Fundamentals of Gear Lubrication

Introduction

Gear teeth may operate in three conditions of lubrication: boundary, mixed and full film. Boundary lubrication occurs when gear sets start or stop. If gear sets were operated under condition of boundary lubrication for extended period of time, wear would be rapid and severe. With increased relative motion the gearing moves to mixed lubrication mode. With further increase in motion full film lubrication mode is attained. Considering contacting condition of two gear teeth in mesh, the contact starts at high relative sliding and some rolling. The sliding decrease toward the pitch line. At the pitch line the only motion is rolling. After the pitch line, sliding again takes place and increase until the gear leave mesh. Viscosity of the lubricant does not remain constant through the meshing cycle, but increase rapidly with pressure. At the high-pressure hertzian region the lubricant is virtually a rigid solid.

Gear Lubricants

Gear lubrication requires an oil that can reduce wear, protect against corrosion and rust, resist oxidation degradation and shear down of itself, inhibit the formation of foam and separate water easily. The variety of gear systems requires that lubricants are application specific.

*Inhibited oil:*
These are mineral oils containing rust and oxidation (R&O) inhibitors and perhaps anti-foaming or anti-wear agent.

*Extreme Pressure (EP) oils:*
These are inhibited oils with added extreme pressure additives. The EP agent is a friction modifier, and there are two basic types of agents:

*Chemically Active:*
Chemically active additive sulfur phosphorous, which reacts with gear tooth surface material under high temperature to form thin film of easily, sheared material. The second type of EP agent is solid lubricant in suspension. The solid particles (such as graphite, molybdenum disulfide, borate, etc.) get between tooth surfaces and prevent metal-to-metal contact. If bearings are to be lubricated from the same system, some caution is required. Active EP agents must be noncorrosive to bronze if any is present in the bearing. Solid lubricant additives may reduce internal clearance in low clearance, precision bearings causing high temperature, self-loading and probable failure.

*Compounded oil:*
These are usually steam cylinder stocks compounded with acid less fat as lubricity additives to reduce friction. These oils are primarily used in warm gear drives.
Open Gear Compounds:
These are heavily bodied lubricants for large, slow speed, heavily loaded gears. These lubricants contain some additives that enable them to adhere to gear teeth and resist being thrown off or squeezed out of mesh.

Greases:
These are liquid lubricants thickened with soap thickeners. The soap holds the liquid portion and releases it as necessary. Suitable only for low speed, low load application because it dose not circulate well, and relatively poor coolant.

Viscosity in Gear Lubricants:
In selecting gear lubricant viscosity, the higher the viscosity, the greater the protection against the various gear tooth failures. However, the viscosity must be limited to avoid excessive heat generation and power loss from churning and shearing of lubricant by high-speed gears or bearings. The operating temperature of the gear drive determines the operating viscosity of the lubricant.

Application of Gear Lubricant
Lubricants can be applied to gear teeth in variety of ways and the methods primarily depend on pitch line velocity. Low speed gear systems are usually lubricated by splash system while high-speed gears use pressure-fed lubrication system.

Splash Lubricating Systems:
are simplest but they are limited to pitch line velocity of ~1000m/min. Lubricant is applied by allowing the gear to run partially submerged in the oil. The gear should dip into the oil bath for about twice the tooth depth to provide adequate splash. Oil picked up by the gear is then carried in the gear mesh where it is needed.

Pressure-Fed Lubrication Systems:
above 1500 m/min pitch line velocity, a pressure fed system lubricates most gears. In this system oil is taken from the gear case, pumped through a filter, heat exchanger, pressure relief valve, and delivered back to the unit under pressure. Oil is applied to the system by spray nozzles in a manifold.

Gear Metallurgy
Most common material used for commercial gearing systems is steel. Different hardening methods are used to achieve the desired hardness. Different carbon content determines what hardness level can be achieved, Carburizing, Nitriding of flame or induction hardening are also used. Nonferrous gear materials, bronze is most common. Frequently used in warm gearing systems due to dissimilar metals that does not size and score under the load and high sliding contacts or acting as sacrificial gear.

