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Lubricating Oil Additives

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1. Introduction

1.1 Lubrication (Rizvi, 2009)

The principle of supporting a sliding load on a friction reducing film is known as lubrication (Ludema, 1996). The substance of which the film is composed is a lubricant, and to apply it is to lubricate. These are not new concepts, nor, in their essence, particularly involved ones. Farmers lubricated the axles of their ox carts with animal fat centuries ago. But modern machinery has become many times more complicated since the days of the ox cart, and the demands placed upon the lubricant have become proportionally more exacting. Though the basic principle still prevails the prevention of metal-to-metal contact by means of an intervening layer of fluid or fluid-like material.

1.2 Lubricants (Rizvi, 2009; Ludema, 1996; and Leslie, 2003)

All liquids will provide lubrication of a sort, but some do it a great deal better than others. The difference between one lubricating material and another is often the difference between successful operation of a machine and failure.

Modern equipment must be lubricated in order to prolong its lifetime. A lubricant performs a number of critical functions. These include lubrication, cooling, cleaning and suspending, and protecting metal surfaces against corrosive damage. Lubricant comprises a base fluid and an additive package. The primary function of the base fluid is to lubricate and act as a carrier of additives. The function of additives is either to enhance an already-existing property of the base fluid or to add a new property. The examples of already-existing properties include viscosity, viscosity index, pour point, and oxidation resistance. The examples of new properties include cleaning and suspending ability, antiwear performance, and corrosion control.

Engine oil at the dawn of the automotive era was not highly specialized or standardized, and exceedingly frequent oil changes were required.

Engine oil lubricants make up nearly one half of the lubricant market and therefore attract a lot of interest. The principal function of the engine oil lubricant is to extend the life of moving parts operating under many different conditions of speed, temperature, and pressure. At low temperatures the lubricant is expected to flow sufficiently in order that moving parts are not starved of oil. At higher temperatures they are expected to keep the

moving parts apart to minimize wear. The lubricant does this by reducing friction and removing heat from moving parts. Contaminants pose an additional problem, as they accumulate in the engine during operation. The contaminants may be wear debris, sludges, soot particles, acids, or peroxides. An important function of the lubricant is to prevent these contaminants from doing any damage.

The lube oil base stock is the building block with respect to which appropriate additives are selected and properly blended to achieve a delicate balance in performance characteristics of the finished lubricant. Various base stock manufacturing processes can all produce base stocks with the necessary characteristics to formulate finished lubricants with the desirable performance levels. The key to achieving the highest levels of performance in finished lubricants is in the understanding of the interactions of base stocks and additives and matching those to requirements of machinery and operating conditions to which they can be subjected.

1.3 Additives

Additives, (Rizvi, 2009, Ludema, 1996, and Leslie, 2003), are chemical compounds added to lubricating oils to impart specific properties to the finished oils. Some additives impart new and useful properties to the lubricant; some enhance properties already present, while some act to reduce the rate at which undesirable changes take place in the product during its service life. Additives, in improving the performance characteristics of lubricating oils, have aided significantly in the development of improved prime movers and industrial machinery.

Modern passenger car engines, automatic transmissions, hypoid gears, railroad and marine diesel engines, high speed gas and steam turbines, and industrial processing machinery, as well as many other types of equipment, would have been greatly retarded in their development were it not for additives and the performance benefits they provide.

Additives for lubricating oils were used first during the 1920s, and their use has since increased tremendously. Today, practically all types of lubricating oil contain at least one additive, and some oils contain additives of several different types. The amount of additive used varies from a few hundredths of a percent to 30% or more.

Over a period of many years, oil additives were identified that solved a variety of engine problems: corrosion inhibition, ability to keep particles such as soot dispersed, ability to prohibit acidic combustion products from plating out as varnish on engine surfaces, and ability to minimize wear by laying down a chemical film on heavily loaded surfaces. In addition, engine oil became specialized so that requirements for diesel engine oils began to diverge from requirements for gasoline engines, since enhanced dispersive capability was needed to keep soot from clumping in the oil of diesel engines.

The more commonly used additives are discussed in the following sections. Although some are multifunctional, as in the case of certain viscosity index improvers that also function as pour point depressants or dispersants or antiwear agents that also function as oxidation inhibitors, they are discussed in terms of their primary function only.

1.3.1 Friction Modifiers (FM) (Ludema, 1996)

These are additives that usually reduce friction (Battez et al., 2010 & Mel'nikov, 1997). The mechanism of their performance is similar to that of the rust and corrosion inhibitors in that they form durable low resistance lubricant films via adsorption on surfaces and via association with the oil, Figure (1.1).

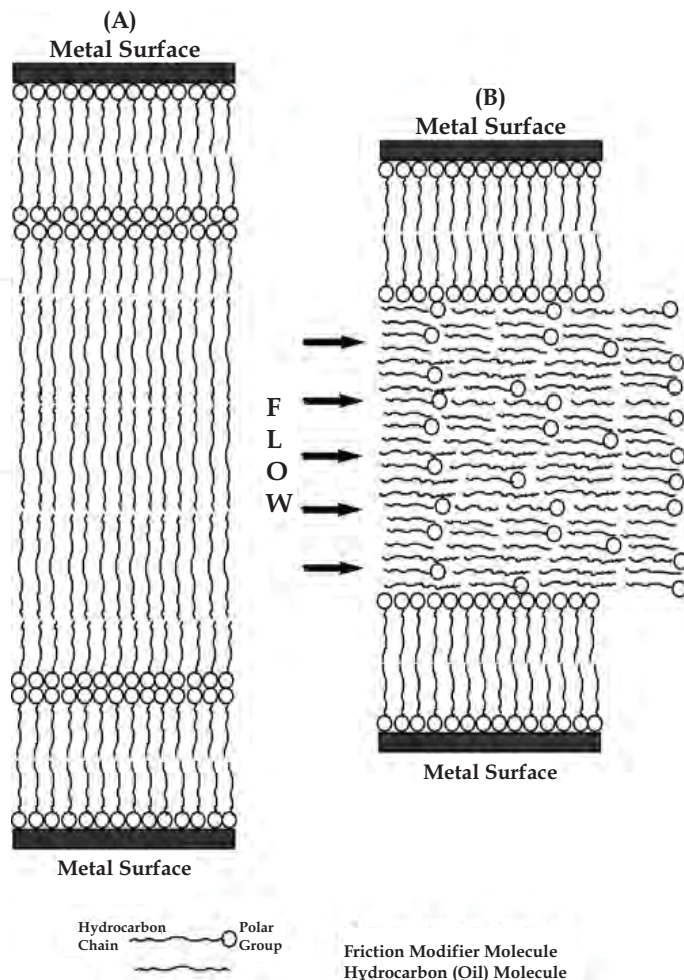


Fig. 1.1 Adsorption of friction modifiers on metal (A) Steady state (B) Under shear

Common materials that are used for this purpose include long-chain fatty acids, their derivatives, and the molybdenum compounds. In addition to reducing friction, the friction modifiers also reduce wear, especially at low temperatures where the anti-wear agents are inactive, and they improve fuel efficiency.

