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Review Article

A Review on Tribological Parameters for Fault Diagnosis in Spur Gears

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Abstract

The gearbox is a crucial element of many rotating machines and needs to be monitored to eliminate the downtime cost. Due to continuous degradation, the gearbox failed in its desired function. To reduce and prevent the catastrophic failure of machinery, it is important to early detection of the faults. The present work reviews the fault detection techniques based on the tribological parameters.

Keywords: *Tribology, In-situ, Ex-situ, Wear debris*

1. Introduction

The gearbox transmits the power and motion by successive teeth engagement. Gearbox found its application in industrial, civilian and military machinery. Most of the gear pairs are lubricated to reduce friction and wear. Lubrication reduces friction and wears and checks the propagation of mild wear by Selecting a lubricant with suitable properties[1–3]. The lubricant can work in two ways: cool and clean the system[4–23], and maintain the layer of lubrication to avoid contact between interfaces—an optimum amount of lubrication is required to form a suitable layer in elastohydrodynamic lubrication [24]. The periodic monitoring of the lubricant properties works as the diagnostic tool[25–47]for the condition monitoring of the machine element. Different properties of the oil (viscosity, additives, etc.) strongly influence gear failures (pitting, mild-wear, scoring etc.)[1,48,57–66,49,67–74,50–56] The lubricant carries the entire history of the machine elements; it has the reach to the parts which are not directly accessible. The lubricant washed away all wear and foreign particle. The degradation level of lubricant can be related to the deterioration of the active gear profile. Degradation of lubricant affects the film thickness formation; sometimes, the lubricant film breakdown and brings the interface into direct contact, and failures occur [75]. The interface starts deterioration and generates wear debris. The interfaces deteriorate the gears' active profile, and the most common types are fatigue wear (pitting), abrasive wear, and adhesive wear [76–87]. The wear particle associated with each type of wear exhibits different types of shape, size, and morphology[4,88].

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The condition monitoring of the system can be carried out in-situ and ex-situ. In in-situ, the lubricant carrying the wear debris passes through an online sensor; the output of the sensor gives information like the temperature of oil[89], the total acid number (TAN)[85,89], total base number (TBN)[85,89], humidity level in oil, the wear particle number count[4,85,89–91], particle per minute[89], total particle mass per hour in micron gram[89], different size particle bin (both ferrous, non-ferrous)[89], and ferrous particle ppm in the lubricant[4,75,85,87,89,90]. In some sense, all this information is utilised to analyse the health of the machine component. In ex-situ analysis the lubricant is analysed under ferrogarm, and Fourier transforms infrared spectroscopy (FTIR). In a ferrogram, the particle size distribution and particle morphology can be analysed. The FTIR output gives the additive depletion and degradation of the oil[4,75,92]. Both in-situ and ex-situ are complementary to each other.

This paper focuses on the direction of reviewing the tribological parameters for the diagnosis of the faults of the gearbox.

2. Gearbox fault through tribological parameters

Gearbox faults are mainly divided into two categories 1. Lubricated (pitting, mild wear etc.) and 2. Non-lubricated (bending, fracture etc.) [93]. The lubricant oil circulating in the system brings complete information about the interacting surfaces. So, the study of changes in the properties of lubricant and different types of wear debris generated on the interface can be used to determine the mechanism of the gear failure. The present study is divided into wear debris-based techniques and lubricant degradation-based techniques.

2.1 Wear debris-based technique of fault detection

The tribological pairs in contact tend to wear out with time. Wear is defined as the progressive loss of material when surfaces in contact have sliding motion at a micro and macro level. The running-in wear improves the contact conditions between the interfaces[93,94]. The transition from normal to severe wear is accompanied by an increase in the size and count of wear particles during operation[95,96]. Figure 1 depicts the wear rate changes over time and at different stages. The count and size of the wear particle[97,98] will give information about two things: loss of lubrication and fatigue failure of the surface. Figure 2 shows the typical gear profile that went under the flank wear, the profile modification in the addendum and the dedendum side of the gear flank. The severity of wear on the addendum and dedendum is high due to the sliding motion between the interface surfaces. The experimental approach to identifying the type of severity of wear depends upon the wear rate, particle per minute, ferrous particle, non-ferrous particle, morphology and texture [4,76,85–91,95,99–108].

