BEST PRACTICES NOTEBOOK

Selecting the correct lubricant

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Before making your decision, evaluate the component function, lubricant film requirement and lubricant capability.

Article highlights:

■ The six functions of a lubricant.

■ Hydrodynamic vs. elastohydrodynamic film regimes.

■ Overview of basestocks and key additives.

■ Three types of common finished lubricants.

Lubricant selection is a pivotal starting point in the pursuit of precision lubrication practices. All the effort applied to clean delivery and handling, filtration, dehydration, alignment, balancing, etc., is lost if the lubricant cannot support the demands placed upon the lubricant film when the machine is running.

Quality-conscious lubricant manufacturers provide field support to ensure products are properly selected for their customers' machines. In the end, though, the lubricant supplier doesn't face production losses and severe organizational stress when the machine fails. Regardless of the amount of effort provided by the supplier, the machine owner must be aware of which products were selected and whether the selections meet the demands imposed by the production process and environment.

It is to the equipment owner's benefit to have the entire mechanical staff (millwrights, mechanics, lubrication technicians, maintenance planners, mainte-

nance engineers) understand these general ideas. In addition, a few of them need to master lubricant selection and management criteria in order to develop reliability-centered lubrication practices.

This article addresses the nature of oil film formation and properties of fluid oil lubricants that are important to the selection process. Greases, solid film lubricants and additives will be addressed in a later article. Gases will not be addressed in this series since gases are not commonly used as lubricants for machines operating in industrial service.

Lubricant functions

It's been said that the industrial world floats on a 10-micron film of oil. If only that were true! The reality is much less assuring: components that roll together ride on an oil film in the 0.5 to 1.5 micron range, and components that slide together experience a relatively fat 3- to 5-micron thick film. That the lubricant is capable of sustaining itself at these dimensions is remarkable.

The lubricant has six clear responsibilities:

1. Reduce friction. Friction occurs when surface high spots, called asperities, collide. The small surface area of the asperity, combined with the full load of the machine components and production materials, causes extremely high unit loads. Machine surfaces resist movement under these circumstances. This resistance to movement is called friction.

2. Reduce wear. Wear occurs between machine surfaces when the asperities and/or surrounding surfaces cut, tear, fatigue and weld. These surface-to-surface wear modes occur at a microscopic level, well below the sensitivity of our humans senses and are consequently overlooked until the components require repair. There are other common wear modes for industrial machines that are fluid to surface in nature, including cavitation, corrosion and erosion (which are all fluid-to-surface wear modes).

3. Remove heat. The microscopic oil film absorbs heat from the machine's surfaces and transfers that heat into the sump, the machine casing and eventually the local atmosphere or a heat-removal device. The key work of heat removal occurs at the point where the machine surfaces interact with the microscopic film.

4. Remove contaminants. Fluid lubricants collect any wear debris or atmospheric debris or fluid contaminants from the working contact area and transfer the contaminants away from the working zone. Semisolid and solid-type lubricants are unable to perform this role as efficiently as a liquid

lubricant, but the responsibility still exists.

5. Control corrosion. Some production environments contain large concentrations of either moisture or corrosive chemicals. These environments seep into the production machines through the normal heating and cooling process. The lubricant is equipped to resist the corrosive action of moisture and mild production environments. The need for corrosion control is pronounced in combustion (spark and compression ignited) engines. In addition, as the lubricant ages it becomes more corrosive itself and must be fortified to prevent corrosion attack of the surfaces that it is assigned to protect.

6. Provide a means for power transfer. This function may be debated on semantic terms. In a hydraulic system, the lubricant (hydraulic oil) provides a dual function: fulfilling these previously noted obligations and providing the means through which electrical energy is converted to fluid energy (increased pressure) and transferred through the hydraulic system piping to mechanical components where work can be accomplished. Power transfer also occurs through fluid clutch applications in many industrial systems.[1]

The six responsibilities of a lubricant

Reduce Friction	→	separate surfaces
Reduce Wear	→	separate surfaces
Control Heat	→	separate surfaces & adsorb heat
Control Corrosion	→	provide surface coating
Control Contamination	→	seal out/flush away contaminants
Hydro-mechanical Power	→	transmit pressure

The lubricant performs these functions by creating a fluid cushion between the interacting machine components and by continuously flushing the interacting surfaces. As was previously stated, the fluid cushion is not very thick, but it only needs to be thick enough to separate the surfaces and clear the high spots (asperities) between the two surfaces. Table 1 shows the typical roughness of surfaces based on common machine surface finishing techniques.