1.3.2 Anti-wear agents (A.W.) and extreme-pressure (E.P.) additives

Anti-wear (AW) (Rizvi, 2009, Ludema, 1996, Leslie, 2003, and Masabumi, 2008), agents have a lower activation temperature than the extreme-pressure (EP) agents. The latter are also referred to as anti-seize and anti-scuffing additives. Organosulfur and organo-phosphorus compounds, Figure (1.2), such as organic polysulfides, phosphates, dithiophosphates, and dithiocarbamates are the most commonly used AW and EP, Rizvi, 2009, Ludema, 1996, Leslie, 2003, agents.

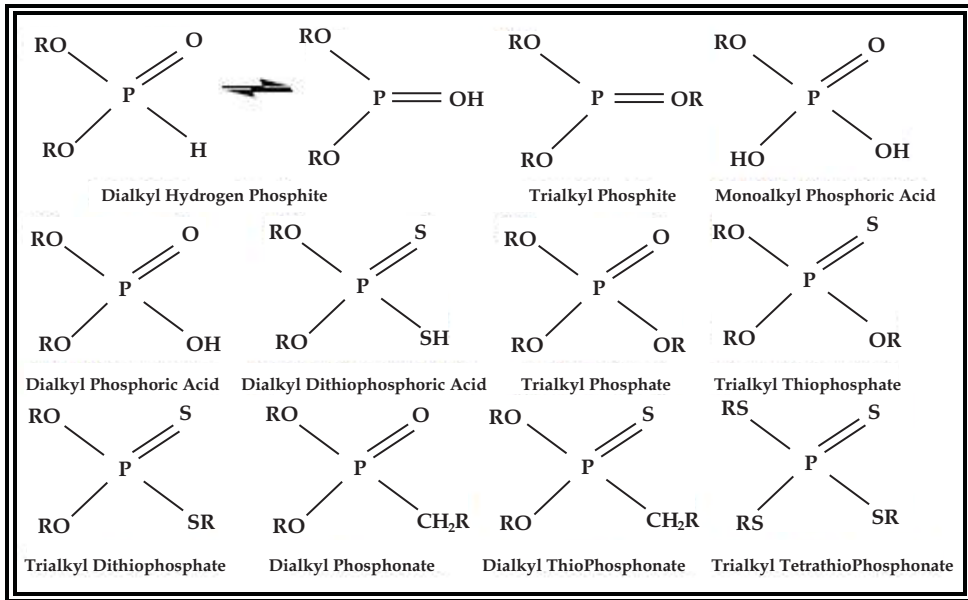
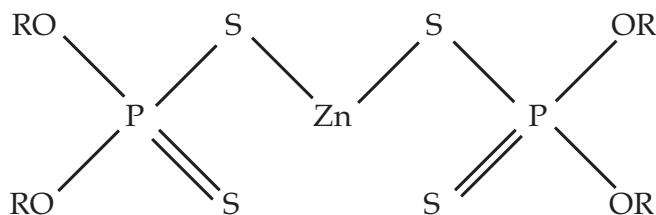


Fig. 1.2 Common phosphorus derivatives used as antiwear agents / extreme-pressure

As the power of engines has risen, the need for additives to prevent wear has become more important. Initially engines were lightly loaded and could withstand the loading on the bearings and valve train. Corrosive protection of bearing metals was one of the early requirements for engine oils. Fortunately, the additives used to protect bearings usually had mild antiwear properties. These antiwear agents were compounds such as lead salts of long-chain carboxylic acids and were often used in combination with sulfur-containing materials. Oil-soluble sulfur-phosphorous and chlorinated compounds also worked well as antiwear agents. However, the most important advance in antiwear chemistry was made during the 1930s and 1940s with the discovery of zinc dialkyldithiophosphates (ZDDP) (Masabumi, et. al., 2008). These compounds were initially used to prevent bearing corrosion but were later found to have exceptional antioxidant and antiwear properties. The antioxidant mechanism of the ZDDP was the key to its ability to reduce bearing corrosion. Since the ZDDP suppresses the formation of peroxides, it prevents the corrosion of Cu/Pb bearings by organic acids. Antiwear and extreme-pressure additives function by thermally decomposing to yield compounds that react with the metal surface. These surface-active compounds form a thin layer that preferentially shears under boundary lubrication conditions.

After the discovery of ZDDP, Figure (1.3) it rapidly became the most widespread antiwear additive used in lubricants. As a result, many interesting studies have been undertaken on ZDDP with many mechanisms proposed for the antiwear and antioxidant action (Masabumi, et. al., 2008).

Extreme pressure additives form extremely durable protective films by thermo-chemically reacting with the metal surfaces. This film can withstand extreme temperatures and mechanical pressures and minimizes direct contact between surfaces, thereby protecting them from scoring and seizing.



The R group may be alkyl or aryl

Fig. 1.3 Zinc dithiophosphate as antiwear additives / extreme pressure

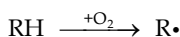
1.3.3 Antioxidant additives (AO)

One of the most important aspects of lubricating oils is that the oxidation stability be maximized. Exposure of hydrocarbons to oxygen and heat will accelerate the oxidation process. The internal combustion engine is an excellent chemical reactor for catalyzing the process of oxidation. Also, the engine's metal parts, such as copper and iron, act as effective oxidation catalysts. Thus, engine oils are probably more susceptible to oxidation than any other lubricant application.

Oxidation mechanism of lubricating oils

The lubricating oils consist of hydrocarbons with ($C_{20} - C_{70}$) carbon atoms. At higher temperature these hydrocarbons are oxidized to form fatty acids, fatty alcohols, fatty aldehydes and ketones, fatty esters and fatty peroxides as shown in the following mechanism, Figure (1.4). All these compounds form the solid asphaltic materials. For this reason, the addition of antioxidants is necessary to all lubricating oils to prevent the formation of such compounds.