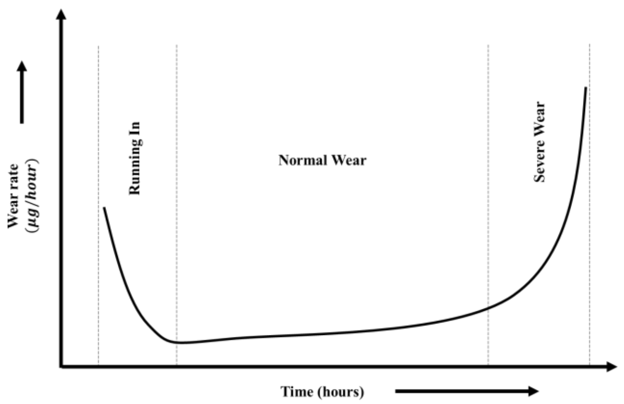


Fig. 1 Bathtub curve: Change of wear rate with operating time[109–111]

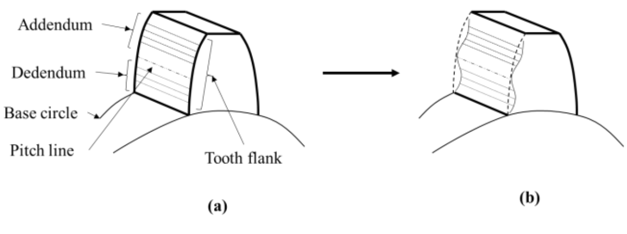


Fig. 2 A typical schematic representation of wear of gear flank

The cyclic loading of the gear teeth takes place during the operation. The Hertzian stress that develops at the contact (line or point contact) is very high. At the pitch point, rolling motion takes place, and above and below the pitch point, the sliding motion takes place[112,113]. Figure 3 depicts the stress, motion, and wear profile at pitch line, addendum, and dedendum.

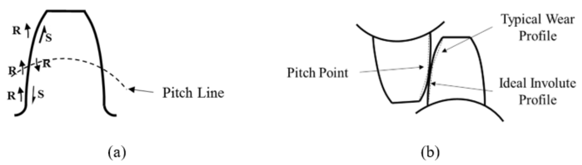


Fig. 3 (a) Gear tooth rolling and sliding contact[93,114], (b) wear profile along the gear flank[115]

Wear particle count is one of the criteria used to find the progression of wear (mild-wear, pitting wear). Large size particles are associated with fatigue failure in the machine. The increase in small-size particles results from the progression of mild-wear along with the micro-pitting. The lubrication degradation and the wear both are complementary to each other. The ferrography (offline and online) is used to determine the faults' severity. In offline ferrography, the samples are taken at regular intervals and processed through the ferrogarph to determine the particle's shape and size and the number of particles in a sample[106,116]. In online ferrography, the ferrograph is attached to the machine, and the lubricant is continuously passed through the ferrograph giving the output like the number of particles, particle size, wear amount (μg/ hour), count of ferrous and non-ferrous particles—the on-line visual ferrography used for the on-line wear debris concentration monitoring. An indicator IPCA is given for the wear debris concentration is the ratio of the area covered by the ferrogram plate by wear debris and the area of the ferrogram plate[111,117].

$$IPCA = \frac{\sum C_i}{W_a \times W_b} \times 100\ \% \qquad (1)$$

The size of the particle in the ferrogram is calculated as the large and small-sized particles, and the percentage of the larger particle size is given as [96]

$$\text{Large particle } (\%) = \frac{D_L - D_S}{D_L + D_S} \times 100 \qquad (2)$$

