Coming Clean on Gearbox Lubrication

Some Dos, Don'ts and Maybes

Jack McGuinn, Senior Editor

It is widely accepted common wisdom that the design and manufacture of gears is among the most complex and difficult disciplines of the industrial arts. From initial conception to machining and finishing, making gears ain't bean-bag. And guess what? Once those gears roll off the assembly line, it doesn't get any simpler. That's because gears — the metal ones at least — require the correct lubrication in order to prevent — or delay as long as possible — such things as wear, scuffing and Hertzian fatigue. (See pg. 73 sidebar, *"Basic Factors to Consider for Gearbox Lubrication,"* from **Bob Errichello**, gear industry consultant (*rlegears@mt.net*) and longtime ***Gear Technology*** technical editor. In a sense, one can say first the gears are manufactured, and specifying the proper lubrication — grease or oil — helps make them work. With that in mind, the following will provide in greater detail information on what makes proper lubrication such an integral part of successful gearbox operation.

Premature, lubrication-related gearbox failure is a painful experience for end-users. And, of course, those end-users are looking for answers to their cause-and-effect questions. Keep in mind, however, that premature gearbox failure can of course be attributed to at least several types of non-lubrication breakdowns.

Gearbox and lubricant failure

"The different major gear failure modes show very different time performance," say Dr. Thomas Tobie and Dr. Klaus Michaelis of the FZG Research Center. (*Ed.'s note: Tobie and Michaelis collaborated on the responses for this article and therefore from this point on will be collectively referred to as FZG.*) "Normal sliding or slow speed wear is a typical continuous failure mode with loss of material during every revolution. For critical operating conditions already after few cycles material loss from the flanks can be found. Before critical conditions of the gear pair are reached some time is required. Pitting, tooth root breakage and flank fracture are failure modes with a distinct range of finite life fatigue strength with failure accumulation in every load cycle and damage after the material strength potential is expired. Micropitting is somewhere in between as a fatigue failure mode, with more or less continuous material loss. Scuffing has no range of time strength; one single critical load cycle can lead to a catastrophic failure within milliseconds. Combined with a very large influence of run-in on scuffing, this failure mode typically occurs, if at all, at the very beginning of the gear life."

Errichello explains that "Time to failure depends on many things, but the most important parameter is the specific failure mode. For example, scuffing is instantaneous, and the most likely time for the initiation of scuffing is the initial start-up when gear tooth surfaces have not yet been smoothed by run-in. On the other hand, fatigue failure modes such as micropitting, macropitting, sub-case fatigue and bending fatigue require time to develop."

As for specific lubricant failure, Errichello lists the following typical causes:

"Selecting the wrong lubricant type, viscosity, or additive package for the gearbox application; oxidation due to too high operating temperature for the base oil type; contamination with solids, water, gases, or other lubricants; and starvation due to inadequate supply."

So how does one go about avoiding such pitfalls that Errichello mentions? What are the central considerations for choosing the correct gearbox lubricant? Who decides which lubricant to use? The following should go a considerable way in answering those questions.

Correct thickness and viscosity are critical

Film thickness is a key consideration in lubrication — both EHL film thickness and specific film thickness.

"EHL film thickness is the thickness of the oil film between Hertzian contacts, such as gear teeth and rolling element bearings," Errichello explains, adding, "Specific film thickness is the ratio of the EHL film thickness to the composite surface roughness of the two contacting surfaces (*see AGMA 925 for definitions and equations*).

(FZG) "EHL film thickness is the distance in micrometers separating the contacting, theoretically smooth surfaces with a lubricant. Specific film thickness is the relation between the EHL film thickness and a relevant value of surface roughness of the mating surfaces, and thus a characteristic value of the lubrication regime from boundary and mixed to full film EHL lubrication."

And what/who dictates which lubricant to use, such as — will it be oil or grease? Are OEMs involved? Designers?

(FZG) "The major tasks of a lubricant in a gear contact are EHL film formation and heat removal. Typically less than 5% of the available lubricant quantity is required for lubricant film formation; more than 95% is required for heat removal. Due to much better heat removal properties of oil compared to grease, the best lubricant for the gear contact would be oil. However, there are many environmental conditions where oil may be not the best choice. These are, e.g. — a missing gear case in open gear drives, difficult and expensive sealing conditions in do-it-yourself machines, or household appliances, etc. The lubricant selection is therefore typically negotiated between manufacturer and user."

"Many applications have specifications that are derived by experience," says Errichello. "Gearbox OEMs usually follow industry standards such as ANSI/AGMA 9005. Ultimately, the gear designer is responsible for ensuring the lubricant selection is appropriate for the gearbox application."

While another issue — viscosity — can be tricky, it is also among the most important considerations regarding lubrication.

