TROUBLESHOOTING GEAR DRIVES

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VISUAL INSPECTION OF GEARS AND SHAFTS CAN DIAGNOSE AND PREVENT FAILURES.

THE FUNCTIONS OF AN INDUSTRIAL POWER transmission gear drive are to multiply and reliably transmit torque and rotary motion between a prime mover and the driven equipment. The gear drive is one part of the power system which has to accommodate certain load characteristics peculiar to a specific application.

Properly specified, designed, and manufactured components, as well as operational considerations, constitute an equation whose sum is effective and reliable gear drive operation. Operational considerations include proper loading, installation and support, alignment, and maintenance. If any factor is incorrect or missing, then gear drive components, including the gears and shafts, can exhibit abnormal distress. Inefficient operation, increased operating expenses, shortened life, or unexpected catastrophic failure can result.

Careful planning and working with gear drive manufacturers experienced in your applications will help ensure that a gear drive system is properly specified, designed, manufactured, and installed. Getting to that point is a good start toward ensuring reliable gear operation. However, the other factors are just as important to this equation. Poor maintenance practices, abrasive or corrosive contaminants, overloads, increased output demands or over-motoring, for example, can result in poor tooth contact, preloaded bearings, or lubrication leakage, among other things—all of which can lead to distressed gears and shafts and their associated problems.

A good maintenance program should include a strong emphasis on preventive maintenance, including checking for proper alignment and lubrication, periodic changing of lubricants, and making sure that noise, vibration and temperature parameters are within recommended guidelines.

Visual inspection of the gears and shafts is also very important. Learning how to read the telltale signs of distress can lead plant engineers and maintenance personnel to the proper corrective measures and prevent failures. However, if a breakdown should occur, failure analysis based on "reading" the failed part can help solve the problem in subsequent operations.

This article will focus on describing distress and failure modes of gears and shafts, their probable causes, and how to solve the related problems.

NONUNIFORM LOADS

The elastic deflection of gears, shafts, bearings, and their supporting structures determines to a large degree the manner in which mating gears will be aligned to one another under operating loads. These deflections, along with manufacturing tolerances, result in loads being nonuniformly distributed across the gear tooth surface, thus stressing some areas of the tooth more highly than others. In the American Gear Manufacturers Association (AGMA) rating formulas, this effect is recognized by incorporating load distribution factors. This, along with other "errors" present in the system, can cause tooth surface distress or tooth fracture.

GEAR DISTRESS AND FAILURE MODE CLASSIFICATIONS

Distress or failure of gears may be classified into four categories: surface fatigue (pitting), wear, plastic flow, and breakage. The appearance of the various distress and failure modes can differ between through-hardened and surface-hardened gear teeth. These differences result from the different physical characteristics and properties and from the residual stress characteristics associated with the surface-hardened gearing.

