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Lubrication of industrial gear drives

Lubrification des entraînements par engrenages industriels

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Foreword

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ISO/TR 18792 was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

Introduction

Gear lubrication is important in all types of gear applications. Through adequate lubrication, gear design and selection of gear lubricant, the gear life can be extended and the gearbox efficiency improved. In order to focus on the available knowledge of gear lubrication, ISO/TC 60 decided to produce this Technical Report combining primary information about the design and use of lubricants for gearboxes.

Lubrication of industrial gear drives

1 Scope

This Technical Report is designed to provide currently available technical information with respect to the lubrication of industrial gear drives up to pitch line velocities of 30 m/s. It is intended to serve as a general guideline and source of information about the different types of gear, and lubricants, and their selection for gearbox design and service conditions. This Technical Report is addressed to gear manufacturers, gearbox users and gearbox service personnel, inclusive of manufacturers and distributors of lubricants.

This Technical Report is not applicable to gear drives for automotive transmissions.

2 Terms and definitions

For the purposes of this document, the following terms, definitions, symbols, indices and units apply.

Table 1 — Symbols, indices and units

Symbol, index	Term	Unit
A, B, C, D, E	points on the path of contact	—
b	face width	mm
C	cubic capacity of the oil pump	cm^3
d	diameter	mm
$d_{a1,2}$	outside diameter pinion, wheel	mm
$d_{b1,2}$	base circle diameter pinion, wheel	mm
$d_{w1,2}$	operating pitch diameter pinion, wheel	mm
f_H	curvature factor	$N^{0,5}/mm^{1,5}$
f_L	load factor	—
F_{bt}	circumferential load at base circle	N
n_{shaft}	rotational speed of the oil pump driving shaft	rpm
p	pressure	bar
p_H	hertzian stress	N/mm^2
P	gear power	kW
P_{vz}	gear power loss	kW
P_{vzsum}	total gearbox power loss	kW
s	slip	—
t	time	sec

Table 1 (*continued*)

Symbol, index	Term	Unit
V	oil quantity	l
Q_e	oil flow	l/min
$Q_{bearings}$	oil flow through the bearings	l/min
Q_{gears}	oil flow through the gear mesh	l/min
Q_{pump}	oil pump flow	l/min
Q_{seals}	oil flow through the seals	l/min
v	pitch line velocity	m/s
$v_{1,2}$	surface velocity pinion, wheel	m/s
v_g	sliding velocity	m/s
v_t	pitch line velocity	m/s
v_Σ	sum velocity	m/s
V_{tank}	oil tank volume	l
z_1	number of pinion teeth	—
β	helix angle	degree
λ	relation between the calculated film thickness and the effective surface roughness	—

2.1
intermittent lubrication
intermittent common lubrication of gears which are not enclosed

NOTE Gears that are not enclosed are referred to as open gears.

2.2
manual lubrication
hand application
periodical application of lubricant by a user with a brush or spout can

2.3
centralized lubrication
intermittent lubrication of gears by means of a mechanical applicator in a centralized system

2.4
continuous lubrication
continuous application of lubricant to the gear mesh in service

2.5
splash lubrication
bath lubrication
immersion lubrication
dip lubrication
process, in an enclosed system, by which a rotating gear or an idler in mesh with one gear is allowed to dip into the lubricant and carry it to the mesh

2.6
oil stream lubrication
pressure-circulating lubrication
forced-circulation lubrication
continuous lubrication of gears and bearings using a pump system which collects the oil in a sump and recirculates it

2.7
drop lubrication
use of oil pump to siphon the lubricant directly onto the contact portion of the gears via a delivery pipe

2.8
spray lubrication
process in oil stream lubrication by which the oil is pumped under pressure to nozzles that deliver a stream or spray onto the gear tooth contact, and the excess oil is collected in the sump and then returned to the pump via a reservoir

2.9
spray lubrication for open gearing
continuous or intermittent application of lubricant using compressed air

2.10
oil mist lubrication
process by which oil mist, formed from the mixing of lubricant with compressed air, is sprayed against the contact region of the gears

NOTE It is especially suitable for high-speed gearing.