"Yes," Errichello confirms regarding 'the V word'; "Firstly, the EHL film thickness must be adequate, and it depends strongly on the base oil viscosity. Secondly, the viscosity must be appropriate for the gear pitch line velocity, which strongly influences the EHL film thickness. Too low viscosity results in inadequate EHL film thickness, whereas too high viscosity results in overheating and low efficiency."

(FZG) "Lubricant viscosity is one important consideration. However, today often a compromise between highest gear load capacity and lowest no-load losses is required. Important considerations are also the base oil type and the additive system. Base oil type strongly influences contact friction losses and oil ageing properties. Additive type and concentration have different but significant influence on the failure modes — especially in the range of boundary and mixed lubrication where many gears operate."

Lubrication and high-tech manufacturing

Given gear lubrication's importance and complexity in any number of ways (not to mention *bearing* lubrication — but we're not going there this trip), might mechatronics play an expanding role in removing some of the guesswork attendant to lubricant maintenance and replacement issues?

Errichello: "Yes. Current technology provides all that is needed to maintain lubrication quality. Mechatronics allows gearbox designers to integrate the mechanical design of the gearbox with electronics to achieve effective condition monitoring."

(FZG) "Online vibration-based condition monitoring systems are (already) used in wind turbine applications and (have externally monitored them for quite a long time.) There are also quite a few lubricant condition monitoring systems on the market which can externally be supervised. Lubricant monitoring systems are based on, e.g. — electric conductivity change; viscosity measurements; acidity measurements; parts of infrared spectrum changes; particle measurements, etc.

Can mechatronics/condition monitoring assist in determining a gearbox lubricant's life?

"Currently," Errichello states, "on-line sensors are available

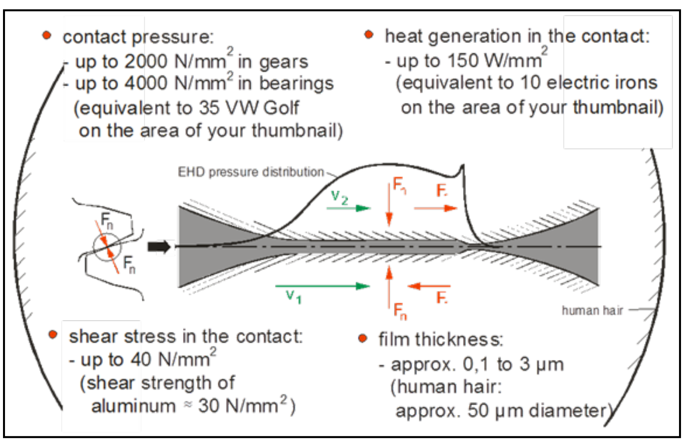

Figure 1 EHL Contact Parameters (acc. FZG/Kopatsch). The very challenging demands on a lubricant in an EHL contact. The contact pressure between the gear flanks is some 15,000 to 20,000 bar, corresponding to the pressure of 35 VW Golf on the area of a thumb nail. At the same time, in the same location heat is generated at a level of 150 W/mm², corresponding to 10 electric irons on the area of the same thumb nail. Shear stress in a fully lubricated contact without metal-to-metal touch is up to 40 N/mm² — or equivalent to the static shear strength of pure aluminum. The EHL film thickness is in the range of 0.1 to over 3 µm on a nanoscale, compared to the thickness of a human hair of 50 µm. (All graphics courtesy FZG.)

for real-time monitoring of both lubricant health and gearbox health. The sensors include particle counters; ferrous debris detectors; viscometers; thermocouples; water detectors (relative humidity); acidity monitors; and oxidation detectors." These sensors provide important information on contamination, oil aging, and wear debris that give significant improvement in condition-based maintenance."

FZG's response is that, "In principle, yes; however, there is only limited experience available today. Further testing is necessary."

Back to the here-and-now, do gear designers typically spec a lubricant type? It appears to be a question that conjures grey-area territory.

"Not often enough," Errichello believes. "Many times, the gearbox is the bastard child and other system priorities preempt gearbox considerations. Ideally, the lubricant and lubrication system are designed with the help of all stakeholders — including the gearbox (manufacturer) OEM, lubricant OEM, and end user."

"There is a discussion over many years that lubricants are calculable design elements and have to be considered in the early design process," (FZG). "Sufficient tribological knowledge of the design team is required. From tribological considerations of the lubrication regime and the expected gear efficiency and load capacity calculations, the gear designer can specify a lubricant that meets the requirements. The lubricant manufacturer confirms the specified lubricant properties with measurements of physical-chemical properties like viscosity at different temperatures, density, flashpoint, pour point, etc., as well as mechanical and technological properties using relevant methods such as scuffing test, wear test, micropitting test, pitting test, efficiency test, etc.