Surface fatigue

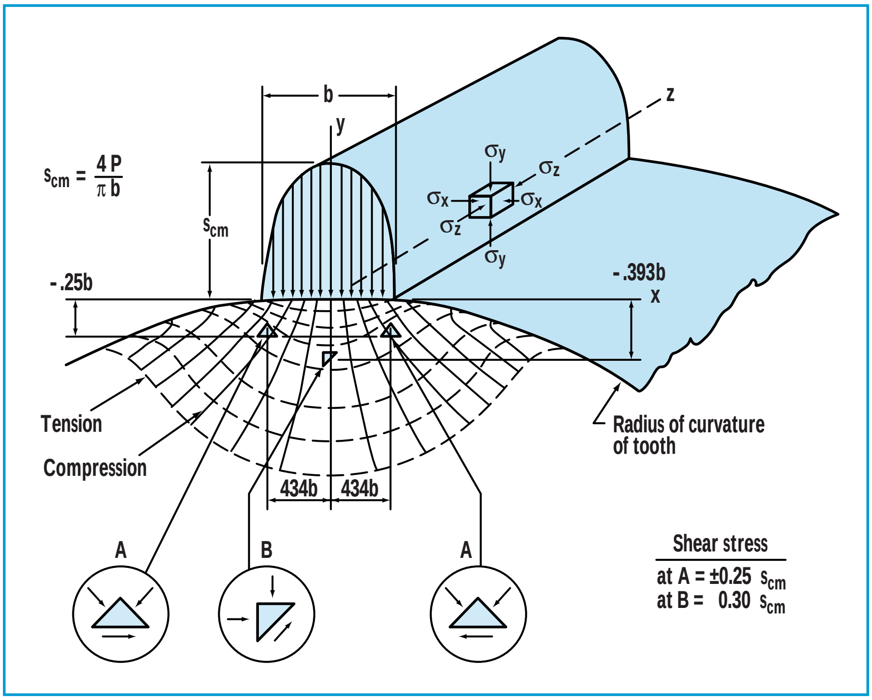
Surface fatigue is the failure of a material as a result of repeated surface or sub-surface stresses beyond the endurance limit of the material. **Figure 1** indicates the theoretical mutual Hertzian stresses occurring when a gear and pinion mesh. There are compressive stresses at the surface and unidirectional and bidirectional subsurface shear stresses.

Pitting. Pitting is a form of surface fatigue which may occur soon after a gear drive begins operation. Pitting types include initial, destructive, or normal.

Initial pitting, or corrective pitting, is caused by local areas of high stress due to uneven surfaces on the gear tooth. This type of pitting can develop within a relatively short time, reach a maximum, and, with continued service, polish to a lesser severity. It is most prominent in through-hardened gearing but is sometimes seen in surface-hardened gears as well.

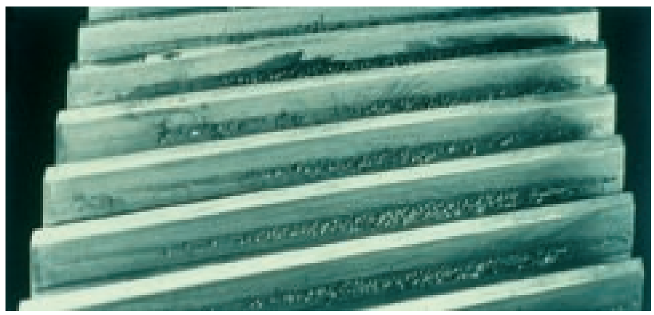
The shape of a classical pit appears as an arrowhead pointing in the direction of oncoming contact. The pit is steep on its back side.

For most through-hardened gears, initial pitting is considered normal and no remedial action is required. Where necessary, initial pitting can be reduced by special tooth finishing means and sometimes by reducing loads and speeds during the break-in period. In some special, critical applications, teeth are copper- or silver-plated.



1. The theoretical mutual Hertzian stresses occur when a gear and pinion mesh.

Destructive, or progressive, pitting usually results from surface overload conditions that are not alleviated by initial pitting. It usually starts below the tooth pitchline in the dedendum portion of the tooth and progressively increases in both size and the number of pits until the surface is destroyed. Destructive pitting occurs in both through- and surface-hardened gears. Corrective measures include reduction of the drive loading, improving lubrication type and viscosity, upgrading the gearing, or increasing the gear drive size.



2. Normal dedendum pitting prior to pit-rim wear is shown on a fully loaded through-hardened gear.

Normal dedendum pitting manifests itself as small or modest sized pits, covering the entire dedendum portion of the tooth flanks. Continued operation results in pit rims being worn away with virtually no further pitting occurring. Normal dedendum pitting results when loads are at or close to maximum allowable surface loading values. **Figure 2** shows the tooth appearance in the pitting phase prior to pit-rim wear.

The dedendums are most vulnerable to this phenomenon because of the preferential orientation of surface micro-cracks along the tooth profile. The orientation of the cracks in the dedendum of both the pinion and gear are such that oil is readily trapped in them as the contact rolls over the surface openings. These cracks then propagate rapidly into pits by hydraulic pressure.

