DESIGNING AUTOMOTIVE GEAR OILS FOR THE NEW MILLENNIUM

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ABSTRACT

New engine design changes and ever increasing requirements make the design of gear oils challenging. Proper understanding of fundamental lubrication theory and formulation knowledge is necessary to develop new gear oils. This paper provides an overview on fundamentals of lubrication theory and functions of each additive. Also, key technical issues facing gear oils are discussed.

INTRODUCTION

Gear oils are a necessity for the proper operation of gear systems. The major functions of a gear oil are:

- Reduce friction and wear
- Provide cooling
- Prevent corrosion
- Resist oxidation and thermal degradation
- Resist foaming
- Provide low temperature properties
- Provide the preceding functions over broad range of temperatures

A typical gear oil consists of base oil, viscosity modifier, pour point depressant, and performance package. The performance package contains antiwear additives, extreme pressure additives, corrosion inhibitors, oxidation inhibitors, and foam inhibitors.

A gear oil is designed to meet specific performance requirements, such as American Petroleum Institute (API) service specifications (e.g., GL-5, MT-1, etc.) and/or military specifications (e.g., MIL-PRF-2105E, which is now SAE J2360) based on its application.

Table 1 shows a list of API service classifications and Tables 2 and 3 show a list of tests required for API GL-5 (axle) and API MT-1 (manual transmission). The MIL-PRF-2105E (SAE J2360) specification is a combination of API GL-5 and API MT-1 specifications and also requires field testing. A proper balance of additives in the performance package along with viscosity modifier and pour point depressant is a must to guarantee the performance of gear oil in today's demanding operating conditions.

Table 1.
API Gear Oil Service Classifications

Designation	Type	Application
API GL-1	Straight Mineral Oil	Specified For Some Manual Transmissions. No Friction Modifiers Or EP Additives Permitted.
API GL-2	Usually Contains Fatty Materials Not In Current Use	Worm Gears – Industrial Oils
API GL-3	Contains Mild EP Additive Not In Current Use	Manual Transmissions / Moderately Loaded Spiral Bevel Axles
API GL-4	Equivalent To Obsolete MIL-L-2105 Specification. Usually Satisfied by 50% GL-5 Additive Level	Spiral Bevel Drive Axles, Light-Duty Hypoids, Manual Transmissions And European Transaxles
API GL-5	Equivalent To Obsolete MIL-L-2105D Specification. Primary Field Service Recommendation Of Most Passenger Car and Truck Builders Worldwide	Hypoid Drive Axles. Equivalent to MIL-L-2105D
API GL-6	Technically Obsolete	Passenger Car and Light Duty Truck Axles Having High Pinion Offset Similar to Ford M2C105A
API MT-1	Recommended for Commercial Vehicle Manual Transmissions	Non-Synchronized Transmissions of Heavy Trucks and Busses

Table 2.
API GL-5 Required Laboratory Tests

Test Designation	Type	Characteristics Measured
L-33	Gear Test Using Axle Components	Resistance To Corrosion In The Presence Of Moisture
L-37	Gear Test Using Complete Axle Assembly	Resistance To Gear Distress Under The Conditions Of Low Speed High Torque
L-42	Gear Test Using Complete Axle Assembly	Resistance To Gear Distress (Scoring) Under Conditions Of High Speed And Shock Loads
L-60	Bench Test Using Spur Gears	Thermal Oxidation Stability
ASTM D892	Bench Test	Foaming Tendencies
ASTM D130	Bench Test	Stability In The Presence Of Copper And Copper Alloys

Table 3.
API MT-1 Requirements

Required Performance	Test Procedure	Limits	
Thermal Stability	ASTM D5704 (L-60-1)		
	Carbon/Varnish Rating		
	(Large Gear Only)	7.5 Minimum	
	Sludge Rating	9.4 Minimum	
Oil Seal Compatibility	ASTM D5662		
	Polyacrylate	***Minimum***	***Maximum***
	150°C, 240 Hours		
	Elongation Change, %	No Limit	- 60
	Hardness Change, Points	- 20	+ 5.0
	Volume Change, %	- 5	+ 30
	Fluoroelastomer		
	150°C, 240 Hours		
	Elongation Change, %	No Limit	- 75
	Hardness Change, Points	- 5	+ 10
	Volume Change, %	- 5	+ 15
Copper Compatibility	ASTM D130	2a Maximum	
Antiwear	ASTM D5182 – FZG (A/8.3/90)	10 Stage Pass Minimum	
High Temperature Lube Stability	ASTM D5579 (Cyclic Durability)		
	Cycles to Failure	Equal to or Better Than Passing Reference	
Oxidation	ASTM D5704 (L-60-1)	MIL-L-2105D Limits	
	Viscosity Increase	100% Maximum	
	Pentane Insolubles	3.0% Maximum	
	Toluene Insolubles	2.0% Maximum	
	Average Carbon/Varnish	7.5 Minimum	
	Average Sludge	9.4 Minimum	
Foam Resistance	ASTM D892, for Tendency Only	MIL-L-2105D Limits	
	Sequence I	20 Maximum	
	Sequence II	50 Maximum	
	Sequence III	20 Maximum	
Compatibility With Existing			

Recently, there is a trend for enhanced vehicle aerodynamics coupled with higher horsepower engines and smaller axle and transmission components. This leads to increased operating temperatures of gear oils which will result in a premature failure of driveline components (gears, bearings, and transmissions) due to spalling, wear, etc. There is thus a need for fluids which reduce operating temperatures. Another demand on gear oils comes from Original Equipment Manufacturers (OEMs) in terms of extended drain lubricants. The increased drain interval provides significant cost savings for customers of OEMs due to reduced maintenance costs and reduced equipment downtime. This requires improved thermal and oxidation resistance for the gear oils.