2.11
brush lubrication
process by which lubricant is continuously brushed onto the active tooth flanks of one gear

2.12
transfer lubrication
continuous transferral of lubricant onto the active tooth flanks of a gear by means of a special transfer pinion immersed in the lubricant or lubricated by a centralized lubrication system

3 Basics of gear lubrication and failure modes

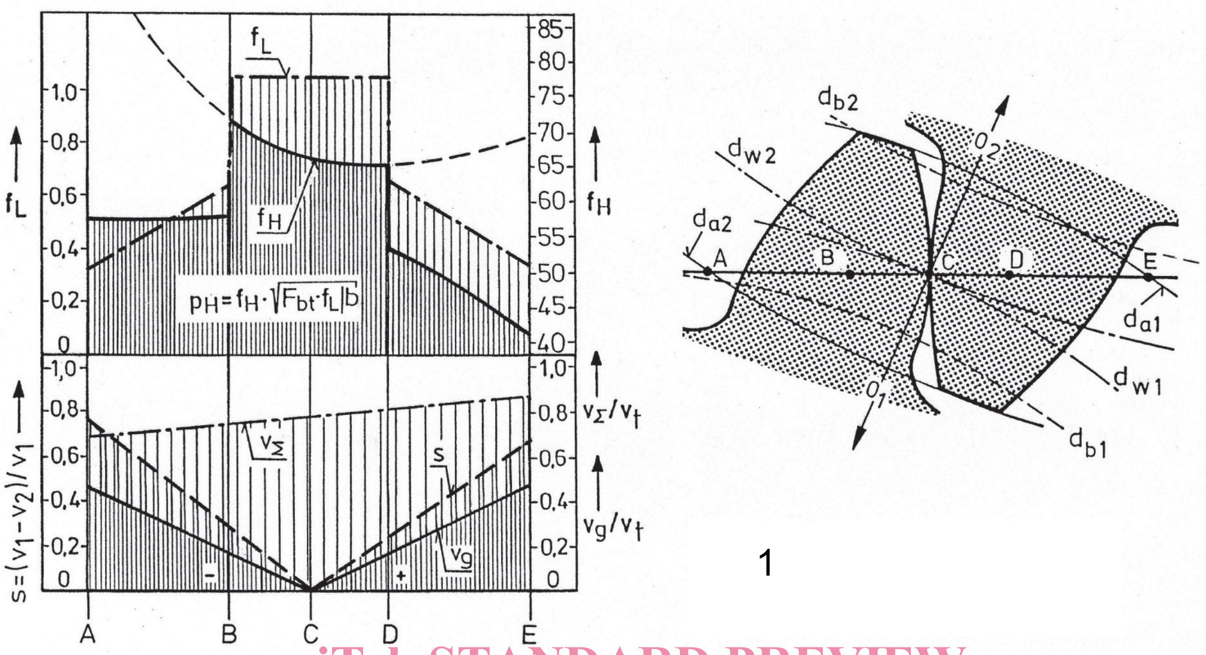
3.1 Tribo-technical parameters of gears

3.1.1 Gear types

There are different types of gear such as cylindrical, bevel and worm. The type of gear used depends on the application necessary. Cylindrical gears with parallel axes are manufactured as spur and helical gears. They typically have a line contact and sliding only in profile direction. Cylindrical gears with skewed axes have a point contact and additional sliding in the axial direction. Bevel gears with an arbitrary angle between their axes without gear offset have a point contact and sliding in profile direction. They generally have perpendicular axes and are manufactured as straight, helical or spiral bevel gears. Bevel gears with gear offset are called hypoid gears with point contact and sliding in profile and axial directions. Worm gears have crossed axes, line contact and sliding in profile and mainly axial direction.

3.1.2 Load and speed conditions

The main tribological parameters of a gear contact are load, pressure, and rolling and sliding speed. A static load distribution along the path of contact as shown in Figure 1 can be assumed for spur gears without profile modification. In the zone of single tooth contact the full load is transmitted by one tooth pair, in the zone of double tooth contact the load is shared between two tooth pairs in contact.



