some simple procedures.

- Change used oil frequently.
- Filter oil with a circulating system with a full-flow, 3-micron filter and reduce ingestion of dirt and water by means of a fine air filter on the vent or breather tube.
- Before operating a new gearbox, clean the gears and gearboxes of all manufacturing debris by vigorous flushing. Grinding and cutting chips, welding splatter, sand from sand blasting, steel shot,

Table 4 — Common Wear Problems Related to Lubricants & Hydraulic Fluids*

Names of Wear		Definition	Susceptible Machine Parts	Conditions Promoting Wear	
	Other				Unaided Eye
Mild Adhesion	Normal[a]	Generally, transference of material from one surface to another due to adhesion and subsequent loosening during relative motion. Mild adhesion involves transfer and loosening of surface films only.	All.	• Moderate loads, speeds & temperatures. • Good, clean, dry lubricants. • Proper surface finish.	• Low rates of wear. • No damage. • Deeper original grinding marks still visible.
Severe Adhesion	• Scuffing • Galling • Scoring[b]	Cold welding of metal surfaces due to intimate metal-to-metal contact.	• Piston rings and cylinder barrels. • Valve train. • Rolling & sliding bearings. • Gears. • Cutting tools. • Metal seals. • Chains.	• High loads, speeds and/or temperatures. • Use of stainless steels or aluminum. • Insufficient lubricant. • Lack of antiscuff additives. • No break in. • Abrasive wear.	• Rough, torn, melted or plastically deformed metal, broad or streaks. • High temperature oxidation. • High friction, high rates of wear. • Possible seizure.
Abrasion[e]	• Cutting • Scratching • "Wire Wool" damage • Gouging • Scoring	Cutting and deformation of material by hard particles (3-body) or hard protuberances (2-body).	All surfaces in relative motion.	• Hard particles contaminating oil. • Insufficient metal hardness. • Hard metal with rough surface against soft metal.	• Scratches or parallel furrows in the direction of motion, similar to "sanding." • High rates of wear.
Erosion	• Solid Particles • Impact Erosion	Cutting of materials by hard particles in a high-velocity fluid impinging on a surface.	• Journal bearings near oil holes. • Valves. • Nozzles.	• High-velocity gas or liquid containing solids impinging on a surface[g].	• Smooth, broad grooves in direction of fluid flow. • Matte texture, clean metal. • Similar to sandblasting.
Polishing	Bore Polishing	Continuous removal of surface films by very fine abrasives.	• Cylinder bores of diesel engines. • Gear teeth. • Valve lifters.	• Combination of corrosive liquid and fine abrasive in oil[h].	• High wear, but a bright mirror finish. • Wavy profile.
Contact Fatigue	• Fatigue Wear • Frosting • Surface Fatigue • Spalling	Metal removal by cracking and pitting due to cyclic elastic stress during rolling and sliding.	• Rolling & sliding bearings. • Valve train parts. • Gears.	• Cyclic stress over long periods. • Water, dirt in oil. • Inclusions in steel.	Cracks, pits and spalls.
Corrosion	• Chemical Wear • Oxidative Wear • Corrosive Film Wear	Rubbing off of corrosion products on a surface.	• All bearings. • Cylinder walls. • Valve train. • Gears. • Seals and chains.	• Corrosive environment. • Corrodible metals. • Rust-promoting conditions[j]. • High temperatures.	Corroded metal surface.
Fretting Corrosion	• False Brinelling • Fretting • Friction Oxidation	Wear between two solid surfaces experiencing oscillatory relative motion of low amplitude.	• Vibrating machines. • Bearing housing contacts. • Splines, keys, couplings. • Fasteners.	Vibration-causing relative motion.	• Corroded, stained surfaces[k]. • Loose colored debris around real contact areas. • Rouge (Fe_2O_3) colored films, debris, grease or oil for steel.
Electrocorrosion	• "Erosion" • Electrical Erosion • Electrochemical Wear • Electrical Attack	Dissolution of a metal in an electrically conductive liquid by low amperage currents.	• Aircraft hydraulic valves. • Hydraulic pumps and motors.	• High-velocity liquid flow causing streaming potentials. • Stray currents. • Galvanic metal combinations.	• Local corroded areas. • Black spots such as made by a small drop of acid. • Corroded, worn metering edges.
Electrical Discharge	• Electrical Pitting • Sparking	Removal of metal by high amperage electrical discharge or spark between two surfaces.	• Bearings in high-speed rotating machinery, such as compressors, atomizers. • Static charge producers.	• High-speed rotation. • High-velocity, two-phase fluid mixtures. • High potential contacts. • Sparks.	Metal surface appears etched. In thrust bearings, sparks make tracks like an electrical engraver.
Cavitation Damage[m]	• Cavitation Erosion • Fluid Erosion	Removal of metal by bubble implosion in a cavitating liquid.	• Hydraulic parts, pumps, valves, gear teeth. • Cylinder liners, piston rings. • Sliding bearings.	Sudden changes in liquid pressure due to changes in liquid velocity or to shape or motion of parts[n].	• Clean frosted or rough-appearing metal. • Deep rough pits or grooves.