It is very difficult to meet all the requirements without sacrificing some of the performance of gear oils and formulating to meet a specific performance category becomes a 'balancing act.' To meet OEMs' demands on extended drain intervals, the usage of synthetic base fluids in gear oils has been increased due to their better thermal and oxidative properties. However, the synthetic base fluids respond differently than mineral base oils to a combination of high pressures and high shear rates which are commonly observed in gears and bearings. This difference leads to a difference in minimum film thickness. The change in the minimum film thickness can affect the performance of gear oils in areas such as wear and fuel efficiency.

An overview on fundamentals of automotive gear lubrication was published fifteen years ago by Schiemann and Schwind[(1)]. In light of new engine design changes and ever increasing requirements, this paper will update and expand on lubrication theory and functions of each additive. Also key technical issues facing gear oils will be discussed. An in-depth analysis of gear tooth failures was reviewed by others[(2-3)] and will not be included in this paper.

FUNDAMENTALS OF LUBRICATION

Generally lubrication is classified into following four regimes:

- Hydrodynamic Lubrication

- Elastohydrodynamic Lubrication
- Mixed Lubrication
- Boundary Lubrication

These lubrication regimes are based on Λ value which is defined as

$$\Lambda = h_{min} / (\Delta_a^2 + \Delta_b^2)^{1/2} \qquad (1)$$

where h_{min} is the minimum film thickness, Δ_a and Δ_b are root mean square (rms) surface finish of surface a and b, respectively.

The lubricant film thickness depends upon the average surface speed and the properties of the lubricant by a relationship known as the Hamrock and Dowson equation for point contact and Newtonian flow[4]:

$$h = k\ U^{0.67}\ \eta^{0.67}\ \alpha^{0.53} \qquad (2)$$

where h is the central film thickness (which is about 110% of the minimum film thickness, h_{min}), U is the mean rolling speed, η is the dynamic viscosity of the lubricant at atmospheric pressure, α is the lubricant pressure-viscosity coefficient, and k is a constant which depends upon the load and the geometry and moduli of two contacting solids.

In general, base oils yield the theoretical film thickness predicted by equation (2). However, this is not always the case when polymers are added since the polymers have different shear characteristics based on chemistry. Therefore, an optical interference technique, called Optical EHD, is often used to provide information on the minimum film thickness under more realistic conditions including high pressures and high shear rates[5,6]. This technique can provide in-situ film thickness so that the shear characteristics of gear oils can be easily measured.

A classical way of presenting different lubrication regimes is the Stribeck-Hersey curve as shown in Figure 1[7]. The Stribeck-Hersey curve shows the coefficient of friction as a function of the ZN/p parameter, where Z is the viscosity of the liquid, N is the velocity, and p is the load.

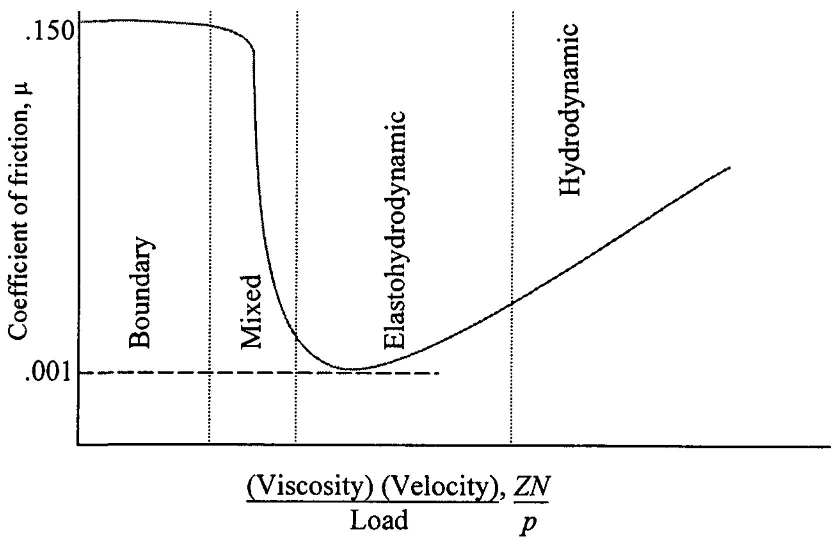


Figure 1. Coefficient of Friction as Function of Viscosity-Velocity-Load Parameter (Stribeck-Hersey Curve)

At high values of ZN/p, which occurs at high velocities, low loads, and high viscosity, the surfaces are completely separated by a thick lubricant film so that surface roughness has little influence on lubrication. This is the hydrodynamic lubrication regime, where friction is determined by the rheology of the lubricant. The hydrodynamic lubrication is generally characterized by surfaces that are conformal.