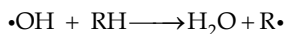
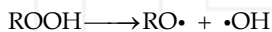
Initiation



Chain propagation



Chain branching



Termination

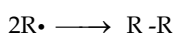


Fig. 1.4 Oxidation mechanism of lubricating oils

Inhibition effects of antioxidants on lubricating oil oxidations

It is known that high temperature, high pressure, high friction, and high metal concentration in motors, lead to oxidation of lubricating oil it is necessary to improve oil stabilities against oxidation. Oxidation generally increase oil viscosity and results in formation of the following compounds:

- Resins, which are oxygen-containing compounds, soluble in oil and can, lead to lacquer formation.
- Lacquers, slightly colored, relatively plastic, and can form deposits on various engine parts (particularly on piston skirts).
- Insoluble asphaltic compounds, when associated in the oil with combustion residues and condensed water from sludge.
- Acidic compounds and hydroperoxides, which may promote corrosion, particularly of hard alloy bearings.

Thus, addition of antioxidant additives to lubricating oils prevents the formation of all resins, lacquers and acidic compounds.

There is no relationship between the two rates of increasing the viscosity and acidity in the oxidation process. The rate of viscosity increased in direct proportion with the rate of decomposition of an organic peroxides. By studying the antioxidant additives mechanism in turbine aviation oils; it was shown that these antioxidants reacted with oxygenic free radical compounds to form the antioxidant N - oxide derivatives and thus decrease the quantity acids, alcohols, esters in the media. However, any lubricating oil exposed to air and heat will eventually oxidize. Antioxidants are the key additive that protects the lubricant from oxidative degradation, allowing the fluid to meet the demanding requirements for use in engines and industrial applications.

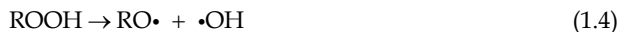
Antioxidant additives mechanism

To define the oxidation stability for lubricating oils, it is necessary to check the rate of acidity and viscosity increase with oxidation time during the oxidation process. Lubricating oils are susceptible to degradation by oxygen. The oil oxidation (Rizvi, 2009, Ludema, 1996, and Leslie, 2003) process is the major cause of oil thickening. This manifests itself as sludge and varnish formation on engine parts, leading to increased engine wear, poor lubrication, and reduced fuel economy. Antioxidants are essential additives incorporated into lubricant formulations to minimize and delay the onset of lubricant oxidative degradation.

The rate of acidity and viscosity was increased (in the oxidation process for oils) due to the continuous repetition of the oxidation process, where a chain reaction occurs. The oxidation process can be considered to progress in the following manner:



Decomposition of the hydroperoxide molecule caused by the so-called branching reaction leads to the formation of oxygen bearing compounds. Their oxidation products form high - molecular - weight -oil -insoluble polymers that settle as deposit causing an increase of oil viscosity. Decomposition of the hydroperoxide as follow:



During oxidation process, in a median period oil viscosity is increased although its acidity is remaining constant because there are alcohol's of unsaturated hydrocarbons, produced from decomposition of hydroperoxides process, so it neutralizes the effect of acidity formed from another oxygen bearing compound such as: aldehydes, ketones and acids.

The proceeding lubricant degradation mechanism makes clear several possible counter measures to control lubricant degradation. Blocking the energy source is one path but is effective only for lubricants used in low-shear and temperature situations. However, more practical for most lubricant applications are the trapping of catalytic impurities and the destruction of hydrocarbon radicals, alkyl peroxy radicals, and hydroperoxides. This can be achieved through the use of radical scavengers, peroxide decomposers, and metal deactivators.

The radical scavengers are known as *primary antioxidants*. They donate hydrogen atoms that react with alkyl radicals and/or alkyl peroxy radicals, interrupting the radical chain mechanism of the auto-oxidation process. The primary antioxidant then becomes a stable radical, the alkyl radical becomes a hydrocarbon, and the alkyl peroxy radical becomes an alkyl hydroperoxide. Hindered phenolics and aromatic amines are the two chemical classes of primary antioxidants for lubricants. The transfer of a hydrogen from the oxygen or nitrogen atom to the radical forms quinones or quinine imines that do not maintain the radical chain mechanism.

The peroxide decomposers are known as *secondary antioxidants* (Rizvi, 2009, Ludema, 1996, and Leslie, 2003). Sulfur and/or phosphorus compounds reduce the alkyl hydroperoxides in the radical chain to alcohols while being oxidized in a sacrificial manner. Zinc dialkyldithiophosphate, phosphites, and thio-ethers are examples of different chemical classes of secondary antioxidants.

There are two types of metal deactivators: chelating agents and film forming agents. The chelating agents will form a stable complex with metal ions, reducing the catalytic activity of the metal ions. Thus, the deactivators can show an antioxidant effect. Film-forming agents act two ways. First, they coat the metal surface, thus preventing metal ions from entering the oil. Second, they minimize corrosive attack of the metal surface by physically restricting access of the corrosive species to the metal surface.

Several effective antioxidants classes have been developed over the years and have seen use in engine oils, automatic transmission fluids, gear oils, turbine oils, compressor oils, greases, hydraulic fluids, and metal-working fluids. The main classes of oil-soluble organic and organo-metallic antioxidants are the following types:

1. Sulfur compounds
2. Phosphorus compounds
3. Sulfur-phosphorus compounds
4. Aromatic amine compounds
5. Hindered phenolic compounds
6. Organo-alkaline earth salt compounds
7. Organo-zinc compounds
8. Organo-copper compounds
9. Organo-molybdenum compounds

1.3.4 Anti-foam (A.F.) agents

The foaming of lubricants, (Rizvi, 2009, Ludema, 1996, and Leslie, 2003), is a very undesirable effect that can cause enhanced oxidation by the intensive mixture with air,

cavitation damage as well as insufficient oil transport in circulation systems that can even lead to lack of lubrication. Beside negative mechanical influences the foaming tendency depends very much on the lubricant itself and is influenced by the surface tension of the base oil and especially by the presence of surface-active substances such as detergents, corrosion inhibitors and other ionic compounds.

In many applications, there may be considerable tendency to agitate the oil and cause foaming, while in other cases even small amounts of foam can be extremely troublesome. In these cases, a defoamant may be added to the oil. It is thought that the defoamant droplets attach themselves to the air bubbles and can either spread or form unstable bridges between bubbles, which then coalesce into larger bubbles, which in turn rise more readily to the surface of the foam layer where they collapse, thus releasing the air.

1.3.5 Rust and corrosion inhibitors

Rust inhibitors, (Rizvi, 2009, Ludema, 1996, and Leslie, 2003), are usually compounds having a high polar attraction toward metal surfaces. By physical or chemical interaction at the metal surface, they form a tenacious, continuous film that prevents water from reaching the metal surface. Typical materials used for this purpose are amine succinates and alkaline earth sulfonates.

Rust inhibitors can be used in most types of lubricating oil, but the selection must be made carefully to avoid problems such as corrosion of nonferrous metals or the formation of troublesome emulsions with water. Because rust inhibitors are adsorbed on metal surfaces, an oil can be depleted of rust inhibitor in time.