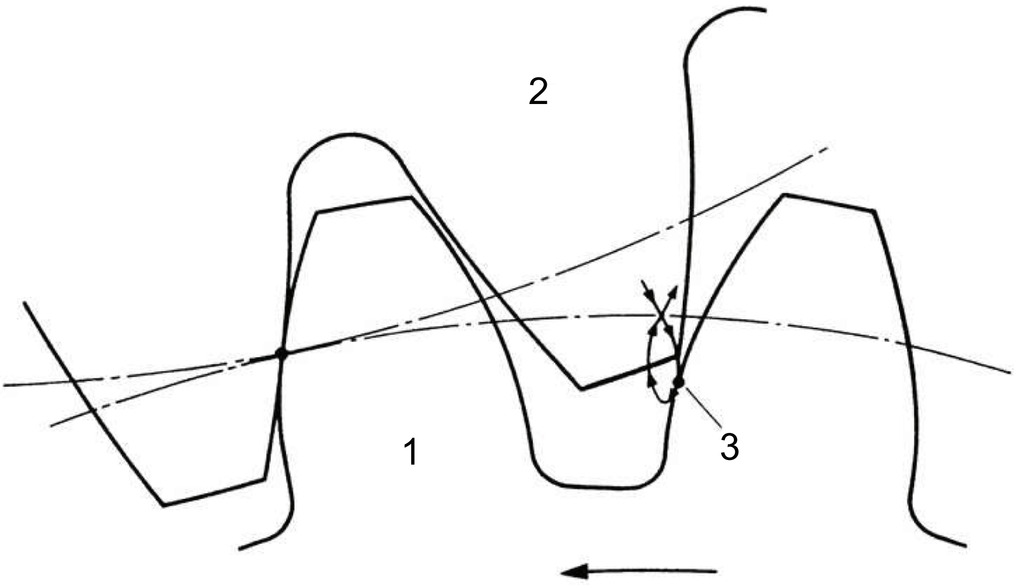
Key

1 spur gear without profile correction

Figure 1 — Load and speed distribution along the path of contact

The static load distribution along the path of contact can be modified through elasticity and profile modifications. Due to the vibrational system of the gear contact, dynamic loads occur as a function of the dynamic and natural frequency of the system. A local Hertzian stress for the unlubricated contact can be derived from the local load and the local radius of curvature (see Figure 1). When a separating lubricating film is present, the Hertzian pressure distribution in the contact is modified to an elastohydrodynamic pressure distribution with an inlet ramp, a region of Hertzian pressure distribution, possibly a pressure spike at the outlet and a steep decrease from the pressure maximum to the ambient.

The surface speed of the flanks changes continuously along the path of contact (see Figure 1). The sum of the surface speeds of pinion and wheel represents the hydrodynamically effective sum velocity; half of this value is known as entraining velocity. The difference of the flank speeds is the sliding velocity, which together with the frictional force results in a local power loss and contact heating. Rolling without sliding can only be found in the pitch point with its most favourable lubricating conditions. Unsteady conditions with changing pressure, sum and sliding velocity along the path of contact are the result. In addition, with each new tooth coming into contact, the elastohydrodynamic film must be formed anew under often unfavourable conditions of the scraping edge of the driven tooth (see Figure 2).



Key

1 pinion (driving)

2 wheel (driven)

3 first contact point

Figure 2 — Scraping edge at the ingoing mesh

3.2 Gear lubricants

3.2.1 Overview of lubrication

Regarding gear lubrication, the primary concern is usually the gears. In addition to the gears there are many other components that must also be served by the fluid in the gearbox. Consideration should also be given to the bearings, seals, and other ancillary equipment, e.g., pumps and heat exchangers, that can be affected by the choice of lubricant. In many open gear drives the bearings are lubricated independently of the gears, thus allowing for special fluid requirements should the need arise. However, most enclosed and semi-enclosed gear drives utilize a single lubricant and lubricant source of supply for the gears, bearings, seals, pumps, etc. Therefore, selecting the correct lubricant for a gear drive system includes addressing the lubrication needs of not only the gears but all other associated components in the system.