Table 1. Common surface roughness dimensions

Surface Type	RMS, μ	Max, μ
Turned	2.8	12.0
Ground	0.6	3.0
Fine Ground	0.2	0.8
Lapped	0.04	0.2

The most common interacting surfaces include various types and sizes of bearings (plain journal bearings; element bearings [roller, ball, spherical roller, needle, tapered thrust]; gears (spur, helical, hypoid, worm); pump surfaces (gear, sliding vane, piston); and other incidental components (linear screw, ball joint, spline, pivot, bushing, etc.). All of these components interact in a sliding action, a rolling action or a combination of the two.

Film formation

Four factors influence the type of oil films that develop and the speed with which they develop:

- The size of the lubricated machine surface (area).

- The type of surface interaction (sliding or rolling).

- The speed with which the machine surfaces interact.

- The viscosity of the lubricant supplied to the machine.

The machine designer controls the component surface area, the nature of the interaction of the surfaces (rolling or sliding) and the speed at which the surfaces interact (at least initially). It is worth noting that the machine load and lubricant viscosity dimensions don't determine the type of oil film but do greatly influence the lowest speed requirement for film formation and whether the film can be maintained at normal running speed.

The type of oil film created within the machine is dependent on the nature of the machine component interactions. When machine components experience sliding interaction (such as a journal and plain bearing), the resulting lubricant film is called a *hydrodynamic* (HD) oil film, as shown in Figure 1. A water skier floats on a hydrodynamic film when the skier achieves enough speed to rise on top of the water on a pressure wedge formed between the ski and the water. If the skis are enlarged, the required speed to lift the skier declines and vice versa.
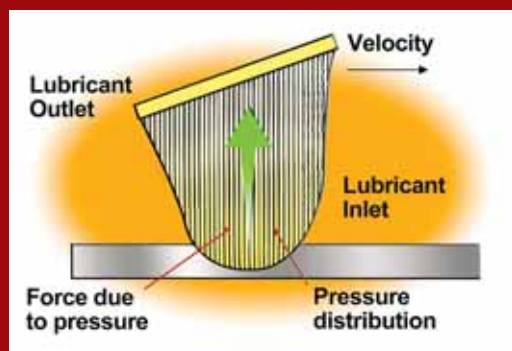
Machine hydrodynamic films occur in a similar fashion with the moment of lift being dictated by the combined influences of component surface area, machine speed, machine load and lubricant viscosity. HD oils films are, relatively speaking, fairly fat at 3 to 10 micrometers thick.

The type of oil film created by components that experience rolling interaction is called *elastohydrodynamic* (EHD) oil film, as shown in Figure 2. The dynamics surrounding this type of oil film are similar to that of a tire hydroplaning on a wet pavement surface. This type of lifting action begins with the tire creating a flat spot where it contacts the road. Without the flat spot the tire would not have enough surface area in contact with the pavement to hold onto the road surface. The tire must be soft enough to deflect at the point of contact with the pavement but firm enough to withstand long-term rubbing against the dry pavement.

On a wet surface, though, the flat spot provides enough surface area that, at a given speed, the vehicle can float on a very thin film of water resting on the pavement. The thicker the film of water, the lower the speed required to make the vehicle float.

EHD oil films are relatively thin, ranging from 0.5 to 1.5 micrometers thick. These films occur wherever machine surfaces interact with a rolling motion. One or both of these surfaces experience a momentary deformation, just like a tire. The resulting flat spot provides enough surface area that at some speed of interaction the rolling surface floats. The wider the surface and the thicker the oil, the lower the speed at which the machine surface floats.