Lubrication Related Failure Modes
In determining mode of failure in gear systems a distinction has to be made between primary and secondary modes of failure. For example pitting or scuffing may cause the gear teeth to deteriorate and generate a dynamic force, which in turn cause the gear teeth to fail by bending fatigue. In this case, the bending failure is secondary and not directly related to lubrication, whereas pitting or scuffing are primary failure modes.
**Overload**
- Brittle Fracture
- Ductile Fracture
- Plastic deformation
  - Cold Flow
  - Hot Flow
  - Indentation
- Bending

**Bending Fatigue**
- Low Cycle Fatigue: <1000 cycles to failure
- High cycle fatigue: >1000 cycles to failure

**Hertzian Fatigue**
- Pitting
  - Initial
  - Superficial
  - Destructive
  - Spelling
- Micropitting
  - Frosting
  - Gray Staining
  - Peeling
- Subsurface Fatigue

**Wear**
- Adhesion
  - Normal
  - Break-in
  - Mild
  - Moderate
  - Severe
  - Excessive
- Abrasion
  - Scoring
  - Scratching
  - Plowing
  - Cutting
  - Gouging
- Corrosion
  - Fretting
  - Corrosion
  - Cavitation
  - Polishing

**Scuffing**
- Scoring
- Galling
- Seizing
- Welding
- Smearing
  - Initial
  - Moderate
  - Destructive

**Pitting**: Pitting is a fatigue phenomenon that occurs when a fatigue crack initiates either at the surface of a gear tooth or at a small depth below the surface. The crack usually propagates for a short distance in the direction almost parallel to the tooth surface before turning or branching to the surface after repeated cycle. When cracks are grown to the extent that they separate a piece of the surface material, pit is formed. If several pits grow together, the resulting large pit is often referred to as a spall.

Contamination from water in lubricant could promote pitting through hydrogen embrittlement of the metal and abrasive particles in lubricants cause pitting by indenting and scratching the tooth surface, causing stress concentrations, and disrupting the lubricant film. Pitting problem in gear systems could be avoided by taking different measures. Reducing contact stress by reducing load will minimize fatigue crack generation. The gear metallurgy and surface nature also affects pit generation. A smooth surface by careful grinding and properly heat-treated gear will reduce pitting.

**Micropitting**: Gears that are surface hardened (carburized, nitride, induction hardened and flame hardened) pitting may occur in smaller scale, typically only 10µm (400µin) deep. To the naked eye the area where micropitting has occurred appear frosted, and frosting is a popular term of micropitting.

**Adhesion**: adhesive wear is classified as mild if it is confined to the oxide layers of the gear tooth surfaces. If however, the oxide layers are disrupted and bare metal is exposed, the transition to severe adhesive wear occurs. Severe adhesive wear is termed Scuffing. Gears operating at low speed and high load are especially prone to adhesive wear because of lubricant operating in the boundary or mixed lubrication mode. For low speed gears increased lubricant viscosity will decrease significantly low speed adhesive wear. Chemically active EP additives (sulfur-phosphorous) can be detrimental in low speed and high load gears causing high wear rate.

**Abrasion**: abrasive wear in gear sets is caused by contamination of lubricants by hard, sharp-edged particles. Contaminants in gear set can be internally generated, ingested through breathers and seals or added during maintenance. Internally generated particles are wear particles in the system. These wear particles are especially abrasive because they become work hardened when they are trapped between gear teeth. Abrasive sand and dirt particles can be ingested through breathers and seals. Abrasive wear due to foreign contaminants or wear debris is called three-body abrasion and is a common occurrence. Inspection of gear tooth surface in case of abrasive wear mode will show scratching of the surface. The use of filtration in cases where circulating-oil systems are used will greatly reduce particle contamination. The use of oil-tight seals and filtered breather vents will minimize ingested contaminants.