For non-conformal concentrated contacts, elastohydrodynamic lubrication occurs. The elastohydrodynamic lubrication is a form of hydrodynamic lubrication where elastic deformation of the surfaces is significant due to high contact stress. The pressure-viscosity coefficients and traction coefficients of the lubricant can play a role under this regime.

As the ZN/p value gets smaller, which occurs at low velocities, high load, and low viscosity, some interactions between asperities as well as fluid film formation occur. This is called mixed film lubrication.

At very low values of ZN/p, penetration of the lubricant film occurs due to high pressures, low speeds, or high surface roughness. This is the boundary lubrication regime where friction is very high. Also wear occurs under the boundary lubrication regime. In this regime, antiwear additives and extreme pressure additives can play a key role in preventing wear. Reaction films formed at contacting asperities by chemical reactions with these additives. The effectiveness of these films in preventing (or minimizing) wear is primarily determined by shear strength, thickness, adhesion, and other physical properties.

COMPOSITIONS OF AUTOMOTIVE GEAR OILS

An automotive gear oil typically consists of two to four of the following:

- 50 - 95 % Base Oil
- 0 - 35 % Viscosity Modifier
- 0 - 2 % Pour Point Depressant
- 5 - 12 % Performance Package

1. Base Oil

The base oil makes up the bulk of a gear lubricant. Its function is to provide adequate viscosity for the gear oil, act as a heat transfer medium and serve as a carrier for the additive package. Table 4 summarizes SAE J306 specification which shows a list of lubricant viscosity classifications for axle and manual transmission fluids. The base oils contained in these lubricants can be either mineral or synthetic in nature.

Mineral base oils are the refined product (aliphatic, alicyclic, aromatic) of crude petroleum through a series of separation process. These oils are a mixture of many different hydrocarbons and are available in a wide range of viscosity, i.e., bright stocks tend to have the highest viscosity. Some mineral base oils are hydrotreated (or hydrocracked) to improve color, oxidation resistance, thermal stability, and viscosity index[8].

Table 4.

Revised SAE J306 Viscosity Specification**

	70W	75W	80W	80	85W	85	90	140	250
100°C Viscosity, cSt									
Min ***	4.1	4.1	7.0	7.0	11.0	11.0	13.5	24.0	41.0
Max *	NR	NR *	NR	<11.0	NR	<13.5	24.0	<41.0	NR
Max Temperature, °C, For Viscosity of 150,000 cP	-55	-40	-26	NR	-12	NR	NR	NR	NR
Channel Point, Max °C	NR	NR	NR	NR	NR	NR	NR	NR	NR
Flash Point, Min °C	NR	NR	NR	NR	NR	NR	NR	NR	NR

* NR = No Requirement
** Proposed as of April 6, 1998
*** Limit must be met after testing in CEC L–45-T-93 (20 hours)

Synthetic base oils are produced by chemical reaction of small molecules into larger ones. These large molecules, called polymers, are designed to have predictable properties. Synthetic base oils provide enhanced thermal stability, low pour point, low volatility, high viscosity index, and fire resistance[8]. Synthetic base oils are available in a variety of chemical types, but the most popular are polyolefins (PAO), polyglycols (PAG) and polyol esters.

The demand for extended drain intervals has increased the usage of synthetic base fluids in gear oils. They offer good thermal and oxidative properties and in many cases excellent low temperature properties.