Regardless of the nature of the oil film (HD or EHD), films form after reaching an equilibrium state where the oil (lubricant) is being supplied into the gap at a high enough rate that the squeezing force applied by the machine cannot push it out of the way. When that balance is reached the

Figure 1. Hydrodynamic oil film

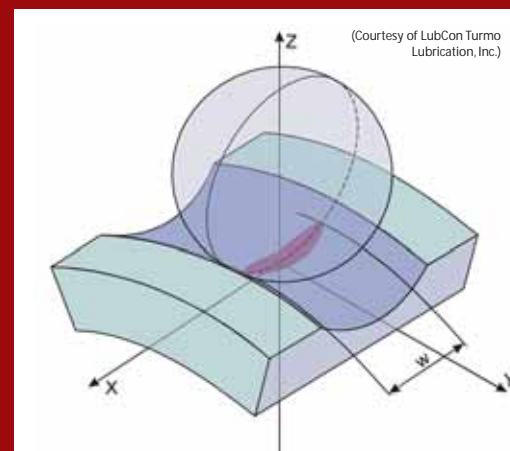### Figure 2. Elastohydrodynamic film formation

(Courtesy of LubCon Turmo Lubrication, Inc.)

Table 2. The API base stock categories

API Product Groups	Group I	Group II	Group III	Group IV	Group V
	Solvent Refined	Hydrocracked / Hydrotreated	Hydrocracked / Hydro Isomerized	Poly alpha Olefin Synthetic	All Other Synthetic
Viscosity Index	90 - 95	97 - 106	115	130	125
Pour Point, °C	-15	-15	-18	-21	< -60
Volatility, NOACK %	23	14 - 15	14 - 15	12	11 - 12
Biodegradability, %	30 - 40		60	70	65
The Following values are dependent on the test methods used					
% Most Desireable	45 - 60	65 - 70	~75	~90	99 - 100
% Saturates	75 - 85	90 - 98	90 - 98	98 - 100	~100
% Aromatics	5 - 25	0.3	0.3	0.1	0

pressure that builds at the point of machine surface interaction overcomes the machine dynamic load and the surfaces separate.

There are several factors that influence the long-term stability of the HD or EHD films:

■ The type of materials used to create the machine surfaces (both surfaces).

■ The way the lubricant is applied to the machine (static-bath or dynamic-forced flow).

■ The total (static) load that is applied to the machine surface.

■ The degree of "shock loads" or dynamic load peaks that occur during operation.

■ The lubricant itself (viscosity, additive types, ongoing maintenance of lubricant health).

These factors influence the extent to which the oil film is adequate for the machine's routine operating state, and/or whether specialized additives are required to provide an additional protective physi-chemical surface protection film.

The performance properties required from a lubricant are based on a combination of the type of film that forms when the machine is running, the machine's ability to sustain the full fluid film during normal operation and the machine's operating environment. These factors may change somewhat during operation but mostly are set by the machine designer and the production process itself.

Now let's examine lubricant composition and function.

Basestocks

A lubricant is a complex organic chemical blend of complimentary and competing ingredients. Creating a successful lubricant is a balance of chemical engineering and trial and error and requires a tremendous amount of testing during development.

The largest component of the lubricant, and the part of the lubricant that does most of the work, is the basestock. The basestock can be any one of a wide variety of man-made (synthetic) or nature-made (refined petroleum) materials.

In 1993 the American Petroleum Institute (API) began categorizing base oils by their production methods in order to differentiate between conventional and higher performance materials that the lubricants industry was starting to produce. As shown in Table 2, there are five categories[i] of materials with varying degrees of quality and performance characteristics. Mineral oil-based products are identified as either Group I, II or III, and the remaining two groups are reserved for man-made synthetic base oil types.[ii]

Footnotes

[i] American Petroleum Institute Publication 1509. API Base Stock Categories.

[ii] Kramer, D.C., Lok, B.K. and Krug, R. R., "The Evolution of Base Oil Technology," *Turbine Lubrication in the 21st Century*, ASTM STP **#1407**, Herguth, W.R. and Warne, T.M., Eds., American Society of Testing and Materials, West Conshohocken, Pa.