A lubricant is used in gear applications to control friction and wear between the intersecting surfaces, and in enclosed gear drive applications to transfer heat away from the contact area. They also serve as a medium to carry the additives that can be required for special functions. There are many different lubricants available to accomplish these tasks. The choice of an appropriate lubricant depends in part on matching its properties to the particular application. Lubricant properties can be quite varied depending on the source of the base stock(s), the type of additive(s), and any thickeners that might be used. The base stock and thickener components generally provide the foundation for the physical properties that define the lubricant, while the additives provide the chemical properties that are critical for certain performance needs. The overall performance of the lubricant is dependent on both the physical and chemical properties being in the correct balance for the application. The following clauses describe the more common types of base stocks, thickeners and additive chemicals used in gear lubricant formulations today.

3.2.2 Physical properties

The physical properties of a lubricant, such as viscosity and pour point, are largely derived from the base stock(s) from which they are produced. For example, the crude source, the fraction or cut, and the amount of refining, such as dewaxing, of a given mineral oil can significantly alter the way it will perform in service. While viscosity is the most common property associated with a lubricant, there are many other properties that contribute to the makeup and character of the finished product. The properties of finished gear lubricants are the result of a combination of base stock selection and additive technology.

3.3 Base fluid components

A key element of the finished fluid is the base oil. The base oil comes from two general sources: mineral; or, synthetic. The term mineral usually refers to base oils that have been refined from a crude oil source, whereas synthetics are usually the product of a chemical reaction of one or more selected starting materials. The finished fluids can also contain mixtures of one or more base oil types. Partial synthetic fluids contain mixtures of mineral and synthetic base oils. Full synthetic fluids can also be mixtures of two or more synthetic base oils. As a current example, mixtures of polyalphaolefins (PAO) and esters are commonly used in synthetic formulations. Mixtures are generally used to tailor the properties of the finished fluid to a specific application or need. An overview of the general characteristics of different base fluids is shown in Table 2. Additional information regarding base fluid characteristics is shown in the following sections.

Table 2 — General characteristics of base fluids

Characteristic	Mineral paraffinic	Polyalpha–olefins (PAO)	Ester	Poly-alkylene-glycol (PAG)	Phosphate esters
Viscosity – temperature relationship (typical viscosity index)	90 – 130	130 – 150	50 – 140	200 – 240	<100
Specific heat (relative)	1,0	1,3 – 1,5	1,1 – 1,3	1,1 – 1,3	1,0 – 1,2
Pressure-viscosity at 1 GPa (relative)	1,0	0,8	0,5	~1,0	1,0 – 1,1
Comparability solvency with mineral fluids	Excellent	Good	Excellent	Poor	Good
Comparability solvency with PAO fluids	Good	Excellent	Excellent	Poor	Good
Additive solvency	Good to Excellent	Good	Excellent	Limited	Good

3.3.1 Mineral-based fluids

Mineral-based gear oils have been successfully used for several years in many industrial gear drive systems. Mineral oil lubricants are petroleum-based fluids produced from crude oil through petroleum refining technology. Paraffinic mineral-based gear oils have viscosity indices (VI) that are commonly lower than most, but not all synthetic-based gear oils. This usually means that the low temperature properties of these mineral-based lubricants will not be as good as for a comparable grade synthetic fluid. If low ambient temperatures are involved with the operation of the equipment, this should be factored into the decision process. At high temperatures, mineral-based lubricants are more prone to oxidation than synthetics due in part to the amount of residual polar and unsaturated compounds in the base component. Mineral-based lubricants will generally provide a higher viscosity under pressure than most synthetics and therefore provide a thicker film at moderate temperatures. On the other hand, at higher temperatures, usually around 80 °C to 100 °C or more, the higher VI of synthetic fluids generally overcomes the disadvantage of having a lower pressure-viscosity coefficient. At these higher temperatures, the film thickness can be higher for PAOs compared to mineral oils. Probably the primary advantages of mineral-based oils over synthetic-based oils are their lower initial purchase cost and greater availability worldwide. If a mineral oil is preferred, some of the weaker properties, compared to a synthetic fluid, can be improved through the thickener and additive systems available today.