And if you are wondering whether some gearbox applications are more problematic than others, "For sure!" (FZG). "The latest challenges come from automotive applications in double-clutch automatic transmissions (DCTs) with low viscosity requirements; this is due to minimization of no-load losses, together with adverse frictional requirements in the gear and bearing, as compared to the clutch contact and high requirements for scuffing capacity. A simpler example is high-speed turbine gears with high demands on scuffing capacity of the oil, which can be realized with EP additives, whereas additives have detrimental influence on the required air release properties of the lubricant. Wind turbine gearboxes with high gear ratios require good wear performance in the slow-speed stage and high scuffing and micropitting performance in the medium- and high-speed stage."

And standards — are AGMA and ISO lubrication standards reliable guides for determining lubrication choice?

"Recommendations in AGMA and ISO lubrication standards are typically conservative and safe guidelines," (FZG). "With profound tribological knowledge and courage to embrace new ideas, still further improvements are possible. The balance between economic and ecological advantages has to be drawn."

"ANSI/AGMA 9005 and ISO/TR 18792 are very helpful guidelines," Errichello offers. "Gear designers should ensure conformance with these standards."

Load-carrying capability is something you often see mentioned in various places. As to its importance in lubrication choice, it apparently depends upon who you ask.

"Extremely important!" — according to FZG. "In comparing the load carrying capacity in terms of transmittable torque between an optimized and a poor lubricant, there is an estimated factor of over 10 for scuffing capacity, 3 for micropitting capacity, and 1.5 for pitting capacity."

For Errichello — not so much. "Lubricant nomenclature such as "load-carrying capacity" and "film strength" are misleading

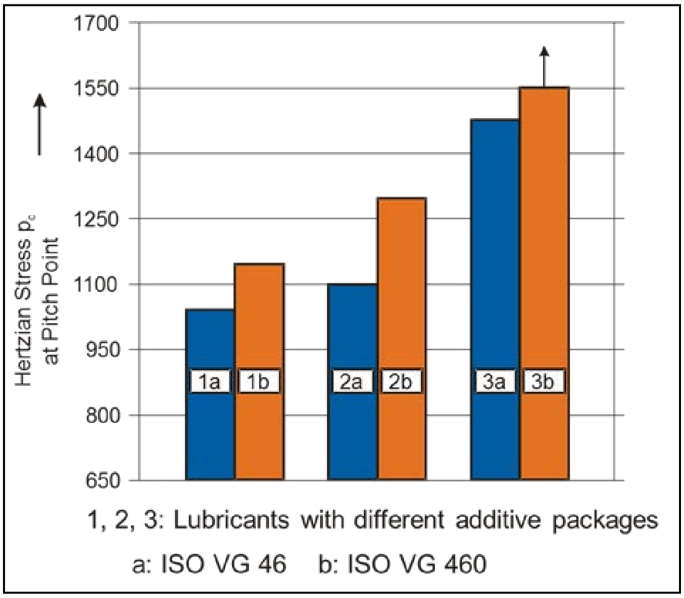

Figure 2 Influence of base oil, additive package and viscosity on micropitting capacity (acc. FZG/Emmert). Shown is the allowable Hertzian stress in a gear contact without risk of micropitting for three different lubricants with different base oils and additive packages — each blended in ISO VG 46 and ISO VG 460. The figure shows clearly the important influence of the lubricant on micropitting failure. It also shows that higher viscosity is always better than lower viscosity for prevention of micropitting. And it shows that if using an inadequate oil, even high viscosity cannot prevent micropitting failures.

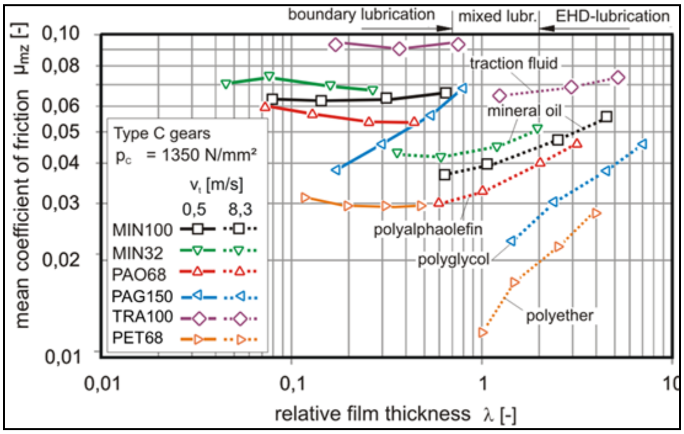

Figure 3 Influence of base oil on coefficient of friction in a gear contact (acc. FZG/Doleschel). A look at measured friction coefficients in a gear contact as a function of the lubrication regime. Investigated were very different base oil types (MIN mineral, PAO polyalphaolefin, PAG polyglycol, TRA traction fluid, PET polyether) at different viscosity grades, including extreme oils from the marketplace with highest friction for a traction drive on the upper scale, and lowest friction for gear applications on the lower scale. Also shown is the very wide range of possibilities to reduce gear contact friction by choosing the adequate oil. For = 2 e.g. the relation between the mineral oil and the polyether is 5.1.

terms. Gear designers should acquire the requisite knowledge of gear tribology so that they can competently specify the lubricant and lubrication system that is appropriate for the gearbox application."