**Scuffing**: Occurs in gear teeth when they operate in boundary lubrication condition. If the lubricant film is
insufficient to prevent large amount of metal-to metal contact, which breaks the oxide films that usually protects the gear surface, bear metal surfaces may weld and tear. This results in catastrophic damage of the gear teeth. The solid phase welding of the gear surfaces results due to extremely high frictional heat. Inspection of gear teeth surface will show torn surfaces and metal transfer from one surface to other. Gears are most vulnerable when they are new and their surfaces are not smoothened due to running-in. Sulfur phosphorous compounds additives are used in lubricants as antiscuff additives. These additives form protective oxide layer by chemically reacting with the gear teeth surface at local point of high temperature. The film of iron sulfide and iron phosphate have a high melting points, allowing them to remain as solids on the gear tooth surface even at high contact temperatures. Scoring of a gear has a similar effect as scuffing in gearsets.

Accurate gear teeth, rigid gear mounting and good alignment will reduce the chance of scuffing. Maintain lubricant temperature low by using heat exchangers in the case of circulating-oil systems will reduce scuffing. Use nitrided steel for maximum scuffing resistance. Do not use stainless steel or aluminum for gears if there is a risk of scuffing.

**Plastic flow**: Gear tooth deformation caused by heavy loads stressing the surface material beyond its elastic limit. Usually occurring in softer metals, the surface material may be extruded out along the ends of the teeth and along the tips causing fins to form.

**Wear Particle Analysis in Gear Systems**

**Normal Sliding**

In normal sliding of gear teeth surfaces the type of wear particles that are generated are rubbing wear particles Fig 1. with particle diameter less than 10µm to 15µm and have a laminar shape and a smooth surfaces. During the running of a new gear, the wear particles that are generated are larger than rubbing wear particles and have a different generation mechanism. All machined surfaces are rough and have asperities. When harder surface slider over the softer surface, the softer asperities either fracture immediately or deform. In break-in wear a shear mixed layer is created in which the surface deform in super ductile behavior that produce a smooth wear track. As long as this surface is stable the surface will wear normally.

![Fig 1 Normal Rubbing](image1)

![Fig 2 Cutting wear](image2)

The rate at which asperities are removed by sliding process and the mechanism of removal depend on the initial surface roughness, the applied load and mechanical properties of the asperities.

**Cutting Wear**

Cutting Wear particles are generated when a harder surface penetrates a softer surface and remove a chip, much like a machine tool does. When hard abrasive particles are present in the lubrication system, some of these particles may become embedded on the surface and cuts the softer surface. Gear operating at high load and low speed will be more affected by the presence of abrasive contaminants because it operates under boundary lubrication mode. The hardness and size of the abrasive particle is important to the rate of
abrasion of the gear surface and the sizes of wear particles generated.

Fatigue Wear

Due to repeated rolling action on gear tooth at the pitch line, fatigue platelets particles that are flat and smooth surfaced with a major dimension to thickness ratio of approximately 10:1 are generated. The mechanism of wear generation is based on crack nucleation and growth. Cracks are nucleated at the subsurface of the gear tooth and propagate parallel to the surface. When these cracks finally shears to the surface at certain weak positions, long and thin wear sheets are generated. The mechanism is known as delamination wear. The thickness of the wear particle is controlled by the location of the subsurface crack growth, which is controlled by the load on the surface. Laminar platelets are also generated when wear particles are entrapped in gear mesh. These particles will frequently have holes and are between 20 and 50µm in size with a thickness ratio of 30:1.

Black Oxide Particles:

During scuffing, when the lubricant film is insufficient to prevent large amount of metal to metal contact, which breaks the oxide film protecting the gear surface, bear metal surface may weld and tear. When this happens black oxide particles are generated due to the extreme heat generated during the welding and the tearing action of the surface.

Red Oxides (Rust)

Red oxide particles in gear system are generated when there is water or moisture in the lubricant resulting in corrosion. If red oxide particles are present during wear particle analysis it is recommended that water test is performed.

Summary:

Gear systems undergo a diverse set of lubrication failure mechanisms, each with their own unique set of
root causes, and unique wear debris generation. Monitoring gearboxes with lubricant analysis provides a powerful method of detecting the onset of severe wear, and with wear debris analysis, root cause diagnostics.

References

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