API Group I (G-I) base oils are manufactured by the solvent-extraction refining technique. This technique, pioneered in the 1930s, separates oil molecules by size and uses solvents to wash out some of the harmful constituents (some wax, some aromatic species) found in raw crude petroleum.

G-I base oils are comprised of three primary molecule types (paraffinic, naphthenic and aromatic) as well as a variety of sulfur- and nitrogen-based compounds. G-I oils, as shown in Table 3, contain a large amount of unsaturated molecules, aromatics and polar compounds and may contain appreciable sulfur. These polar constituents are responsible for accelerating aging and degradation of finished lubricants.

Some aromatic compounds and sulfur-containing materials behave as natural antioxidants in the absence of specific oxidation-inhibiting agents (additives).[2] However, these species of molecules also can interfere with the function of the primary antioxidants (amines and phenols) added to interrupt the oxidation-reaction processes. It is also well known that the sulfur compounds and aromatic molecule structures themselves are unstable and tend to react rapidly with oxygen to form various soluble and insoluble oxidation degradation byproducts.

Table 3. Properties of light neutral base oils[3]

	Solvent Refined 100N Base Oil	Hydrocracked 100N Base Oil
Clay Gel Analysis (ASTM D2007)		
Saturates, wt. %	85 – 90	>99
Aromatics, wt. %	9-15	<1
Polar compounds, wt. %	0-1	0
Sulfur, wt. %	.05 - .11	<.001
Nitrogen, PPM	20 – 50	<2
Color (ASTM D1500)	0.5 – 1.0	<0.5

A hydrotreating process was added to solvent refining techniques in the 1950s. Hydrotreating is a process where hydrogen is added to the basestock at high temperatures and in the presence of a catalyst in order to stabilize the reactive components, improve the color and extend the useful life of the finished lubricant product. This step helped improve product quality but was not severe enough to fully neutralize the aromatic components in the finished products. Roughly two-thirds of lubricant base oil in North America is produced using the solvent-refining technique.[4]

Group II (G-II) base oils follow a processing path similar to the G-I products except that instead of using solvents to extract the problematic compounds, G-II oils are "hydrocracked." Hydrocracking techniques, borrowed from fuel-refining processes, are a more severe hydrogen processing method wherein hydrogen is added to the base oil feed at much higher temperatures and pressures than with conventional hydrotreating. The hydrogen catalytically reacts with the basestock, restructures the naphthenic and aromatic molecules and eliminates sulfur and nitrogen components. This is accomplished through a series of molecular rearrangements (formation of paraffin isomers, breaking of long chain molecules and ring structures).

Group III (G-III) base oils follow the same hydrogen processing path as the G-IIs except they are more severely treated (higher pressure, higher temperature, longer process times). G-III oils perform on par with, and in some cases superior to, some synthetic Group IV (polyalphaolefin) types.

Group IV (G-IV) and Group V (G-V) base oil stocks are man-made. The G-IV base oil category is reserved for a single type of basestock called polyalphaolefin (also known as PAO and synthetic hydrocarbon). PAOs are made from ethylene (derived from petroleum) but are not hydrocarbons in the naturally occurring sense. G-V base oils are made using a wide variety of hydrocarbon and non-hydrocarbon raw materials and are also strictly man-made.

The performance properties of the G-III, G-IV and G-V basestocks are fairly predictable, both the pros and cons. Given their production methods, their cost of raw materials and their relatively low demand levels, the prices are higher than Group I and Group II products. The resulting finished lubricants purchase prices range from three to 10 times that of Group I and Group II products.

Basestock characteristics are considered, according to the type of machine, to be lubricated and how the basestock supports the needs of the machine's components. Several key properties are considered:

1. **Compatibility.** Degree to which the basestock mixes with other hydrocarbons.
2. **Additive response.** Characteristics determining how the base oil and additives work together.
3. **Viscometrics.** Measures of viscosity, viscosity index and pour point.
4. **Safety.** Flash point and toxicity.
5. **Consistency.** Repeatability from batch to batch.
6. **Oxidation stability.** Influenced by raw material properties and response to antioxidants.
7. **Volatility.** Flash point and NOACK volatility (engine oils in particular).
8. **Appearance.** Color, cleanliness and clarity.