A number of kinds of corrosion can occur in systems served by lubricating oils. Probably the two most important types are corrosion by organic acids that develop in the oil itself and corrosion by contaminants that are picked up and carried by the oil.

Corrosion by organic acids can occur, for example, in the bearing inserts used in internal combustion engines. Some of the metals used in these inserts, such as the lead in copper-lead or lead-bronze, are readily attacked by organic acids in oil. The corrosion inhibitors form a protective film on the bearing surfaces that prevents the corrosive materials from reaching or attacking the metal. The film may be either adsorbed on the metal or chemically bonded to it. It has been found that the inclusion of highly alkaline materials in the oil will help to neutralize these strong acids as they are formed, greatly reducing this corrosion and corrosive wear.

1.3.6 Detergent and dispersant (D / D) additives

Modern equipment must be lubricated in order to prolong its lifetime. One of the most critical properties of the automotive lubricants, especially engine oils, is their ability to suspend undesirable products from thermal and oxidative degradation of the lubricant. Such products form when the byproducts of fuel combustion, such as hydroperoxides and free radicals, go past piston rings into the lubricant and, being reactive species, initiate lubricant oxidation. The resulting oxidation products are thermally labile and decompose to highly polar materials with a tendency to separate from the bulk lubricant and form surface deposits and clog small openings.

Oxidation inhibitors, detergents (Rizvi, 2009, Ludema, 1996, Leslie, 2003, and Ming et. al., 2009), and dispersants (Alun, 2010) make up the general class of additives called *stabilizers and deposit control agents*. These additives are designed to control deposit formation, either by inhibiting the oxidative breakdown of the lubricant or by suspending the harmful

products already formed in the bulk lubricant. Oxidation inhibitors intercept the oxidation mechanism, and dispersants and detergents perform the suspending part (Kyunghyun, 2010). Detergents are metal salts of organic acids that frequently contain associated excess base, usually in the form of carbonate. Dispersants are metal-free and are of higher molecular weights than detergents. The two types of additives work in conjunction with each other.

The final products of combustion and lubricant decomposition include organic and inorganic acids, aldehydes, ketones, and other oxygenated materials. The acids have the propensity to attack metal surfaces and cause corrosive wear. Detergents, especially basic detergents, contain reserve base that will neutralize the acids to form salts. While this decreases the corrosive tendency of the acids, the solubility of the salts in the bulk lubricant is still low. The organic portion of the detergent, commonly called "soap", has the ability to associate with the salts to keep them suspended in the bulk lubricant. However, in this regard, detergents are not as effective as dispersants because of their lower molecular weight. The soap in detergents and the dispersants also have the ability to suspend non-acidic oxygenated products, such as alcohols, aldehydes, and resinous oxygenates. The mechanism by which this occurs is depicted in Figure (1.5).

Dispersants and detergents together make up the bulk, about 45-50%, of the total volume of the lubricant additives manufactured. This is a consequence of their major use in engine oils, transmission fluids, and tractor hydraulic fluids, all of which are high-volume lubricants.

As mentioned, detergents neutralize oxidation-derived acids as well as help suspend polar oxidation products in the bulk lubricant. Because of this, these additives control rust, corrosion, and resinous buildup in the engine. Like most additives detergents contain a surface-active polar functionality and an oleophilic hydrocarbon group, with an appropriate number of carbon atoms to ensure good oil solubility. Sulfonate, phenate, and carboxylate are the common polar groups present in detergent molecules. However, additives containing salicylate and thiophosphonate functional groups are also sometimes used, Figure (1.6).

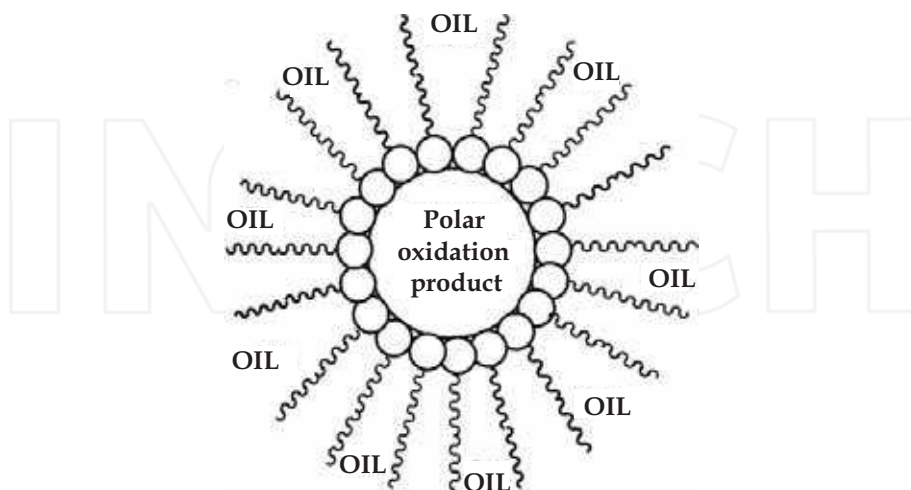


Fig. 1.5 Oil Suspension of polar oxidation products

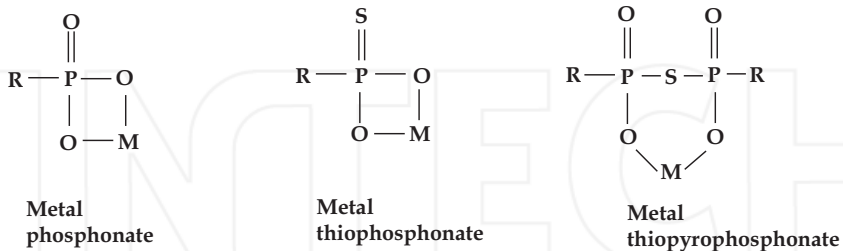
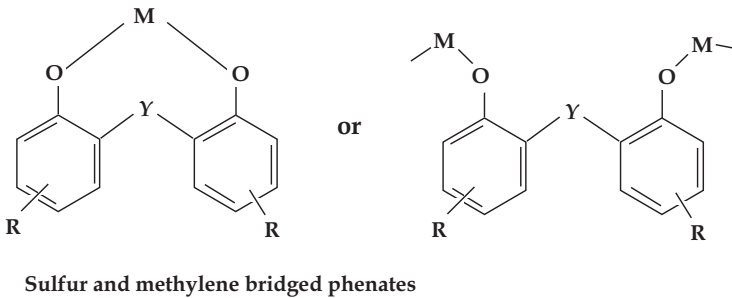
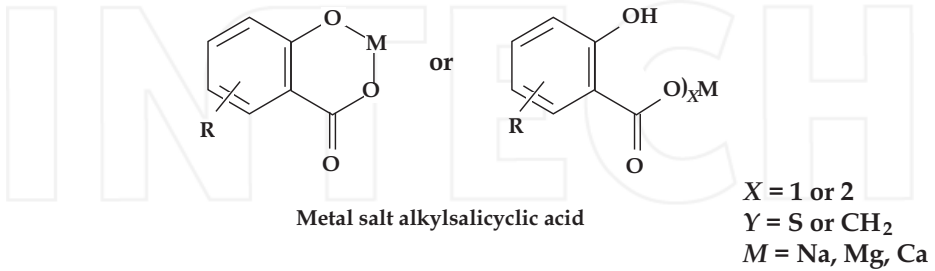
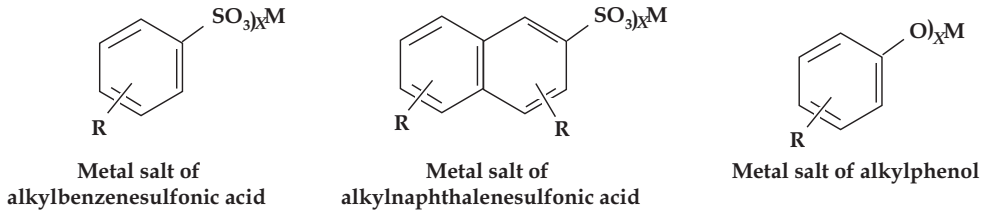