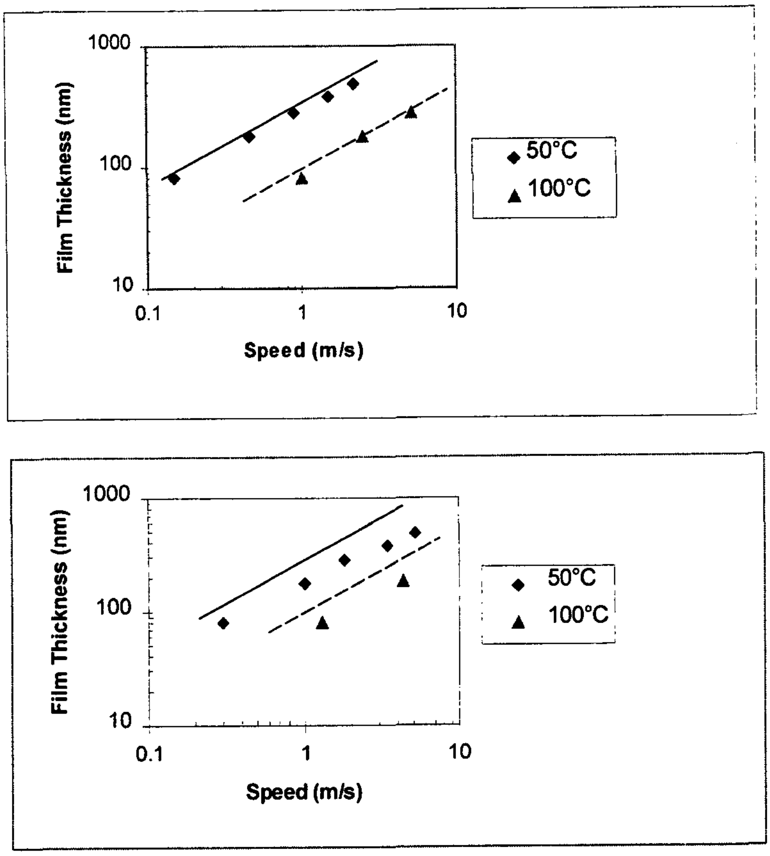
2. Viscosity Modifiers

Gear oils can be subjected to temperatures in excess of 200°C (for a short duration) or exposed to subzero temperatures. Ideally, a gear oil should not be too viscous at low temperatures since this will impede the flow of lubricant to critical surfaces, or the oil should not lose too much viscosity at higher temperatures since this will lead to loss of lubricant film.

Viscosity modifiers are polymeric molecules which are known to coil into a ball-like shape at low temperatures[9]. Therefore, there is little viscosity change to the base oil at low temperatures. These molecules uncoil at high temperatures compensating for the loss of viscosity of base oil.

There are several key performance requirements for viscosity modifiers. The viscosity modifiers should have good solubility in the base oils, which guarantees long-term usage under different operating temperatures. Another key requirement is shear stability.

Increased emphasis on fuel economy and extended fluid life has resulted in increased use of wide-range multi-grade gear oils such as SAE 75W-90. The wide-range multi-grade gear oils usually contain relatively high levels of polymers. If not properly selected, these polymers have the potential to shear significantly since gear oils are operated under very high shear rate up to 10^7/s. Figure 2 shows film thicknesses of synthetic base oils containing different viscosity modifiers using an optical EHD technique[10]. The straight lines were drawn based on Equation (2) assuming Newtonian behavior. The synthetic PAO base oil containing a polyolefin viscosity modifier showed similar film thickness compared to the theoretical predictions indicating good shear stability. However, the synthetic base oil containing a typical polymethcrylate viscosity modifier showed a significant reduction of film thickness, indicating a shear loss. The shear loss at the contact area due to unstable viscosity modifiers will reduce the fluid film provided by the lubricant, thus increasing the potential for premature failure.



(A) PAO4 + Polyolefin + GL-5Additive
(B) PAO4 + PMA + GL-5 Additive

Figure 2. Film Thickness Obtained at 50° and 100°C

Most OEMs specify a maximum shear loss in specific tests such as the tapered roller bearing test (KRL bearing test). For example, Eaton and Mack requires the maximum shear loss of 15 % and 17 %, respectively. To address OEMs' concerns, SAE J306 was revised in July 1998 as shown in Table 4. In order to ensure that the designated high temperature viscosity is retained during the use of gear oils, the gear oils must meet the 100°C viscosity limits listed in Table 4 not only when new, but also following 20 hours of KRL testing (CEC L-45-T-93).

Typical viscosity modifiers used in gear oil formulations are shear stable polymethacrylates (PMAs), olefin copolymers (OCPs) and polyolefins.

3. Pour Point Depressant

Pour point depressants allow base oils to flow at low temperatures. Small amounts of pour point depressants are usually required to satisfy SAE "W" (see Table 4) grades to meet the low temperature viscosity requirements. Pour point depressants are not needed in the case of synthetic base oils. Low temperature viscosity requirements are measured by Brookfield viscosity.

As oil cools, a temperature is reached at which wax crystals begin to form, known as the cloud point. Further cooling eventually solidifies the oil. Pour point depressants are high MW polymers believed to coat wax crystals preventing their growth and aggregation. This in turn suppresses solidification of the oil. The effectiveness of the pour point depressant depends on its chemical type, concentration and the nature of the base oil.

4. Performance Package

The principle types of additives used in the automotive gear oils are:

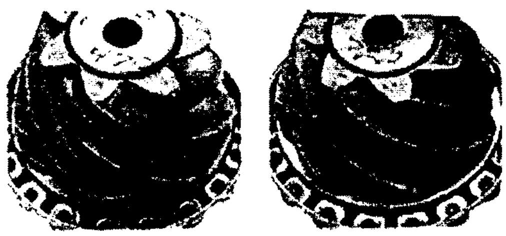
- Antiwear/Extreme Pressure Additives
- Oxidation Inhibitors
- Corrosion Inhibitors
- Foam Inhibitors
- Friction Modifiers

4.1. Antiwear (AW)/Extreme Pressure (EP) Additives. Generally, the antiwear and extreme pressure additives are organic compounds that contain one or more elements such as sulfur, zinc, and phosphorus, and are intended to prevent or minimize wear and surface damage to gears.

Antiwear additives, such as organo-phosphorus additives, are believed to absorb on the iron surfaces, and degrade under conditions of increasing severity to form polar species which react with the iron to form iron organo/inorgano phosphorus films[11, 12]. These films are effective at low to moderate temperatures and loads.