3.3.2 Synthetic-based fluids

Synthetic oils differ from petroleum-based oils in that they are not found in nature, but are manufactured chemically and have special properties that enhance performance or accommodate severe operating conditions. Because they are manufactured, many of their properties can be tailored to meet specific needs through the choice of starting materials and reaction processing. Many synthetic oils are stable at high operating temperatures, have high VI, i.e. smaller viscosity changes with temperature variations, and low pour points. This means that equipment filled with most commercially available synthetic gear oils can be started without difficulty at lower bulk oil temperatures than those using mineral oils. Another key advantage is that they are inherently more stable at higher temperatures against oxidative degradation than their mineral counterparts, again owing this advantageous property to the uniformity and composition of the fluid structure.

Each type of synthetic lubricant has unique characteristics and the limitations of each should be understood. Characteristics such as compatibility with other lubrication systems and mechanical components (seals, sealants, paints, backstops and clutches), behaviour in the presence of moisture, lubricating qualities and overall economics should be carefully analysed for each type of synthetic lubricant under consideration for a given application. In the absence of field experience in similar applications, the use of synthetic oil ought to be coordinated carefully between the user, the gear manufacturer and the lubricant supplier. Synthetic lubricants can improve gearbox efficiency and can operate cooler than mineral oils because of their viscosity-temperature characteristics and structure-influenced heat transfer properties. Decreasing the operating temperature of a gearbox lubricant is desirable. Lower lubricant temperatures increase the gear and bearing lives by increasing lubricant film thickness, and increase lubricant life by reducing oxidation.

There are several different types of synthetic base oils available today. Their compositions and properties result from the different chemicals that are combined in their manufacture. Some of the major types of synthetic base oils are described in the following clauses. The lubricant supplier is generally consulted for additional information on synthetics for a given application.

3.3.2.1 Polyalphaolefin-based oils

PAOs, or olefin oligomers, are paraffin-like liquid hydrocarbons which can be synthesized to achieve a unique combination of high viscosity-temperature characteristic, low volatility, excellent low temperature viscometrics and thermal stability, and a high degree of oxidation resistance with appropriate additive treatment along with a structure that can improve equipment efficiency. These characteristics result from the wax-free combination of moderately branched paraffinic hydrocarbon molecules of predetermined chain length. Compared to conventional mineral oils, some PAO lubricants have poorer solvency for additives and for sludge that can form as the oil ages. Lubricant formulators commonly add a higher solvency fluid, such as ester or alkylated aromatic fluids, in order to keep the additives in solution and to prevent sludge from being deposited on the gearbox components.

3.3.2.2 Synthetic ester lubricants

Esters are produced from the reaction of an alcohol with an organic acid. There are a wide variety of esters available that can be produced because of the numerous existing combinations of acids and alcohols. The principal advantage of many esters is their excellent thermal and oxidative stability. A primary weakness of some is poor hydrolytic stability. When in contact with water, esters can deteriorate through a reverse reaction and revert to an alcohol and organic acid. A secondary weakness with some esters is a VI lower than most paraffinic mineral-based oils. Some esters do, however, provide a VI higher than mineral or PAO lubricants. It is possible for some ester-based gear oils to be suitable in water protection areas since they can be biodegradable.

On the negative side, ester-based gear oils or lubricants containing esters can adversely affect filters, elastomeric seals, adhesives, sealants, paint, and other surface treatments such as layout lacquer used for contact pattern tests. Therefore, lubricants with esters should be tested for compatibility with all gearbox components before they are used in service. Another weakness of the ester class of lubricants is their poor film-forming capabilities. Esters tend to have very low pressure-viscosity coefficients which relate to the ability of the fluid’s film thickness in the contact region. This could lead to higher wear.