Fig. 1.6 Idealized structures of neutral salts (soaps)

As mentioned, common metals that can be used to make neutral or basic detergents include sodium, potassium, magnesium, calcium, and barium. Calcium and magnesium find most extensive use as lubricant additives, with a preference for calcium due to its lower cost. The use of barium-derived detergents is being curbed due to concerns for barium's toxicity. Technically, one can use metal oxides, hydroxides, and carbonates to manufacture neutral (non-overbased) detergents; for non-overbased detergents, oxides and hydroxides are the

preferred bases. For sodium, calcium, and barium detergents, sodium hydroxide, calcium hydroxide, and barium hydroxide are often used. For magnesium detergents, however, magnesium oxide is the preferred base. Dispersants differ from detergents in three significant ways:

1. Dispersants are metal-free, but detergents contain metals, such as magnesium, calcium, and sometimes barium. This means that on combustion detergents will lead to ash formation and dispersants will not.
2. Dispersants have little or no acid-neutralizing ability, but detergents do. This is because dispersants have either no basicity, as is the case in ester dispersants, or low basicity, as is the case in imide / amide dispersants. The basicity of the imide/amide dispersants is due to the presence of the amine functionality. Amines are weak bases and therefore possess minimal acid-neutralizing ability. Conversely, detergents, especially basic detergents, contain reserve metal bases as metal hydroxides and metal carbonates. These are strong bases, with the ability to neutralize combustion and oxidation-derived inorganic acids, such as sulfuric acid and nitric acid, and oxidation-derived organic acids.
3. Dispersants are much higher in molecular weight, approximately 4–15 times higher, than the organic portion (soap) of the detergent. Because of this, dispersants are more effective in fulfilling the suspending and cleaning functions than detergents.

The dispersants suspend deposit precursors in oil in a variety of ways. These comprise:

- Including the undesirable polar species into micelles.
- Associating with colloidal particles, thereby preventing them from agglomerating and falling out of solution.
- Suspending aggregates in the bulk lubricant, if they form.
- Modifying soot particles so as to prevent their aggregation. The aggregation will lead to oil thickening, a typical problem in heavy-duty diesel engine oils.
- Lowering the surface / interfacial energy of the polar species in order to prevent their adherence to metal surfaces.

At the low-temperature regions, such as the piston skirt, the deposits are not heavy and form only a thin film. For diesel engine pistons, this type of deposit is referred to as “lacquer”; for gasoline engine pistons, this type of deposit is called “varnish”. The difference between lacquer and varnish is that lacquer is lubricant-derived and varnish is largely fuel-derived. In addition, the two differ in their solubility characteristics. That is, lacquer is water-soluble and varnish is acetone soluble. Lacquer usually occurs on piston skirts, on cylinder walls, and in the combustion chamber. Varnish occurs on valve lifters, piston rings, piston skirts, valve covers, and positive crankcase ventilation (PCV) valves.

Another component of the combustion effluent that must be considered is soot. Soot not only contributes toward some types of deposits, such as carbon and sludge, but it also leads to a viscosity increase. These factors can cause poor lubricant circulation and lubricating film formation, both of which will result in wear and catastrophic failure.

Deposit control by dispersants

Fuel and lubricant oxidation and degradation products, such as soot, resin, varnish, lacquer, and carbon, are of low lubricant (hydrocarbon) solubility, with a propensity to separate on surfaces. The separation tendency of these materials is a consequence of their particle size. Small particles are more likely to stay in oil than large particles. Therefore, resin and soot particles, which are the two essential components of all deposit-forming species, must grow

in size via agglomeration prior to separation. Alternatively, soot particles are caught in the sticky resin, which is shown in parts A and B of Figure (1.7). Dispersants interfere in agglomeration by associating with individual resin and soot particles. The particles with associated dispersant molecules are unable to coalesce because of either steric factors or electrostatic factors. Dispersants consist of a polar group, usually oxygen- or nitrogen-based, and a large non polar group. The polar group associates with the polar particles, and the non polar group keeps such particles suspended in the bulk lubricant. This is shown in parts C and D of Figure (1.7). Neutral detergents, or soaps, operate by an analogous mechanism.