Extreme pressure additives, such as organosulfur additives and organochlorine additives, react with the metal under high temperatures and high loads[11, 13]. The formation of a reaction film is essential to prevent metal-to-metal contact, however, excess formation of sulfur or chlorine-containing film is also detrimental. The extreme pressure additives are not effective at lower temperatures.

The presence of antiwear/extreme pressure additives in gear lubricants is essential for the prevention of rapid gear wear leading to catastrophic failure[14]. Figure 3 shows gears tested in the L-37 test with an API GL-5 gear oil (SAE 80W-90) containing antiwear/extreme pressure additives and AP2 GL-1 oil (SAE 80W-90) containing no antiwear/extreme pressure additives.



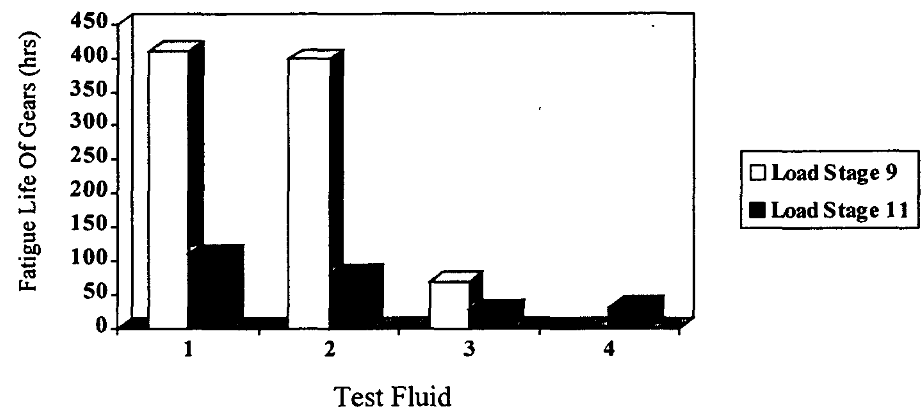
API GL-5
SAE 80W-90
Pass, Duration: 24 Hrs.

API GL-1(No EP Additive)
SAE 90
Failed at: 3 Min.

Figure 3. Gears Tested in L-37 Test

The API GL-5 oil passed this test, while the API GL-1 oil failed just after three minutes, indicating that antiwear/extreme pressure additives are absolutely necessary to achieve normal life expectancy from hypoid gear axles.

It has been reported that sulfur containing extreme pressure additives alone cannot provide adequate protection under severe operating conditions[15]. A proper balance of antiwear and extreme pressure additives is a must to protect the surface of gears. Figure 4 shows the fatigue life of FZG gears tested with an API GL-5 formulation with/without EP and antiwear additives. The removal of the EP additive from the fully formulated gear oil decreased the fatigue life slightly; however, the removal of the primary antiwear additive decreased the fatigue life of the gears significantly.



Test Fluid	SAE 90 Base Stock Containing	Physical and Analytical Characteristics			
		Kinematic Viscosity			
		@ 100°C (cSt)	@ 40°C (cSt)	%P (theor)	%S (theor)
1	API GL-5 Formulation	17	189	0.11	2.1
2	GL-5 Formulation Less EP	18	204	0.11	0.2
3	GL-5 Formulation Less AW	17	185	0	1.9
4	GL-5 Formulation Less AW and EP	18	201	0	<0.1

Figure 4. FZG Pitting Test Results at Load Stages 9 and 11 [15]

Subsequent surface analysis of gears showed that the formation of a mixed phosphate/phosphite - oxide layer on the surface of gears tested with a fully formulated gear oils as shown in Figure 5[15]. This layer acts as a binding layer which provides better adhesion and controls the kinetics of sulfide film formation. The formation of this layer and subsequent formation of sulfide layers seems to prolong the surface fatigue life of gears. The presence of a binding layer and its relationship to better tribological performance was also reported in metalworking areas[16].