The worn state is the function of the IPCA; large particle concentration and number of wear particles are given as $f(IPCA, \text{Large particle } (\%), \text{Number of wear particle})$ [96]. The particle count is the better criteria for the early detection of the wear (mild-wear) in the machine component. There is an equilibrium state between the particle count and the lubricant quality (the additive depletion state, TAN, viscosity etc.)[118], every time change in the oil brings a new equilibrium state between the number of particles count and the oil quality. The online ferrography provides the edge over the offline ferrography by providing the real-time state of the system. An offline study for taking the sample from the system needs to wait for periodic maintenance or when the system would shut down due to breakdown. There is some limitation to the online study of the wear the morphological attributes are missing from the output data.

The morphology of the wear particle provides information about the wear mechanism and severity[119]. The magnetic plug[120] is installed in the lubricating system to collect the wear debris. Then the particle is processed and analysed using different techniques (SEM, EDX etc.) to know the composition, size and shape. Figure 4 and Figure 5 show the relationship between wear mode and wear mechanism and wear particle and the shape of the wear particle, the possible machine state. In Figure 6, many statistical parameters are defined for the morphology of the wear particle.

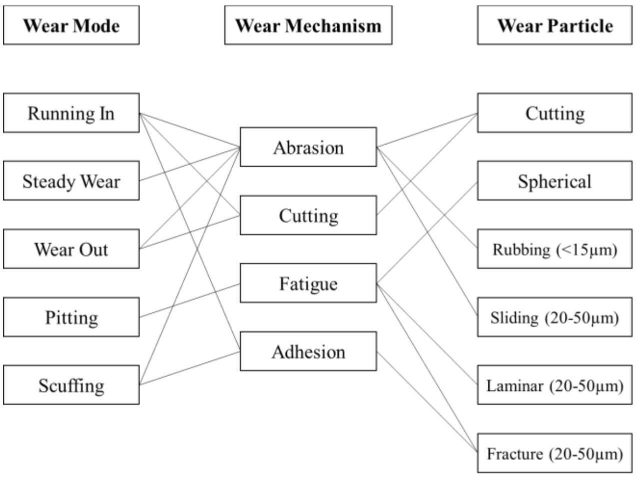


Fig. 4 Relationship between different particle sizes, morphology and mechanism[97,106,116,121–126]

2.2 The lubrication-based fault diagnosis technique

Lubricating oil serves two primary functions in the system: minimising friction between the interfaces and reducing the wear by interposing a lubricant layer on the interface. Lubricant serves many things in the system besides reducing friction and wear, taking away heat, dirt and wear debris. Gear teeth have unique rolling and sliding motion combinations during the contact cycle, due to which the gear operates under elastohydrodynamic and mixed lubrication regimes[127]. The factor affecting the performance of the lubricant in such contact is viscosity (dynamic viscosity and kinematic viscosity)[128], lubricant additives (viscosity index (VI) improver, defoaming, oxidation inhibitors, dispersant, extreme pressure), flash point, total acid number (TAN), total base number (TBN)[108,129].

The wear rate of the component is dependent upon the lubrication mechanisms. The thickness of the lubricant film[130–132] affects the performance and service life of the machine component. The film thickness is defined as[133–135]

$$h_{min} = \frac{1.6\xi^{0.6}(\eta_0 u)^{0.7}(E')^{0.03}R^{0.43}}{w^{0.13}} \tag{3}$$

This film thickness helps in calculating the film parameter called specific film parameter, defined as

$$\Lambda = \frac{h_{min}}{\left(R_{q,1}^2 + R_{q,2}^2\right)^{1/2}} \tag{4}$$

The specific film parameter helps in distinguishing the lubrication mechanism[136]

$5 < \Lambda < 100$ hydrodynamic lubrication
$3 < \Lambda < 10$ elastohydrodynamic lubrication
$\Lambda < 1$ boundary lubrication