Additive types and functions

Individual additives impart chemical or physical reactions that create three different types of responses. An individual lubricant additive may:

1. Enhance existing favorable base oil properties (viscosity, pour point, water release).
2. Suppress existing unfavorable base oil properties (oxidation and corrosion control).
3. Impart properties to the lubricant that the base oil cannot provide (EP, AW performance).

Lubricant manufacturers use a variety of additives to support the basestock or add new properties. There are a few standardized recipes that lubricant manufacturers might use to create the common lubricant types: AW (antiwear), EP (extreme pressure), R&O (rust and oxidation inhibited).

For this reason, it is always best to avoid mixing different brands of lubricants, even within a particular viscosity grade and additive type. In addition, practitioner should know about the following specific additive properties:

1. Viscosity modifiers (VI improvers for high temperatures; pour point depressants for low temperatures).
2. Wear resistance additives (EP and AW).
3. Oxidation inhibitors.
4. Demulsifiers.
5. Foam inhibitors.

Viscosity modifiers help change the viscosity behavior of the lubricant across a temperature range. All base oils thin as the temperature rises. Viscosity modifiers help to slow the thinning process such that it is possible to use a lighter grade of oil for a cold-start requirement and still have sufficient oil thickness at normal operating temperature to protect the machine surfaces.

The tell-tale indicator for the use of a viscosity modifier is the 'W' designation in the label. A 80W90 gear oil is one designed to behave like 80-weight gear oil during cold start-up and perform like 90-weight oil once the machine has reached its normal operating temperature.

Pour point depressants help a lubricant stay fluid to lower temperatures than would otherwise be possible. Some lubricant base oils, particularly synthetics, remain fluid to extremely low temperatures (-40 F) and do not require any help in this area. Most petroleum base lubricants are either paraffinic or contain sufficient paraffin stocks and have a waxy component that causes the lubricant to solidify at low temperatures. The higher the viscosity grade, the higher the temperature at which the lubricant will solidify.

Pour point depressants prevent the waxy component (paraffin wax) from crystallizing, which, in turn, lowers the point at which the lubricant solidifies.

Wear resistance (EP and AW). There are two classes of surface-protecting additives that are commonly used in industrial machines. AW (antiwear) additives work by forming resilient films on metal surfaces that are somewhat like the layer of tarnish that forms on silver eating utensils. AW additives often include zinc phosphorous chemicals that adsorb onto the metal surface to create an organo-metallic oxide layer. This tarnish-like layer is easily rubbed off when the opposing metallic surfaces interact. The malleable oxide layer reforms and rubs away continuously, and at low operating component temperatures, leaving the machine component's metal surface intact.

EP (extreme pressure) additives function similarly but have quite a different end result. EP agents are intended to prevent seizure of surfaces due to severe metal contact where AW additives are intended to prevent ongoing wear due to light-to-moderate metal contact. EP additives operate by chemically reacting with a metallic surface following a destructive scoring or adhesive contact event. The event produces spike temperatures and the EP additives go to work at the localized hot surface. The EP agent, typically a sulphur-phosphorous compound, chemically reacts with the hot area forming an organo-metallic oxide layer that is softer and more forgiving than the underlying metal layer. Once the additives have bonded they are removed only after another adhesive or abrasive event scours away the organo-metallic film and underlying metal surface.

The difference between the two is the way the additives function and the amount of protection each offers. AW additives afford only mild wear

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protection. In severe wear environments, they provide little protection. When selecting oils for wear protection, it is necessary to gauge how much wear the normal operating environment will generate.

Oxidation inhibitors are provided to extend lubricant life cycles and reduce the formation of oxidation reaction byproducts in the sump. However, the primary driver for determining the type and amount of oxidation inhibitors is the base oil quality and type.

High operating temperatures, high moisture and air concentrations and the catalytic effects of wear metals all increase the need for oxidation inhibitors. The greater the additive treatment, the more complex the additive balance and the greater need for oxidation inhibitors.

Demulsifiers help the lubricant release moisture. This is important when the equipment is operating in very humid climates or in a plant atmosphere that is wet or humid. Paper mills, steel mills and food-processing operations have significant exposure to water-based process fluids.