In the addendum, the oil is forced out of the micro-cracks before the contact progresses far enough to seal off the surface openings. Thus hydraulic propagations of the crack are almost nil and few pits are formed in this region.

At loadings currently used for industrial surface-hardened gears, pitting is much less prevalent than with through-hardened gears.

Spalling. Spalling is a term used to describe a large or massive area where surface material has broken away from the tooth. Spalling is caused by high-contact stresses possibly associated with proud areas of the tooth surface. Excessive internal stresses from improper heat treatment can cause spalling in surface-hardened gears.

In through-hardened and softer material, spalling appears to be a massing of many overlapping or interconnected large pits in one locality. In surface-hardened gears it manifests itself as the loss of one or several large areas of material. Frequently the bottom of the spall appears to run along the case-core interface.

Case crushing is another form of spalling associated with heavily-loaded case-hardened gears. It appears as long, longitudinal cracks on the tooth surface. Material along the cracks may subsequently break away. It often occurs suddenly, without warning signs, on only one or two teeth of the pinion or gear. The cracks differ from those of pits in that they not only extend below the hard case, but most of the depth is in the softer core material. Failure may be due to insufficient case depth or core hardness, high residual stresses, or too high loading.

If any type of spalling is evident, the drive manufacturer should be contacted for an application review and a determination of remedial action.

Wear

Wear describes the loss of material from the contacting surface of a gear. There are varying degrees of wear ranging from light to moderate to excessive. Degrees of wear are measured in terms of thousandths of an inch per million, or 10 million, contact cycles.

Degrees of wear. Polishing or light wear is the slow loss of metal at a rate that will little affect gear performance during the life of the gear. It is a normal, very slow wear-in process in which asperities of the contacting surfaces are gradually worn until very fine, smooth, conforming surfaces develop. Light wear can occur by either abrasive or adhesive mechanisms when thin oil films, or what is known as boundary lubrication conditions, prevail. Such conditions usually occur on slow-speed applications. Abrasive and adhesive wear are described more fully in the next section.

Moderate wear, sometimes called normal wear, progresses at a rate slow enough that it will little affect satisfactory performance of the gears within their expected life. Metal is removed from the entire tooth surface but generally more from the dedendum areas. The operating pitch line begins to show as an unbroken line. Surface-hardened gears manifest less wear than do through-hardened gears.

Moderate wear is affected by the lubrication regime, the nature of the load, the surface hardness and roughness, and the contaminants present in the lubricating oil that might promote abrasive or corrosive wear. Moderate wear is normal, and remedial action other than maintenance of the lubrication system is not usually required. Filtering and more frequent lube changes are appropriate if contaminants are present.

Excessive or destructive wear is surface destruction that has changed the tooth shape to such an extent that meshing action is impaired and the gear life is appreciably shortened. Continued operation results in still greater wear and may eventually lead to tooth breakage. The occurrence of such wear early in the operational history can be caused by excessive loads, contaminated oil, or too light an oil viscosity. Excessive wear incurred over a long period of operational history would be considered an advancement of normal wear from the moderate to the excessive degree and may not be detrimental to the operation of the gear drive.

Types of wear. Wear types can be classified into two major categories: abrasive and adhesive. Abrasive wear, sometimes called cutting wear, occurs when hard particles slide and roll under pressure across the tooth surface. Sources of hard particles include dirt in the housing, sand or scale from castings, metal wear particles from gear teeth or bearings, and particle infiltration into the housing during maintenance and operations.

Adhesive wear results from high attractive forces of the atoms composing each of two contacting, sliding surfaces. Teeth contact at random asperities, and a strong bond is formed. The junction area grows until a particle is transferred across the contact interface. In subsequent encounters, the transferred fragment fractures or fatigues away, forming a wear particle.