* From "Recognition and Solution of Some Common Wear Problems Related to Lubricants & Hydraulic Fluids," *Lubrication Engineering*, February, 1987. Reprinted with permission.

Symptoms		Prevention	
Microscopically	Oil Analysis	Mechanical Changes	Lubricant Changes
• Smooth microplateaus among original grinding marks. • Slight coloration due to films.	• 1–5 ppm wear metals by emission spectroscopy. • Low % solids by filtration. • Metal salts (oxides, sulfides, phosphates, etc.) in wear fragments by X-ray diffraction.	None.	None.
• Rough irregular surface. • *Metal from one surface* adhering to other surface by spot tests or microprobe analysis.	Large metallic wear fragments *of irregular shape*[c].	• Reduce load, speed and *temperature*. • Improve oil cooling. • Use compatible metals. • Apply surface coatings such as phosphating. • Modify surface, such as ion implantation[d].	• Use more viscous oil to *separate surfaces*. • Use "extreme pressure" additives, such as a sulfur-phosphorous or borate compound.
• Clean furrows, burrs, chips. • Embedded abrasive particles. • In sliding bearings with soft overlay, embedded particles cause polished rings.	• High metal content in oil and high silicon (>10 ppm) by emission spectroscopy. • High % solids by filtration. • Chips and burrs by ferrography.	• Remove abrasive by improved air and oil filtering, clean oil handling practices, improved seals, flushing and frequent oil changes[f]. • Increase hardness of metal surfaces.	• Use oil free of abrasive particles. • Use more viscous oil.
• Short V-shaped furrows by scanning electron microscopy. • Embedded hard particles.	Elements of hard particles by emission spectrography. Chips and burrs by ferrography.	• Same as above. • Reduce impact angle to less than 15°.	Same as above.
Featureless surface except scratches at high magnification by electron microscopy.	Combination of fine metal corrosion products and fine abrasive by X-ray diffraction.	None.	• Choose less chemically active additive. • Remove corrosive contaminant. • Remove abrasive.
• Combination of cracks and pits with sharp edges. • Subsurface cracks by metallographic cross section. Numerous metal inclusions.	• Particles of metal with sharp edges. • Metal spheres by electron microscopy.	• Reduce contact pressures and frequency of cyclic stress. • Use high quality vacuum melted steels. • Use less abusive surface finish.	• Use clean, dry oil. • Use more viscous oil. • Use oil with higher pressure viscosity coefficient[i].
Scale, film, pits containing corrosion products. Dissolution of one phase in a 2-phase alloy.	• Detection of corrosion products of worn metal. • Detection of anions, such as chlorine, by X-ray *fluorescence*.	• Use more corrosion resistant metal (not stainless). • Reduce operating *temperature*. • Eliminate corrosive material.	• Remove corrosive material such as too chemically active additives and contaminates. • *Use improved corrosion* inhibitor. • Use fresh oil.
Thick films of oxide of metal. Red and black for steel.	Indentify metal oxide (∝ Fe_2O_3 for steel) by X-ray diffraction.	• Reduce or stop vibration by tighter fit or higher load. • Improve lubrication between surfaces by rougher (then honed) surface finish.	• Use oil of lower viscosity. • Relubricate frequently. • Use oxidation inhibitors in oil.
Corrosion pits, films, dissolution of metals.	• Detection of corrosion products. • Electrically conductive liquids[l].	• Decrease liquid velocity and velocity gradients. • Use corrosion-resistant metals. • Eliminate stray currents. • Use nongalvanic couples.	Decrease or increase electrical conductivity of lubricants of hydraulic fluids.
• Pits near edge of damage, showing once molten state, such as smooth bottoms, rounded particles, gas holes. • Rounded particles near pits welded to surface.	Detection of large rounded particles by microscopic examination of filtrate or in ferrography.	• Improve electrical insulation of bearings. • Degauss magnetic rotating parts. • Install brushes on shaft. • Improve machine grounding.	Use oil of higher electrical conductivity.
• Clean, metallic bright rough metal, pits. • Removal of softer phase from 2-phase metal[o].	Observation of large chunks or spheres of metals in oils.	• Use hard tough metals, such as tool steel. • Reduce vibration, flow velocities and pressures. • Avoid restrictions and obstructions to liquid flow.	• Avoid low vapor pressure, aerated, wet oils. • Use noncorrosive oils.