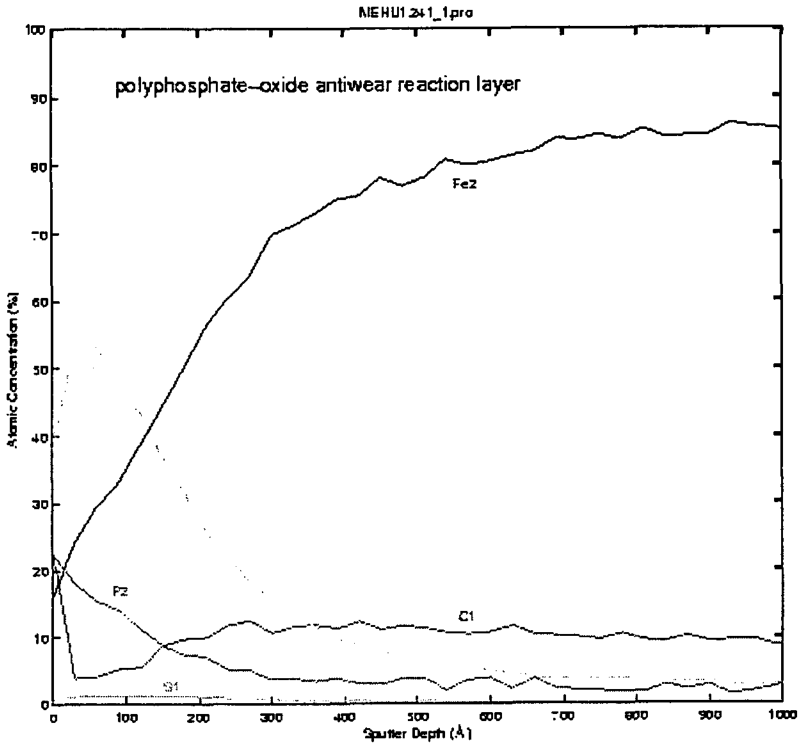
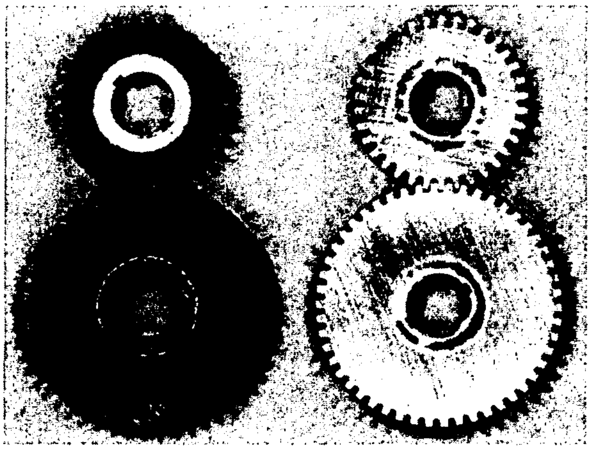


Figure 5. Scanning Auger Microscopy Depth Profiles from Gear Tooth Tested with a Fully Formulated Gear Oil

The effectiveness of antiwear/extreme pressure additives is examined using the L-37, L-42 test, and FZG scuffing and wear tests which are required for GL-5/MIL-PRF-2105E specifications (Tables 2 and 3).

4.2. Oxidation Inhibitors. The demand from OEMs for extended drain intervals requires close attention to oxidation inhibitors. Oxidation inhibitors prevent breakdown of the base oil which results in oxidative thickening and sludge/deposit formation. Figure 6 compares L-60-1 gears tested with a reference oil containing good oxidation inhibitor and a reference oil containing a bad oxidation inhibitor[14].



API MT-1 FAIL
Non-Thermally Stable
Lubricant

API MT-1 PASS
Thermally Stable
Lubricant

Figure 6. Thermal Stability Discrimination in the L-60-1 Deposit Test[14]

The oxidation stability of gear oils also affects the seal performance. The potentially abrasive carbonaceous deposits formed due to poor oxidative stability of gear oils can cause a leak leading to total component failure.

The oxidation of lubricants occurs via a free-radical chain reaction. These unstable free-radical chains can propagate leading to base oil polymerization. The polymerization of oils increases viscosity and prevents oil flow to critical surfaces.

Typical oxidation inhibitors used in automotive gear oils are hindered phenols, aromatic amines, and some sulfur containing compounds. The effectiveness of oxidation inhibitors is measured by the L-60-1 test (North America – see Table 2), DKA (European) test, and ISOT (Japanese) test.

4.3. Corrosion Inhibitors. Oxidized oil contains acids which can chemically attack metal surfaces. Some extreme pressure additives can also attack metal surfaces if not properly formulated. Corrosion inhibitors can protect either ferrous (iron containing) or soft metals (copper alloys).

Ferrous metal corrosion inhibitors coat the surfaces, especially when the equipment is inoperative, to prevent attack by moisture or oxygen. Typical corrosion inhibitors for ferrous alloys are basic sulfonates and fatty amines.

Soft metal corrosion inhibitors are highly surface active materials used at very low levels in the performance package. Their limited solubility allows them to coat and protect copper alloys (e.g., bronze) from the effects of acids and active sulfur. Effective compounds are heterocycles containing nitrogen and/or sulfur.

The effectiveness of corrosion inhibitors is measured by the L-33 test and the ASTM D-130 test (Table 2).

4.4. Foam Inhibitors. The churning action of the gears in transmissions and axles through the lubricant can cause air entrainment or foaming in the lubricant. These problems become more severe as the temperature decreases and lubricant viscosity increases. Foam inhibitors are used to reduce the surface tension of the oil allowing air bubbles to collapse.

Typical foam inhibitors include polydimethylsiloxanes ("silicones") and polyacrylates. The effectiveness of foam inhibitors is measured by the ASTM D-892 test.

4.5. Friction Modifiers. Friction modifiers are added to packages to reduce the coefficient of friction between contacting metal surfaces. These compounds generally do not react, but are adsorbed onto the metal. This reduces the frictional heating at the oil/metal interface and allows for improved efficiency under certain conditions.

Typical friction modifiers are generally fatty derivatives containing phosphorus or nitrogen.

KEY TECHNICAL ISSUES

To meet the demands from OEMs for extended drain lubricants and to protect gears under severe operating conditions, there are some issues which should be addressed when formulating gear oils:

• **Surface Fatigue**

Surface fatigue is defined as a failure of material due to repeated contact. Figure 7 shows a spiral bevel gear with a spall in the gear tooth. Gear surface fatigue (or spalling) is currently considered a key limitation in component life due to the growing demand for extended drain intervals by OEMs. Also, increased engine power output and small component size increase the possibility of gear surface fatigue. The combination of increased power and extended service life places significant stress on the oil such that the load carrying capacity and thermal and oxidative stability could be greatly diminished under these conditions.