The lubricant works as a sacrificial component in the system, degrading gradually with degradation: the lubricant loses its primary function and acts as a catalyst for further degradation of the component. Lubricant oxidation, thermal breakdown, micro-dieseling, additive depletion, and contamination are a few causes of lubricant degradation. Oxidation is the reaction of oil molecules with oxygen molecules. It can lead to an increase in viscosity and the formation of varnish, sludge and sediment. Due to oxidation, the wear rate also increases. Micro-dieseling is when an air bubble transitions from a low-pressure region in a system to a high-pressure zone. Micro dieseling results in adiabatic compression of the air bubble within the oil, which then cooks the surrounding oil molecules, causing instant oxidation. The additive is meant to be sacrificial purposes. The additive used as the antifriction, anti-wear, and extreme pressure additives will deplete over time, and these can cause the loss in performance of the lubricant oil and support the wear of the components. Contamination such as dirt, water, air etc., can significantly influence the rate of lubrication degradation. Dirt containing fine metal particles can be a catalyst that sparks and speeds up the degradation process of the lubricant. Air and water can provide a source of oxygen that can react with the oil and leads to oxidation of the lubricant.

The lubricant degradation over time changes the oil's chemical composition. Fourier transform infrared spectroscopy (FTIR) is used to analyse the oil degradation and the presence of a new bond in the oil. FTIR provides information about new chemical bonds and functional groups in the investigated sample. The covalent bonds absorb infrared radiation at the characteristic wavelength, depending on the molecule's chemical composition and the chemical bond's strength [92,108,134].

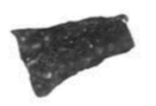
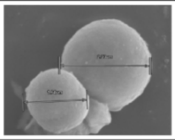
Particle Geometry Type	Particle Feature	Wear Type	Wear Level	Possible Machine Condition	
Regular	Thin, plan and oblique shape size <50μm	Rubbing, mild adhesion	Normal	Normal wear particle without dramatic increase	
Irregular	Irregular edge with scratches, laminar or chunk shape size> 50μm	Adhesion and fatigue fracture	Severe	Abnormal condition	
Elongated	Slender or curved particle Size <50μm	Plowing	Severe	Impending trouble of severe cutting wear	
Spherical	Ball like, hollow spheres	Rolling fatigue	Abnormal	Indicate the early surface pitting	

Fig. 5 Correlation of geometrical classification of wear particle shapes to wear mode [89,97,100,114,120–122,122,124,125,137–140]

Method	Attribute	Descriptor	Abbreviation	Definition
Form Factor	Profile	Aspect Ratio Roundness Factor	AR RF	Length / Breadth $(\text{Perimeter})^2/4\pi(\text{Area})$
Fourier Analysis	Profile and Edge Detail	1st, 2nd ,…, Harmonics	$C_1, C_2, \ldots, C_8$ $\mu_0, \mu_1, \mu_2, \mu_3$	$C_n = \sqrt{(C\, x_n^2 + C_n^2)}$ $R_0 = a_0^2 + \frac{1}{2}\sum_{n=1}^{x}(a_n^2 + b_n^2)$ $\mu_0 = L_0 R_0$, $\mu_1 = 0,\ \mu_2 = R_0^2 \sum_{n=1}^{x} L_{2,n}$ $\mu_3 = R_0^3 \sum_{n=1}^{x}\sum_{m=1}^{x} L_{3,m,n}$
Curvature Analysis	Edge Detail	Standard Deviation Skewness Kurtosis	R_q R_{sk} R_{ku}	$R_q = \sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2/n-1}$ $R_{sk} = \sum_{i=1}^{n}(x_i - \bar{x})^3/nR_q^3$ $R_{ku} = \sum_{i=1}^{n}(x_i - \bar{x})^4/nR_q^4$
Fractal Analysis	Edge Detail and Profile	Structure Texture	δ_s δ_T	$\delta_s = 1 + \lvert m_s \rvert$:m_s:m_s is slope of the line of best fit from the plot of log normalized perimeter vs. log step length (large step length) $\delta_T = 1 + \lvert m_T \rvert$:m_T is slop of the line of best fit from the plot of log normalized perimeter vs. log step length (very small step length)
Size Analysis	Size	Weibull Parameter	α β	$P(\chi)P(\chi) = 1 - exp\left\{-\left(\frac{\chi - \chi'}{\alpha}\right)^{\beta}\right\}$