3.3.2.3 Polyalkyleneglycol (PAG) lubricants

PAG-based oils have a chemical structure that is distinctly different from both PAO and ester-based oils. PAGs are generally made from the reaction product of ethylene oxide and propylene oxide to form a polyether type structure. The properties of the structure are dependent on the molecular weight and the ratio of ethylene and propylene oxides used in the reaction mixture. PAG-based gear oils can have excellent thermal and oxidative stability and most have exceptionally high VI, many of which are greater than 200. However, many PAGs have poor corrosion properties in the presence of salt water. In standard distilled water corrosion tests, carefully selected additives can control rust.

The primary difficulties with PAG lubricants are that they can be very hygroscopic (tend to absorb water) and not very miscible with mineral or other synthetic fluid-type base fluids. The affinity for water and compatibility with more common fluids is a function of the ethylene oxide to propylene oxide ratio. Special flushing procedures are required when switching between a PAG and mineral or other synthetic fluid lubricant; the lubricant supplier is consulted for specific details. A secondary difficulty with PAG lubricants is that they can require different specifications for paints, seals, sealants, and filters. Also, special handling would be required for the disposal of PAG-type lubricants.

3.3.2.4 Phosphate esters

While there are many groups of phosphates, it is the trisubstituted, neutral esters of orthophosphoric acid that have found significant use as synthetic base stocks. The commercially significant derivatives used as synthetic base stocks are compounds in which all three substituents on the phosphorus molecule are alky, aryl, or alkyl-aryl moieties containing at least four carbon atoms plus hydrogen and oxygen. They are probably best known for their inherent fire-resistance and find wide use as fire-resistant industrial hydraulic fluids. Additionally, they can be used as gear lubricants in the gearboxes of gas and steam turbines.

The trisubstituted phosphate esters, being neutral, have demonstrated chemical stability through many years of practical industrial service over a wide temperature range. They generally do not react with most organic compounds and are excellent solvents for most commonly used lubricant additives. In addition, they have demonstrated excellent thermal and oxidative stability in various laboratory tests. When one thinks of synthetics, the most common characteristic is excellent viscosity-temperature relationships. This, however, is not the case for phosphate esters as they typically have viscosity indices (VI) below 100.

Consideration should also be given to phosphate ester-type fluids during service due to their affinity with water.

3.4 Thickeners

Thickeners, also known as viscosity modifiers (VM) or viscosity index improvers (VII), are not common in industrial gear oil formulations, but are used in some applications. Thickeners are generally polymers, which cause the oil to thicken to a much greater extent per unit volume of material than a conventional base stock, such as a bright stock or cylinder stock. At higher temperatures the molecule expands creating a thickening effect. As the temperature decreases the polymer molecule tends to contract minimizing the thickening effect. A schematic diagram of this principle is shown in Figure 3. The unique ability of these polymers to expand and contract as a function of temperature enables the finished blend to have much better viscosity-temperature characteristics, thus the terms VM and VII.

Polymers are merely a chemical combination of one starting unit, known as a monomer, into many repeating units. The properties of the polymer are a function of the relative molecular mass (M_r, the number of repeating units) and the chemical structure of the monomer. Some of the more common polymer types used as viscosity modifiers include poly-alpha-olefin, poly-isobutylene, poly-alkyl-acrylate and -methacrylate, and olefin copolymers.

In addition to altering the viscosity-temperature properties of the finished fluid the choice of polymer can also have an impact on the supporting film in the gear and bearing contact regions. The film formed in the contact will be a function of the temperature, pressure and velocity of the surfaces that come into contact with each other. On the negative side, polymers are subject to mechanical and thermal shearing which results in a temporary and/or permanent loss of viscosity. The rate of loss is directly proportional to the molecular weight (M_r) of the polymer, i.e., higher relative molecular mass polymers result in higher viscosity losses (see

Figure 3). Different polymer structures can also influence the response to pressure, temperature, and shear rate. Each of these parameters becomes important in the overall choice of a thickener.