Synthetic lubricants

We can't get away with at least a brief discussion of synthetic lubricants. They of course cost more, just like the synthetic oil on offer at your local auto repair shop. Is it money well spent?

"Synthetic lubricants are becoming more prevalent — especially for applications that involve wide-ranging temperatures or applications requiring high efficiency," Errichello says, but cautions, "However, synthetics are not a panacea, and they may not be appropriate for some applications. In some applications they are necessary, whereas in other applications the costs are prohibitive."

By way of elucidation, FZG offers, "First, a definition of 'synthetic lubricants' is necessary. SAE group I lubricants are purely mineral oil based. If group II and III oils, which are modified mineral oils, cracked and hydrogenated, reducing and eliminating double bonds in their molecules are regarded as semi-synthetic they are already most commonly used in many applications.

Gas-to-liquid (GTL) base stocks are also entering the market. Only polyalphaolefins (PAOs), polyglycols (PAGs), and polyesters (Pes) are regarded as fully synthetic (and are) entering the market gradually. Taking the potential of these synthetic lubricants on friction reduction and lubricant life extension into account, there are quite a few applications where the extra costs pay off! Individual analysis of the specific situation and application is required."

Is correct gearbox lubrication an energy saver?

"Absolutely," says Errichello. "Both lubricant type and lubricant viscosity influence efficiency. Generally, mineral oils are the least efficient. In order of increasing efficiency, lubricant base oils rank as mineral, PAO, PAG, and esters. Generally, the lower the viscosity, the higher the efficiency."

"'Correct'" is probably not the right (word)," (FZG). "Any lubricant choice is a compromise between different requirements and typically not in a win-win situation. Energy saving is possible with synthetic lubricants having longer thermal oxidative life, but higher material costs."

Is gearbox lubrication still an evolving process? Is the arrow pointing up regarding future advances?

FZG: "Base oil technologies of mineral group II and III oils as well as PAOs, PAGs, and PEs as well as traditional additive technologies of organic sulfur-phosphorus and metal containing sulfur-phosphorus are probably on a degressive innovation course with only minor improvements possible. However, very new approaches with e.g. water-based lubricants with a friction reduction potential of 1/50 compared to mineral oils using alternative gear materials are highly innovative.

Errichello: "Depending on one's point of view, lubrication technology has advanced to the point where the information can be overwhelming, or to the point where it offers many opportunities for improving gearbox lubrication. Gear designers should take advantage of the technology advances."

Table 1 Required oil cleanliness for wind turbine gearboxes

Source of oil sample	Required cleanliness per ISO 4406:99
From new oil before adding to gearbox	16/14/11
From gearbox after factory load testing	17/15/12
From gearbox during service	18/16/13

Final Comments

FZG: "Since the introduction of the term 'tribology' by Peter Jost in the UK in the 1960s, in the last century lots of investigations were supported and a lot of knowledge was gathered in research institutes around the world. Our impression, however, is that in daily use there yet remain fundamental knowledge gaps among engineers that have to be faced, and substantial improvements are still possible."

Errichello: "To maximize gearbox life, it is imperative that gearboxes be assembled in a clean room that is separated and insulated from any contamination from manufacturing or environmental debris. For critical applications such as wind turbines, the gearbox should be run-in under a carefully controlled load spectrum at the gearbox OEM. Oil cleanliness should meet the specifications shown in Table 1."

For more information

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Bob Errichello's Basic Factors to Consider for Gearbox Lubrication

- Lubrication-related failure modes, including wear, scuffing, and Hertzian fatigue (macropitting and micropitting)
- Elastohydrodynamic lubrication (EHL) film thickness, surface roughness, and specific film thickness
- Lubricant selection including types: oil, grease, open-gear, or solid
- Selecting lubricant viscosity
- Lubricant application including splash or pressure fed
- Lubricant quantity
- Lubricant heating and cooling including temperature limits, pour point, and oxidation
- Lubricant cleanliness including particle counts, filtration, change interval
- Lubricant contamination with water, wear debris, other lubricants, and gases
- Lubricant compatibility with seals, paint, and other lubricants
- Gear materials and heat treatment
- Condition monitoring including on-site, online, and laboratory analyses
- Lubricant laboratory tests
- Lubricant maintenance and troubleshooting