Although oil is hydrophobic it still retains a certain amount of water from the atmosphere. Even at low levels moisture is particularly harmful to lubricated components and increases wear from cavitation, adhesion and abrasion. In addition, when mixed with heat and wear metals, moisture rapidly accelerates the rate of oxidation. Moisture control is one of several critical contamination control parameters.

Foam inhibitors help prevent accumulation of air (formation of a foam layer) in the oil sump. Air contains oxygen, which is a primary cause of oxidation. Foaming increases the extent of air-to-oil surface contact and increases oxidation. Low viscosities do not require foam-release agents. Medium to heavy grade oils (ISO 150 and higher) tend to retain air and benefit from foam inhibitors. This type of additive is one of the few additives that can be replaced if/when it is stripped from the lubricant through filtration or normal use.

Lubricant selection

Finished lubricants represent a carefully engineered balancing act between the strengths and weaknesses of the many types of additive agents and basestocks. Practitioners should be well aware of the performance properties of the three common types of finished lubricants.

■ R&O (rust and oxidation inhibited) lubricants are selected for machines that operate without any expected metallic component interaction (a constantly turning journal bearing, for example), where machines with interacting

components run with continuous moderate to high speeds and/or relatively low loads (pumps, compressors, bearing circulation systems) and where the lubricant is needed primarily to keep surfaces wetted and protect the surfaces from moisture-induced corrosion.

Table 4. Lubricant types, additive concentrations and typical applications

Application Type	Typical Additive Type	Additive % Used in Oil
Circulation Oil (Turbine, Compressor)	**R&O Classification –** Antioxidants, Corrosion Inhibitor, Defoamant, Demulsifier	0.5 to 5%
Hydraulic Oil (Non FR Hydraulic)	**AW Classification –** Antiwear Agents, Antioxidants, Defoamant, Demulsifier, Corrosion Inhibitors, Pour Point and VI Improvers	2.0 to 5.0%
Gear Oils (Automotive and Industrial Torque Reducer / Increaser, Geared Drive)	**EP Classification –** Antiwear Agents, Antiseizure Agents, Antioxidants, Defoamant, Demulsifier, Corrosion Inhibitors, Pour Point and VI Improvers	2.0 to 10.0%
Engine Oils (Gasoline, Diesel, Natural Gas)	**PCMO/DEO Classification –** Antiwear Agents, Antioxidants, Defoamant, Corrosion Inhibitors, Dispersants, Alkaline Reserve, Pour Point & VI Improvers	10.0 to 30.0%

■ Antiwear lubricants are selected for machines that operate with expected metallic component interaction but where the interactions are moderate to low loads and generally moderate to high speeds. These conditions are found almost universally in hydraulic applications where a significant amount of the AW product type is found. Other machines with light and continuous machine interactions also may be served with AW products, such as plain and element bearing circulation systems, crankcase applications (compressor crankcases) and some instances of chain bath lubrication.

Finished lubricants are a carefully engineered balancing act between the strengths and weaknesses of the many types of additive agents and basestocks.

■ EP lubricants are selected for machine applications that operate routinely (by design) with continuous component interaction or with high continuous loads and intermittent shock loading. EP lubricants are typically recommended for geared machines (excluding those with internal backstops and yellow-metal gears).

Conclusion

Machine surface interactions dictate the type of oil films that form during normal machine use. Lubricant chemists work to define the types of conditions that exist and match the best blend of lubricant basestocks and additives to meet lubricant film requirements. There are many individual additive functions, and three common types of finished lubricant: EP, AW and R&O product types. Each of these product types can be achieved by blending a wide variety of petro-chemical compounds, and some of these compounds conflict with one another. Therefore, it is generally best not to mix finished lubricants.

Once the lubricant types and grades are understood, it is possible to apply a systematic process for identifying the best options from the wide vari-

ety of combinations of base oils, additives and lubricant weight grades.

In ensuing articles we will look more closely at the oil films and the physi-chemical barrier films. We'll also go through a systematic process for selecting specific product types and grades for five common types of industrial machine components. **TLT**

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