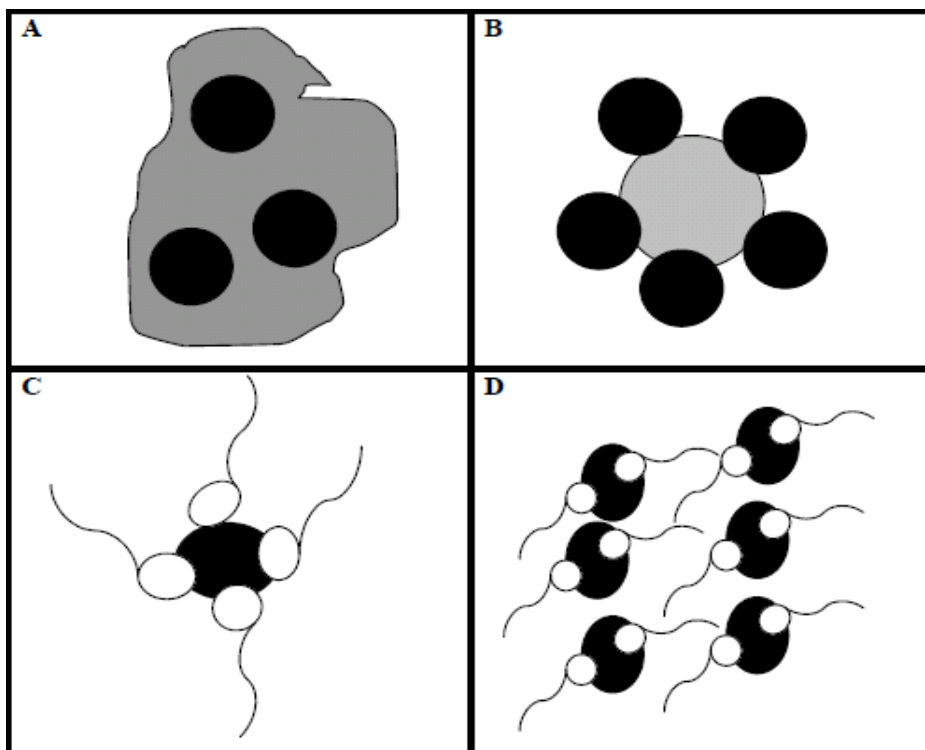


Fig. 1.7 Mechanism of soot-resin-additive interaction

Dispersant structure

A dispersant molecule consists of three distinct structural features:

A *hydrocarbon group*, a *polar group*, and a connecting group or a *link* (see Figure 1.8). The *hydrocarbon group* is polymeric in nature and, depending on its molecular weight; dispersants can be classified into *polymeric dispersants* and *dispersant polymers*. Polymeric dispersants are of lower molecular weight than dispersant polymers. The molecular weight of polymeric dispersants ranges between 3000 and 7000 as compared to dispersant polymers, which have a molecular weight of 25,000 and higher. While a variety of olefins, such as polyisobutylene, polypropylene, polyalphaolefins, and mixtures thereof, can be used to make polymeric dispersants, the polyisobutylene derived dispersants are the most common.

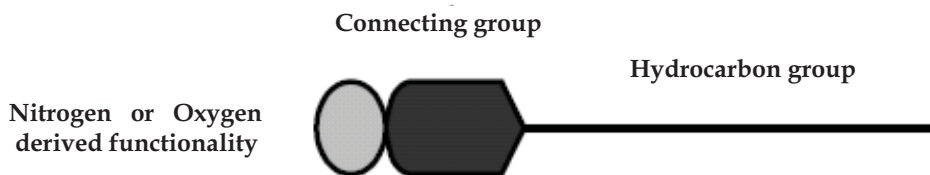


Fig. 1.8 Graphic representation of a dispersant molecule

1.3.7 Viscosity index improvers

Probably the most important single property of a lubricating oil is its viscosity. A factor in the formation of lubricating films under both thick and thin film conditions, viscosity (Rizvi, 2009, Ludema, 1996, Leslie, 2003 and Margareth, et. al., 2010), affects heat generation in bearings, cylinders, and gears; it governs the sealing effect of the oil and the rate of consumption or loss; and it determines the ease with which machines may be started under cold conditions. For any piece of equipment, the first essential for satisfactory results is to use an oil of proper viscosity to meet the operating conditions.

In selecting the proper oil for a given application, viscosity is a primary consideration. It must be high enough to provide proper lubricating films but not so high that friction losses in the oil will be excessive. Since viscosity varies with temperature, it is necessary to consider the actual operating temperature of the oil in the machine. Other considerations, such as whether a machine must be started at low ambient temperatures, must also be taken into account.

The kinematic viscosity of a fluid is the quotient of its dynamic viscosity divided by its density, both measured at the same temperature and in consistent units. The most common units for reporting kinematic viscosities now are the stokes (St) or centistokes (cSt; 1 cSt = 0.01 St), or in SI units, square millimeters per second (mm^2/s ; $1 \text{ mm}^2/\text{s} = 1 \text{ cSt}$). The viscosity of any fluid changes with temperature, increasing as the temperature is decreased, and decreasing as the temperature is increased. Thus, it is necessary to have some method of determining the viscosities of lubricating oils at temperatures other than those at which they are measured. This is usually accomplished by measuring the viscosity at two temperatures, then plotting these points on special viscosity-temperature charts developed by ASTM. The two temperatures most used for reporting viscosities are 40°C (104°F) and 100°C (212°F).

VI improvers are long chain, high molecular weight polymers that function by causing the relative viscosity of an oil to increase more at high temperatures than at low temperatures. Generally this result is due to a change in the polymer's physical configuration with increasing temperature of the mixture. It is postulated that in cold oil the molecules of the polymer adopt a coiled form so that their effect on viscosity is minimized. In hot oil, the molecules tend to straighten out, and the interaction between these long molecules and the oil produces a proportionally greater thickening effect.

As temperature increases, solubility improves, and polymer coils eventually expand to some maximum size and in so doing donate more and more viscosity. The process of coil expansion is entirely reversible as coil contraction occurs with decreasing temperature (see Figure 1.9).

Different oils have different rates of change of viscosity with temperature. For example, a distillate oil from a naphthenic base crude would show a greater rate of change of viscosity

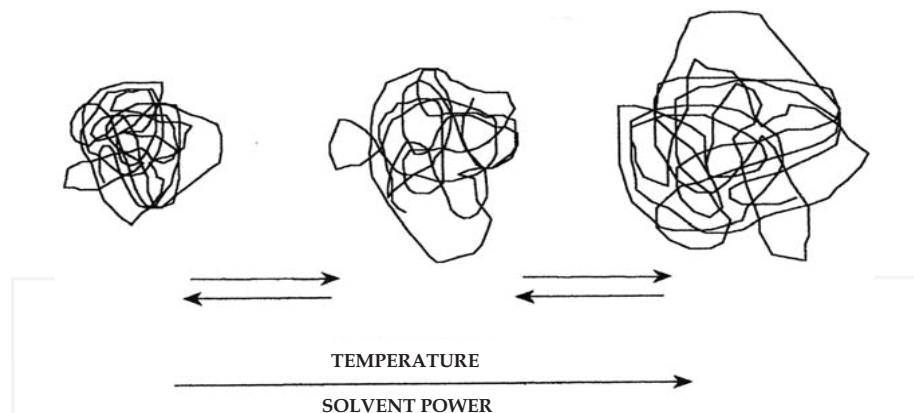


Fig. 1.9 Polymer coil expansion

with temperature than would a distillate oil from a paraffin crude. The viscosity index is a method of applying a numerical value to this rate of change, based on comparison with the relative rates of change of two arbitrarily selected types of oil that differ widely in this characteristic. A high *VI* indicates a relatively low rate of change of viscosity with temperature; a low *VI* indicates a relatively high rate of change of viscosity with temperature. For example, consider a high *VI* oil and a low *VI* oil having the same viscosity at, say, room temperature: as the temperature increased, the high *VI* oil would thin out less and, therefore, would have a higher viscosity than the low *VI* oil at higher temperatures. The *VI* of an oil is calculated from viscosities determined at two temperatures by means of tables published by ASTM. Tables based on viscosities determined at both 104°F and 212°F, and 40°C and 100°C are available. Finished mineral-based lubricating oils made by conventional methods range in *VI* from somewhat below 0 to slightly above 100. Mineral oil base stocks refined through special hydroprocessing techniques can have *VI*s well above 100.