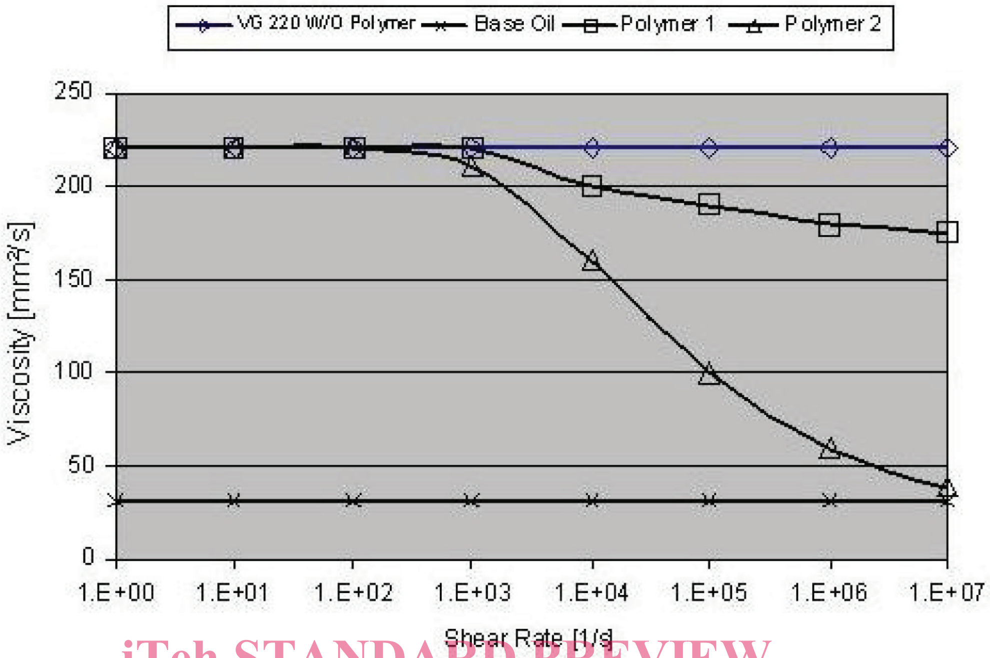


Figure 3 — Schematic diagram of shear effects on thickeners

3.5 Chemical properties of additives

Additives are typically a small (volume-wise), but critical part of the overall formulation. Additive is a broad term that encompasses many different chemicals, each providing performance or protection against certain types of damage or distress. These performance areas include, but are not limited to, antiwear (AW), extreme pressure (EP) or antiscuff, ferrous corrosion, non-ferrous corrosion, demulsibility, oxidation and foam inhibition. The chemicals impart or control these performance aspects in the application through reaction with the component surface or in the bulk oil phase. Most gear lubricants use a variety of chemicals in order to satisfy the many needs of the application. These chemicals must be selected properly not only for the desired performance function but for compatibility with the other chemicals in the package so that performance is not degraded.

Most commercial gear lubricants contain additives or chemicals that enable them to meet specific performance requirements. Typical additives include: rust inhibitor, oxidation inhibitor, defoamant, AW and antiscuff agents. Many of the chemicals used to form the additive “package” are single function, but some can provide benefit in multiple areas. For example, certain thiophosphorus compounds while primarily used for AW can also provide protection against scuffing or function as oxidation inhibitors. As a minimum base, oils are treated with some type of rust inhibitor and antioxidant; these are commonly known as R&O or circulating oils. These oils are not intended for applications where boundary lubrication is expected to occur. Blends containing AW and antiscuff agents are generally referred to as EP oils.

Additives alone, however, do not establish oil quality with respect to oxidation resistance, demulsibility, low temperature viscomentrics and viscosity index. Lubricant producers do not usually state which compounds are used to enhance the lubricant quality, but only specify the generic function such as AW, EP agents, or oxidation inhibitors. Furthermore, producers do not always use the same additive to accomplish a particular goal. Consequently, it is possible for any two brands selected for the same application not to be chemically identical. Users should be aware of these differences, which can have significant consequences when mixing different products. Another important consideration is incompatibility of lubricant types. Some oils, such as those used in turbine, hydraulic, and gear applications, are naturally acidic. Other oils, such as engine oils and some automotive driveline fluids, are alkaline. Acidic and alkaline lubricants are incompatible. Oils for similar