Fig. 6 Shape classification parameters [99,100,105,120,122,139,141–146]

After the sample collection, the lubricant can be passed through the different tests and analysed in such a way that the condition of both lubricant and the machine can be determined.

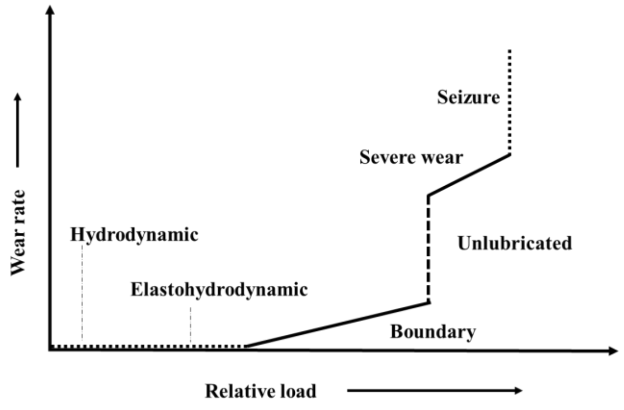


Fig. 7 Wear rate under different lubrication conditions

The samples of lubricant are taken in the turbulent state of the lubricant form by a vacuum pump or suitable tap-off; if not possible in the running condition, the lubricant sample is taken after the temperature of the sump reaches the operating temperature of the system.

The turn-round time should not be more than 48 hours for all tests. For gearbox condition monitoring, the following parameters need to be determined viscosity, water contents (humidity), TAN, TBN, ferrous particle count (Fe ppm), presence of chemical bonds etc.

The kinematic viscosity of a fluid is the quotient of its dynamic viscosity divided by its density. High specific viscosity is required to reduce components' excessive wear and friction. The viscosity of the lubricating oil is affected by the contamination by foreign particles and oil, oxidation, and solvents. The viscosity index (VI) is calculated to find the relationship between the viscosity and lubricant temperature. The viscosity is detrimental for wear and high-temperature operation of lubricant life. It is also essential to know the water content in the lubricant. The presence of water can accelerate wear and corrosion. The water is ingress from seals, gaskets or by condensation. The presence of water in the lube is determined by the sample's relative humidity (RH%). TAN is typically indicating high-temperature use or oxidation of the lubricant. High oxidation leads to a rise in the viscosity of the lubricant. Lubricant oxidation is characterised by discolouration of lubricant and release of brunt odour. TBN is the determination of the alkalinity of the lubricant. The high temperature leads to the formation of alkaline lubricants. The lubricant is changed when the TBN is depleted to 50%. Due to the component's degradation, the ferrous particle concentration increases in the oil.

The ferrous particle presence in the lubricant can also be one of the criteria for condition monitoring. The increase in the concentration of ferrous particles can trigger the progression of the wear in components and depict more metal-to-metal contact—the ferrous particle measured in particles per million (ppm). The ISO and NAS provide the codes for the cleanliness of the lubricant. Spectroscopic studies are carried out to differentiate between virgin oil from recycled oil. The spectrometric study shows different bonds present in the lubricant, which determine the presence of volatile hydrocarbons, solid products (asphalts, carbenes), gases (CO, CO2), liquids (alcohols, acids, eather, resins, ketones, aldehydes etc.), and chemical products. The spectrometric analysis provides information regarding the diagnosis of the component within the error span of 0.5%-1%. The ASTM standard provides information about the relation of wavelength with substantial oil functional groups.