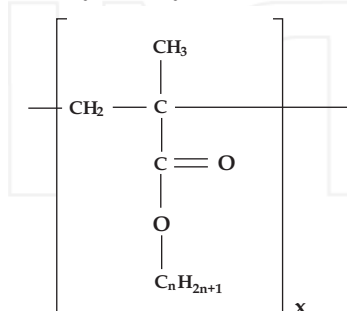
Additives called *VI* improvers can be blended into oils to increase *VI*s; however, *VI* improvers are not always stable in lubricating environments exposed to shear or thermal stressing. Accordingly, these additives must be used with due care to assure adequate viscosity over the anticipated service interval for the application for which they are intended.

Among the principal *VI* improvers are methacrylate polymers and copolymers, acrylate polymers, olefin polymers and copolymers, and styrene butadiene copolymers, Figure (1.10). The degree of *VI* improvement from these materials is a function of the molecular weight distribution of the polymer.

The long molecules in *VI* improvers are subject to degradation due to mechanical shearing in service. Shear breakdown occurs by two mechanisms. Temporary shear breakdown occurs under certain conditions of moderate shear stress and results in a temporary loss of viscosity. Apparently, under these conditions the long molecules of the *VI* improver align themselves in the direction of the stress, thus reducing resistance to flow. When the stress is removed, the molecules return to their usual random arrangement and the temporary viscosity loss is recovered. This effect can be beneficial in that it can temporarily reduce oil friction to permit easier starting, as in the cranking of a cold engine. Permanent shear breakdown occurs when the shear stresses actually rupture the long molecules, converting

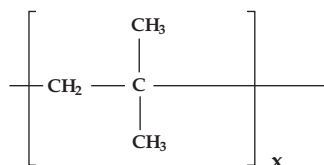
them into lower molecular weight materials, which are less effective *VI* improvers. This results in a permanent viscosity loss, which can be significant. It is generally the limiting factor controlling the maximum amount of *VI* improver that can be used in a particular oil blend. *VI* improvers are used in engine oils, automatic transmission fluids, multipurpose tractor fluids, and hydraulic fluids. They are also used in automotive gear lubricants. Their use permits the formulation of products that provide satisfactory lubrication over a much wider temperature range than is possible with straight mineral oils alone.

(a) Polymethacrylates (PMA)



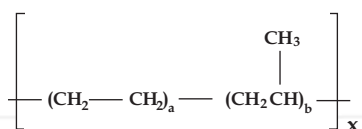
These are polymerised esters of methacrylic acid. They normally exhibit pour-point depressing activity. Dispersant properties can be obtained by incorporating polar groups in the molecular structure.

(b) Polyisobutenes (PIB)



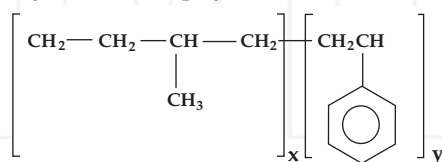
These are non-dispersant polymers and they have no effect on the pour point of formulated lubricants. They have limited use in modern formulations.

(c) Olefin co-polymers (OCP)



These are usually co-polymers of ethylene and propylene. Dispersant properties can be obtained incorporating polar groups in the molecular structure.

(d) Styrene/diene co-polymers



The molecular weight distribution is optimised to give good shear stability in crankcase applications. Its uniquely effective thickening power in solution gives an overall thickening efficiency that is superior to other polymers of equivalent shear stability.

Fig. 1.10 Viscosity index improvers

1.3.8 Pour point depressants

The pour point, (Rizvi, 2009, Ludema, 1996, and Leslie, 2003), *PP* of a lubricating oil is the lowest temperature at which it will pour or flow when it is chilled without disturbance

under prescribed conditions. Most mineral oils contain some dissolved wax and, as an oil is chilled, this wax begins to separate as crystal that interlock to form a rigid structure that traps the oil in small pockets in the structure.

When this wax crystal structure becomes sufficiently complete, the oil will no longer flow under the conditions of the test. Since, however, mechanical agitation can break up the wax structure; it is possible to have an oil flow at temperatures considerably below its pour point. Cooling rates also affect wax crystallization; it is possible to cool an oil rapidly to a temperature below its pour point and still have it flow.

While the pour point of most oils is related to the crystallization of wax, certain oils, which are essentially wax free, have viscosity-limited pour points. In these oils the viscosity becomes progressively higher as the temperature is lowered until at some temperature no flow can be observed. The pour points of such oils cannot be lowered with pour point depressants, *PPDs*, since these agents act by interfering with the growth and interlocking of the wax crystal structure.

Certain high molecular weight polymers function by inhibiting the formation of a wax crystal structure that would prevent oil flow at low temperatures, Figure (1.11).



Crystal Morphology Without
Pour Point Depressant



Crystal Morphology With
Pour Point Depressant

Fig. 1.11 The mechanism of the pour point depressant performance

Two general types of pour point depressant are used:

1. Alkylaromatic polymers adsorb on the wax crystals as they form, preventing them from growing and adhering to each other.
2. Polymethacrylates co-crystallize with wax to prevent crystal growth.

The additives do not entirely prevent wax crystal growth, but rather lower the temperature at which a rigid structure is formed. Oils used under low-temperature conditions must have low pour points.

Oils must have pour points (1) below the minimum operating temperature of the system and (2) below the minimum surrounding temperature to which the oil will be exposed.

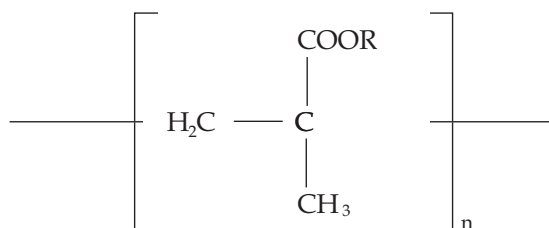
While removal of the residue waxes from the oil is somewhat expensive, pour point depressants are an economical alternative to reduce the pour point of lubricants. The most common pour point depressants are the same additives used for viscosity index improvement. The mechanism through which these molecules reduce pour point is still poorly understood and somewhat controversial.