Figure 7. Spiral Bevel Gear with Spalled Tooth

Due to the OEMs' concern and desire to improve surface fatigue performance of gear oils, surface fatigue (spalling) protection was included in the proposed PG-2 specification which is intended for final drive axles (both spiral bevel and hypoid gearing).

• **Synchromesh performance**

Synchronized manual transmissions are used globally for passenger cars and light/medium duty vehicles. Synchronizers are friction devices that match the input shaft (engine side) speed to the output shaft speed of a selected gear. The synchromesh performance is one of the most important features of the manual transmission fluids. The use of a dedicated manual transmission fluid is paramount in meeting the specific needs of vehicles with synchronized manual transmissions.

The key to a successful gear shift is a fluid that provides the correct frictional properties in a timely and consistent manner. A manual transmission fluid (MTF) should provide high dynamic friction coefficient (μ_d) to avoid any delay in synchronization and clashing and low static friction coefficient (μ_s) to fully engage the gears. Figure 8 shows the friction coefficients as a function of test cycles for API GL-4, API GL-5, and dedicated MTF fluids[17] The dedicated MTF provided high dynamic friction at the onset of engagement and low static friction to maintain smooth engagement during the operation of the vehicle.

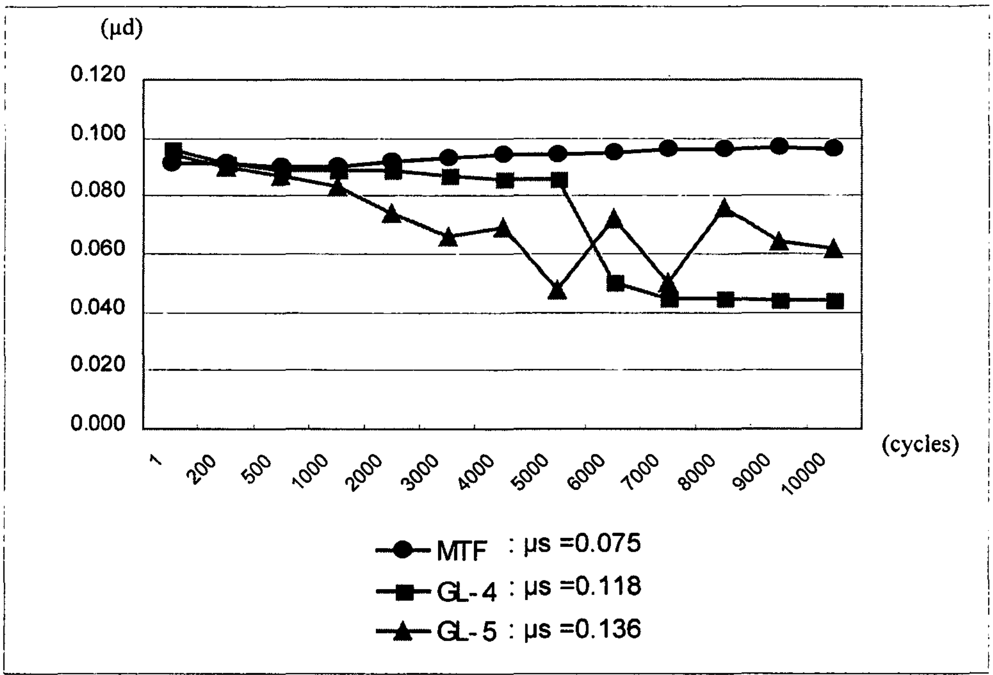


Figure 8. Friction Coefficients of MTF, GL-4, and GL-5 Gear Oil at 120°C

• **Fuel Efficiency**

Small improvements in fuel efficiency provides significant savings for customers of OEMs, especially in the commercial transportation sector. There is a definite trend for a low viscosity gear oil in these applications. It has been reported that the low viscosity gear oil provides better fuel efficiency at lower temperatures. However, the low viscosity gear oil may not provide enough protection at higher temperatures. Therefore, selection of proper viscosity and performance packages is critical. Figure 9 shows that there are significant improvements of axle efficiency (thereby fuel efficiency) with lower viscosity oils at lower operating temperatures[18]. However, at higher temperatures, boundary lubrication may be encountered due to the presence of thin films at the contact areas. Therefore, a careful balance between fuel efficiency and gear protection should be considered when formulating a gear oil.