Scuffing is an adhesive wear type occurring at normal temperatures where smooth burnishes, appearing as radial striations, are observed in the direction of sliding on the tooth surfaces. It can appear where tooth pressures are high and oil films are in the boundary regime, and where speeds are slow enough that high-contact temperatures do not occur. This type of wear can be reduced by increased oil viscosities, where applicable, or by reduced load.

Scoring is another type of wear. Also referred to as galling or seizing, scoring is the smearing and rapid removal of material from the tooth surface, resulting from the tearing out of small particles that become welded together due to oil film and high temperature metal-to-metal contact in the tooth mesh zone. After welding occurs, sliding forces tear the metal from the surface, producing a minute cavity in one surface and a projection on the other. Although initially microscopic in size, scoring progresses rapidly.

Scoring most frequently occurs in localized areas on the tooth where high-contact pressure exists or at the tip or root where sliding velocities and contact temperatures are high. Scoring is caused by high-contact temperature and pressure and marginal lubrication. Scoring can sometimes be prevented by the use of more viscous oil or by an extreme pressure type oil. Localized high-contact pressure can be relieved by improved finishing of the tooth surface. Sometimes profile modifications are required on highly loaded teeth to minimize high localized pressures.

Plastic flow

Plastic flow is the cold working of the tooth surfaces, caused by high-contact stresses and the rolling and sliding action of the mesh. It is a surface deformation resulting from the yielding of the surface and subsurface material. It is usually associated with softer gear materials, although it can occur in heavily loaded case-hardened gears as well.

Cold flow, a plastic flow type, is indicated by the surface material having been worked over the tips and the ends of the gear teeth, giving a finned appearance. Sometimes the tooth tips are heavily rounded over, and a depression appears on the contacting tooth surface.

A gear set change or drive system upgrade is usually required to correct plastic flow wear and failures. Additionally, most plastic flow wear and failures can be eliminated by reducing the contact stress and by increasing the hardness of the contacting surface and subsurface material. Increasing the accuracy of tooth-to-tooth spacing and reducing profile deviations will give better tooth action and reduce dynamic loads.

Breakage

Breakage is the ultimate type of gear failure. A gear tooth is a cantilever plate with tensile stresses on the contact side of the tooth and compressive stresses on the opposite side. If the tensile stresses at the critical location are allowed to exceed the endurance strength of the tooth material, fatigue cracks will eventually develop. With continued operation, the fatigue cracks will ultimately progress to the point where the tooth will break away from the rim material.

Classical tooth root fillet fatigue fracture is the most common fatigue breakage type. The crack originates at the root fillet on the tensile side of the tooth and slowly progresses to a complete fracture either along or across the tooth. **Figure 3** illustrates such a fracture.

3. In a classical tooth root fillet fatigue fracture such as this one, the crack originates at the root fillet on the tensile side of the tooth and slowly progresses.

Fatigue fractures result from repeated bending stress above the endurance limit of the material. If the tooth contact pattern appears even across the entire face, system overloads would be suspect. If the contact pattern is confined or "heavy" in the region of the fracture and at one end of the tooth, an alignment problem of the gearing would be suspect. When the contact is good, the system load must be reduced, or increased strength rating of the gearing is needed. If "localized loading" is indicated, gear alignment should be examined or face modifications considered.

Low-cycle fatigue or impact fractures are due to a low number of high-load fatigue cycles or to a single very high load. With lower hardness, more ductile materials, the fracture is coarse, fibrous, and torn in appearance. With harder, less ductile material, the appearance may be smooth or silky looking.

In some cases, a single overload may break out a tooth or several teeth. A more common occurrence is the plastic yielding of a group of teeth in one load zone from a high-impact load. The plastic yielding displaces the pitch on this group of teeth with respect to the other teeth on the gears, thus subjecting them to abnormally high dynamic loads in subsequent operations. These teeth then develop very rapidly progressing fatigue cracks which soon lead to tooth breakage.