The FTIR spectroscopy is the tool to estimate the presence of the oxide's residue in the oil, the purification of the oil, qualitatively and quantitatively elemental[134]. Salt slides are used as the windows; lubricant or oil samples are initially dispersed over the salt window; infrared radiation is through over the window, and the lubricant spectra are acquired. The NaCl and KBr slides are used because the salt has excellent transmittance for the infrared range of the spectrum. The information generated can be used as the diagnosis for the lubricant, and the correspondence can be used to determine the component's health. Table 1 shows the relation of the transmittance/ absorption with the specific functional group. In the presence of the compound, new-formed functional groups in virgin and used oil can be detected. The newly formed compound peaks are seen in the spectra, and the depletion of the bond or compound shows the peak's disappearance.

Table 1 The functional group and associated frequency [147–150]

Group frequency (cm^{-1})	Functional group
3600-3200 and 1600-1200	H-O-H stretching
2200-1800 and 2000-1650	O=C=O stretching and C-H bending
3500-3300 and 1700-1500	N-H stretching (amine) and N-H bending (amine)
3800-3500 and 1400-1300	O-H bending (phenol)
1200-800, 3000-2800 and 500-400	ZnO
1700-1600 and 1000-650	C=C stretching (alkane, ketone)
1600-1300	N-O stretch and C-H stretch (alkane, aldehyde)
900-700	C-H bending
1400-1000	O-H bending, S=O stretching, C-N stretching, C-O stretching (Carboxylic acid, sulfate, aromatic amine, ester)

Conclusions

Complete diagnosis techniques based on the lubrication and wear debris are discussed above. The oil and wear techniques provide the closest information on the concerned component. These techniques are not working for the faults like cracks etc. The following suggestions about research prospects can be drawn from the above study:

a. The gearbox should be considered a single unit is combining bearing, shaft, seals and gears. The fault in one can act as a catalyst for the failure in the other element. So, the global faults deserve some investigation.
b. Mild wear is a progressive type of wear and supplements the other processes like fatigue failure and bending failure. So, the optimal limit of mild wear should be defined to avoid the other failure mechanism.
c. The distinguishing source of wear debris deserves some investigation.

Nomenclature

$g_o(x,t)$ Unloaded geometric gap $\left[\frac{x^2}{2R_{eq}(t)}\right]$
R_{eq} The equivalent radius of curvature $\left[\frac{1}{R_1(t)}+\frac{1}{R_2(t)}\right]^{-1}$
$S_1(x,t)$ and $S_2(x,t)$ Surface roughness profiles in rolling and sliding direction
μ_f Friction coefficient
IPCA Index of particle coverage area
c Total coverage area of wear debris
w_a Length of ferrographic plate
w_b Width of ferrographic plate
D_L Particles greater than 5 microns
D_S Particles less than 5 microns
$'\alpha'$ and $'\beta'$ Weibull parameter
$'\delta_S'$ and $'\delta_T'$ Fractal descriptor
R_q Standard deviation/roughness of the surface
R_{sk} Skewness
R_{ku} Kurtosis
ξ Damping ratio and pressure viscosity coefficient
E' Dimensionless elasticity modulus
u Effective peripheral velocity
η_o Absolute viscosity (cP)
h_{min} Minimum oil film thickness
Δ Specific film parameter
μ Lubricant dynamic viscosity
$\bar{\mu}$ Non-dimensional lubricant viscosity
τ_o Lubricant reference stress
τ_m Viscous shear stress $\tau_m = \tau_o \sinh^{-1}\left[\frac{\mu u_s(t)}{(\tau_o \text{h})}\right]$
$u_s(t)$ Time-dependent sliding velocity
$u_r(t)$ Time-dependent sliding velocity in x-direction
$v_r(t)$ Time-dependent sliding velocity in y-direction
h Film thickness
p Pressure
$\bar{p}$ Dimensionless pressure
ρ Lubricant density
ρ_o Lubricant density at ambient pressure

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