grinding grit, such as silicon carbide, paint chips and fibers are all frequently found in *new* gearboxes.

• Clean and assemble gearboxes in a dedicated clean room, not a dusty shop.

• Filter fresh oil as it is added to a gearbox.

This kind of simple, basic practice should greatly reduce the risk of lubricant contamination and consequent gear wear and failure. ○

References:

1. Radovich, J.L. "Gears," *The Handbook of Lubrication, Theory and Practice of Tribology, Vol. 2, Theory and Design*. E. Richard Booser, ed. CRC Press, Boca Raton, FL, 1984, pp. 539–564.

2. Errichello, R. "Lubrication of Gears, Parts 1–4," *Lubrication Engineering*, 46, Jan, pp. 11–13, Feb, pp. 117–121, Mar, pp. 181–185, Apr, pp. 230–237, 1990 or *Gear Technology*, Vol. 8, Nos. 2, 3, 4, 1991, Mar/Apr, pp. 18–26, May/June, pp. 18–22, July/Aug, 14–22.

3. *Standard Nomenclature of Gear Tooth Failure Modes*. American Gear Manufacturers Association, Arlington, VA, ANSI/AGMA 110.04, Aug, 1980.

4. Godfrey, D. "Clean, Dry Oil Prolongs Life of Lubricated Machines," *Lubrication Engineering*, 45, Jan, 1989, pp. 4–8.

Douglas Godfrey *is the principal in Wear Analysis, a tribology consulting firm in San Rafael, CA. He has over 50 years' experience in tribology research and study and is a well-known author and lecturer in the field.*

Notes for Table 4

a — Mild adhesion is a desirable wear condition.
b — Scoring is not recommended because it implies a scratch or furrow cut by abrasion.
c — Emission spectroscopy usually misses large (> 5 micron) wear fragments.
d — Increasing metal hardness does not reduce scuffing.
e — The most common wear problem.
f — Do not shot peen, bead or sandblast any surface in a lubricated machine because abrasive cannot readily be removed completely.
g — Sandblasting embeds sand in surfaces.
h — An example of polishing combination in oil is active sulfur additive and Fe_2O_3 (jeweler's rouge).
i — A new additive reduces promotion of contact fatigue by water; some extreme pressure additives are suspected of promoting contact fatigue.
j — Rust (hydrated iron oxide $Fe_2O_3H_2O$) is common corrosion product of ferrous metal.
k — Damage on one surface is mirror image of damage on other.
l — Highly compounded oils can be electrically conductive—or electrolytes; phosphate ester hydraulic fluids are conductive.
m — Not to be confused with pump cavitation, which is a different phenomenon.
n — Corrosion and abrasive in oil increase cavitation damage.
o — Graphite phase in cast iron susceptible to removal by cavitation.

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