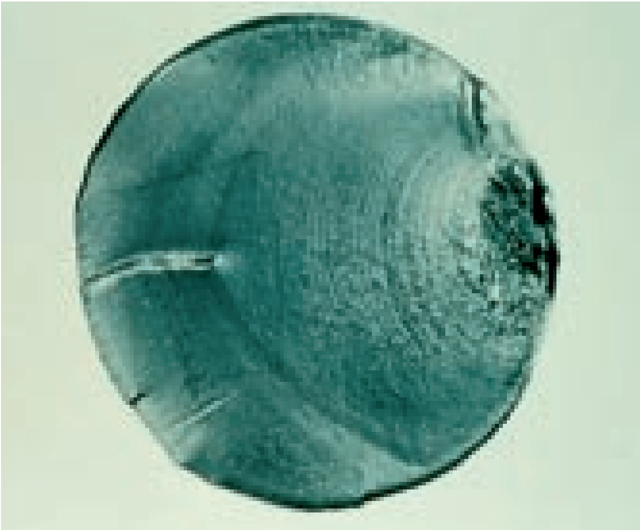
This type of failure is prevented by protecting the gearing from high-impact or transient loadings. This may involve the use of fluid, controlled torque, or resilient couplings in the connected drive train, or it may require better control of the process being performed by the driven equipment.

Sometimes a severe maldistribution of load on gear teeth can occur from damage to associated parts. For example, a severe bearing failure can cause the load to shift to one end of the teeth, resulting in breakage. Similarly, fractures can occur from a shaft that is severely bent or broken.

SHAFT DISTRESS AND FAILURE MODE

The performance of a gear set is dependent on the shafting for the gear elements. The shafting must be rigid enough to prevent excessive deflection that would result in abnormal load distribution on the gear teeth. The fits between the shaft and the bearings, and between the shaft and the mounted gears, must be proper so that mounted members are not too loose nor too tight. Either of the latter conditions can contribute to shaft failure. The shafts must be strong enough to resist permanent yield from shock loads and the reverse bending fatigue loads that are superimposed on the transmitted torsional loads.

The most common type of shaft fracture encountered with gear drives is that resulting from the alternating



4. In general, fractures resulting from bending stresses are perpendicular to the shaft axis.

5. Gear drive lubrication should be changed and periodically sampled to prevent sludging, metal-to-metal contact, or boundary lubrication.

bending stresses that occur as the shaft rotates while transmitting a unidirectional torque load. The fatigue cracks almost always start at some stress raiser on the shaft, such as sharp cornered fillets, snap-ring grooves, fit corners, fretted areas, key or keyway ends, or tool or stamp marks. **Figure 4** shows how these stresses are generally perpendicular to the shaft axis.There may be other situations where an unexpected dynamic load is imposed on the shaft which may be two or three times greater than the operating load.

As **Fig. 5** illustrates, gear drive lubrication should be changed and periodically sampled as a preventive measure.

SUMMARY

This article has described many of the distress and failure modes encountered with mechanical power transmission gear drives. Although they are described as separate distress entities, actual observations can reveal several modes occurring together. These descriptions should help you better understand the nomenclature and "read" the telltale signs you see upon opening the cover of an enclosed gear drive and inspecting the gear sets.

This information should help you initiate any needed corrective measures to ensure reliable, efficient, and long-life gear drive operations. And, when necessary, this knowledge should help you communicate information regarding specific problems to the gear drive manufacturer's service personnel who are familiar with the subtleties of the gear drive design and with the load characteristics of the particular application. TJ

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This article was condensed from the Falk document "Failure Analysis: Gears, Shafts, Bearings and Seals." For a copy of the document, please contact the Falk Corporation, 1-800-545-5215, ext. 108. Or, for additional information, contact the American Gear Manufacturers Association, 1500 King St., Alexandria, VA 22314, and ask for the information sheet "American National Standard: Nomenclature of Gear Tooth Failure Modes, ANSI/AGMA 110.04-1980, Reaffirmed 1989."