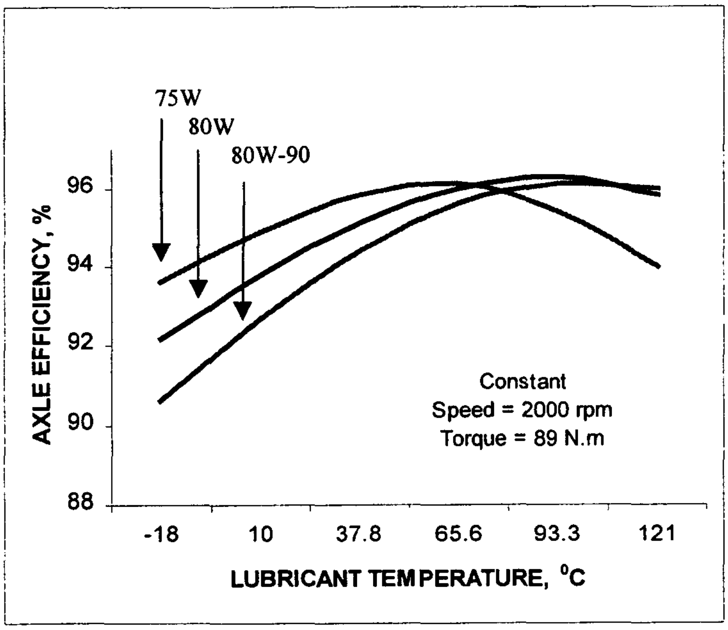


Figure 9. Axle Efficiency vs. Lube Temperature[18]

• **Temperature Reduction**

A trend toward enhanced vehicle aerodynamics coupled with higher horsepower engines and smaller axle and transmission components increases the operating temperatures of gear oils. The increase of operating temperatures will often result in a premature failure of driveline components. Therefore, OEMs are demanding lower operating temperatures for gear oils. A lower operating temperature provides benefits for OEMs such as longer drain intervals.

CONCLUSIONS

New engine design changes and ever increasing requirements make the design of gear oils challenging. Proper understanding of fundamental lubrication theory and formulation knowledge is necessary to develop new gear oils. Communication between gear design engineers and lubricant formulators is a must to increase equipment reliability.

REFERENCES

1. Schiemann, L. F. and Schwind, J. J., "Fundamentals of Automotive Gear Lubrication", SAE #841213, 1984
2. Dudley, D.W., "Gear Wear", Wear Control Handbook (ed. by M.B. Peterson and W.O. Winer), ASME, 1980, pp. 755-830.
3. Errichello, R., "Lubrication of Gears, Part I, II, III, and IV", Lub. Eng., 46, 1990, PP 11-13, 117-121, 181-185, 231-236.
4. Hamrock, B.J. and Dowson, D., "Isothermal EHD Lubrication by Point Contacts, Part III: Fully Flooded Results", ASME J. Lub. Tech., 11, 1968, pp. 31-43.
5. Bair, S. and Winer, W.O., "Friction/Traction Measurements with Continuously Variable Slide-roll and Side Slip at Various Lambda Ratios", Proceedings of the Leeds/Lyon Conference, 1980.
6. Johnston, G.J., Wayte, R., and Spikes, H.A., "The Measurement and Study of Very Thin Lubricant Films in Concentrated Contacts", Trib. Trans., 34, 1991, pp. 187-194.
7. Jones, W.R., "Boundary Lubrication – Revisited", NASA TM-82858.
8. Schmidt, G.K. and Forster, E.J., "Modern Refining for Today's Fuels and Lubricants Technology, An Overview", SP. 603, Society of Automotive Engineers, 1984, pp. 1-10.
9. Mishra, M.K. and Saxton, R.G., "Polymer Additives for Engine Oils", ChemTech, 1995, pp. 35-41.
10. Hong, H. and Bair, S., "Film Forming Tendencies of Some Base Fluids and Viscosity Modifiers", Proceedings of 11th International Colloquium – Industrial and Automotive Lubrication, Technische Akademie Esslingen, 1998, pp. 1687-1686.

11. Forbes, E.S., "Antiwear and Extreme Pressure Additives for Lubricants", Tribology, 3, 1970, pp. 145-152.
12. Kapsa, Ph. and Martin, J.M., "Boundary Lubricant Films: A Review", Trib. Inter., 15, 1992, pp. 37-42.
13. Hiley, R.W., Spikes, H.A., and Cameron, A., "Polysulfides as Extreme-Pressure Lubricant Additives",
14. Schieman, L.F., Bigelow, S.S., Nai, P., and Hasegawa, H., "Designing Driveline Lubricants to Satisfy Global Market Needs", Proceedings of 3rd Annual Fuels and Lubes Asia Conference, 1997.
15. Hong, H., Huston, M.E., B.M. O'Connor, and N.M. Stadnyk, "Evaluation of Surface Fatigue Performance of Gear Oils", Lub. Sci., 10, 1998, pp. 365-380.
16. Hong, H., Riga, A.T., Cahoon, J.M., Vinci, J.N., "Evaluation of Overbased Sulfonates as Extreme-Pressure Additives in Metalworking Fluids", Lub. Eng., 49, 1993, pp. 19-24.
17. Hong, H., M.E. Huston, Kurihara, Y., Hasegawa, H., Gahagan, M.P. and Kojima, N., "Manual Transmission Fluid to Satisfy Global Market Needs – part II", Proceedings of 5th Annual Fuels and Lubes Asia Conference, 1999, Paper #32.
18. Schieman, L.F., "Formulating Gear Oils for Efficiency and Durability", NLGI Spokesman, 1980, pp. 204-207.