It has been suggested that these molecules adsorb into the wax crystals, (Chen et. al., 2010, and Bharambe, 2010) and redirect their growth, forming smaller and more isotropic crystals that interfere less with oil flow.

Depending on the type of oil, pour point depression of up to 50°F (10°C) can be achieved by these additives, although a lowering of the pour point by about (20F° - 30F°) (-6.67C° to -1.1C°) is more common.

There is a range of pour point depressant additives of different chemical species ^(102 - 105).

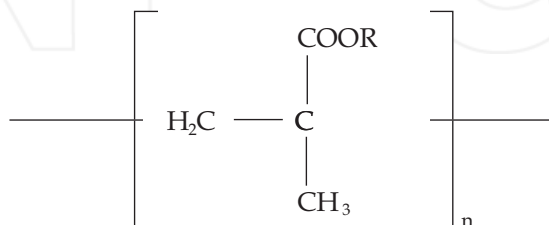
Polymethacrylates



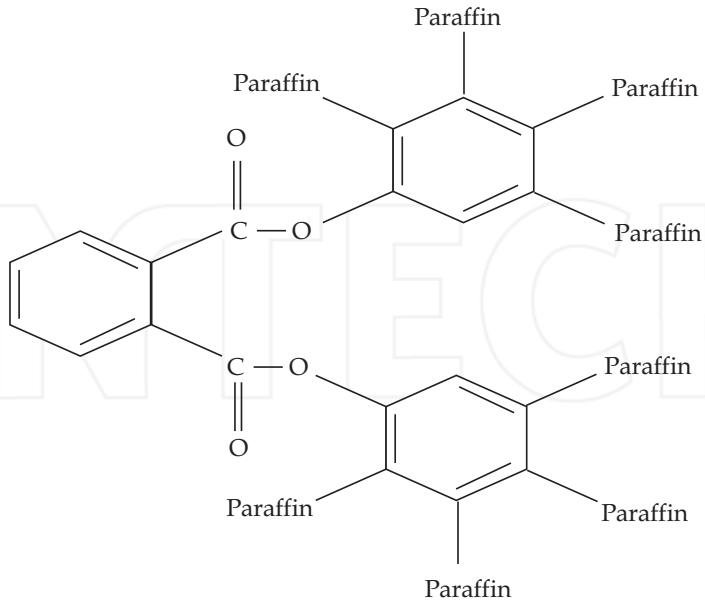
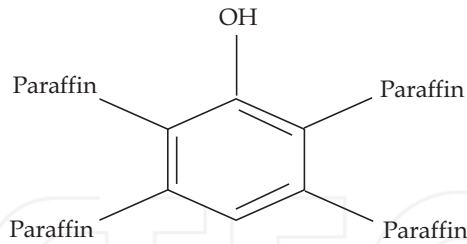
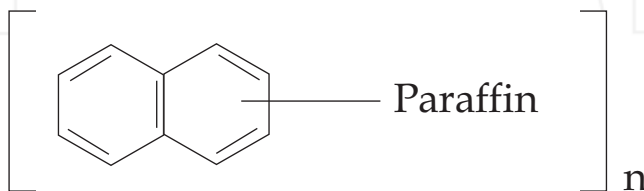
Polymethacrylates polymers

Methacrylate polymers are much used as additives in lubricating oils, as pour point depressants and viscosity index improvers. Although the mechanism of such pour point depression is still controversial, it is thought to be related to the length of the alkyl side chains of the polymethacrylate, and to the nature of the base oil. R in the ester has a major effect on the product, and is usually represented by a normal paraffinic chain of at least 12 carbon atoms. This ensures oil solubility. The molecular weight of the polymer is also very important. Typically these materials are between 7000 and 10,000 number average molecular weights. Commercial materials normally contain mixed alkyl chains, which can be branched.

Polyacrylates



These are very similar in behavior to the polymethacrylates.

Di (tetra paraffin phenol) phthalate**Condensation products of tetra paraffin phenol****Condensation product of a chlorinated paraffin wax with naphthalene ⁽¹⁰⁷⁾**

It has been suggested that these molecules adsorb into the wax crystals and redirect their growth, forming smaller and more isotropic crystals that interfere less with oil flow.

1.3.9 Multifunctional nature of additives (Rizvi, 2009)

A number of additives perform more than one function. Zinc dialkyl dithiophosphates, known mainly for their antiwear action, are also potent oxidation and corrosion inhibitors. Styrene-ester polymers and functionalized polymethacrylates can act as viscosity modifiers, dispersants, and pour point depressants. Basic sulfonates, in addition to acting as detergents, perform as rust and corrosion inhibitors. They do so by forming protective surface films and by neutralizing acids that arise from fuel combustion, lubricant oxidation, and additive degradation.

2. Future work

- Using nanotechnology in preparation of lube oil additives, "synthesis of overbased nanodetergent". Production of stable, efficient nanodetergent system depends on development and new generation of surfactant. These nano-particles are relatively insensitive to temperature.
- In spite of the increasing temperature, loads and other requirements imposed on lubricants, mineral oils are likely to continue to be employed in the foreseeable future for the majority of automotive, industrial and marine applications. However, in the aviation field, synthetic lubricants are extensively used and there are a growing number of critical automotive, industrial and marine application where the use of synthetic lubricants can be justified on a cost / performance basis.

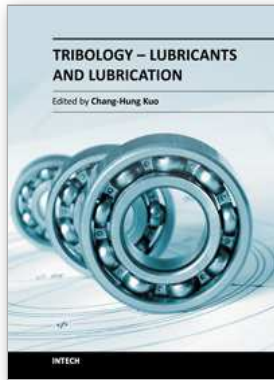
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Tribology - Lubricants and Lubrication

Edited by Dr. Chang-Hung Kuo

ISBN 978-953-307-371-2

Hard cover, 320 pages

Publisher InTech

Published online 12, October, 2011

Published in print edition October, 2011

In the past decades, significant advances in tribology have been made as engineers strive to develop more reliable and high performance products. The advancements are mainly driven by the evolution of computational techniques and experimental characterization that leads to a thorough understanding of tribological process on both macro- and microscales. The purpose of this book is to present recent progress of researchers on the hydrodynamic lubrication analysis and the lubrication tests for biodegradable lubricants.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Nehal S. Ahmed and Amal M. Nassar (2011). Lubricating Oil Additives, Tribology - Lubricants and Lubrication, Dr. Chang-Hung Kuo (Ed.), ISBN: 978-953-307-371-2, InTech, Available from:

<http://www.intechopen.com/books/tribology-lubricants-and-lubrication/lubricating-oil-additives>

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