Vegetable-Based Oil as a Gear Lubricant

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Summary

Universal tractor transmission oil (UTTO) is multifunctional tractor oil formulated for use in transmissions, final drives, differentials, wet brakes, and hydraulic systems of farm tractors employing a common oil reservoir. In the present work, the gear protection properties of two formulated vegetable-based UTTO oils, one synthetic ester-based UTTO oil, one synthetic ester gear oil, and one mineral-based UTTO oil are investigated.

The data, presented in this paper, have demonstrated that the formulated vegetable-based UTTO oils have high lubricity, high viscosity indexes and provide equivalent or—in some aspects—superior gear protection performance compared with the mineral-based UTTO oil. The high-oleic sunflower oil formulation derived from the genetically modified plant has shown better results than the rapeseed-based (canola-based) oil formulation.

Introduction

It is generally recognized that mineral oil lubricants represent a potential danger in many applications because they are not readily biodegradable and are toxic. The need for biodegradable and nontoxic lubricants has been recognized especially in the areas where they can come in contact with soil, ground water, and crops.

Biodegradability is the ability of a substance to be decomposed by the action of bacteria into CO2, water, mineral compounds and bacterial bodies. Biodegradability is influenced by numerous factors, of which the main are the molecular structure and the chemical properties of organic compounds and the environmental conditions of biodegradability, such as the presence of oxygen, the possible level of nutrition and the pH (Ref. 1).

Vegetable oils and synthetic esters are the most common base stocks for biodegradable lubricants. Synthetic oils represent a fairly recent development in the lubrication market. They can be made by reacting alcohols with fatty acids. Synthetic oils offer improved performance compared with all other lubricants, but at a price. Both vegetable oils and synthetic esters are highly biodegradable and readily available, but vegetable oils occur naturally, have a "greener" image, and are, in general, three times cheaper. Properly balanced additives can compensate for low temperature performance and oxidative stability of the vegetable oils and favor them as the base stock of choice (Refs. 2–3).

A comparison of the simplified chemical structures of mineral and vegetable oils shows great similarities. The major difference is that vegetable oil is an ester, while mineral oil is a hydrocarbon. The presence of the polar ester group impacts several properties, making vegetable oil better than mineral oil in reducing friction and wear. The polar group also makes vegetable oil a better solvent for sludge and dirt, which would be otherwise deposited on the surfaces being lubricated. Because of these properties, it may be possible to reduce the amount of friction modifiers, antiwear agents, and dispersants required to formulate vegetable oil-based lubricants.

The agricultural equipment is ideally suited to use vegetable oil-based lubricants, because the equipment operates close to the environment. The opportunity exists to create a continuous cycle in which the agricultural equipment is lubricated by the oil from a plant growing in the field being cultivated by that same equipment (Ref. 2).

Universal tractor transmission oil (UTTO) is multipurpose oil widely used for agricultural, construction and other off-road vehicles. UTTO oil is

Table 1—Test Oils.

		Viscosity (mm2/s)			
Base stock	Oil type	$\nu_{40°C}$	$\nu_{100°C}$	VI	Oil code
Rapeseed oil	biodegradable UTTO	48.8	10.4	209	R
High-oleic sunflower oil	biodegradable UTTO	51.4	10.6	203	S
Synthetic ester	biodegradable gear oil	101	17.8	195	G
Synthetic ester	biodegradable UTTO	51.3	10.9	211	H
Mineral oil	UTTO	55.1	9.2	150	M

Table 2—Fatty Acid Content In Test Vegetable Base Stocks.

Base stock	Fatty acid content (%)					
	Palmitic C 16:0	Stearic C 18:0	Oleic C 18:1	Linoleic C 18:2	Linolenic C 18:3	Other
High-oleic sunflower oil	4.7	3.7	72.6	17.0	/	2.0
Rapeseed oil	6.1	2.5	49.1	32.2	6.9	3.2

C X:Y .... fatty acid chain of length X and containing Y double bonds; e.g. C 18:3 is an 18 carbon-chain fatty acid with three double bonds.

specially designed for lubricating the transmissions, final drives, wet brakes and hydraulic systems employing a common oil reservoir. UTTO oil has to meet some specific requirements to operate in agricultural and construction equipment. The oil must provide the correct frictional balance to prevent wet brake chatter and to allow smooth transmission clutch engagement.

At the same time, the oil must provide enough clutch capacity for efficient power transmission and enough brake capacity to stop the tractor in a reasonable time and distance. UTTO oil must also provide sufficient antiwear (AW) and extreme pressure (EP) properties for the whole transmission system, especially for the spiral bevel ring and pinion gears in the axles. The AW/EP additives must not be so active as to cause corrosion in the tractor's hydraulic system, where pumps containing alloys of copper can be present (Refs. 2 and 4).

Rapeseed and sunflower oils are currently used in Europe for the formulation of the biodegradable lubricants. In the present work, the antiwear and extreme pressure properties of formulated rapeseed and high-oleic sunflower-based UTTO oils, synthetic ester-based UTTO oil, synthetic ester gear oil, and mineral-based UTTO oil are investigated on FZG test equipment. The selected formulated vegetable-based UTTO oil was further tested on the helical gear test rig.

Sample Preparation

Oil samples. We have formulated two different vegetable-based UTTO oils for the investigations. The first formulation is based on the rapeseed base stock, while the second base stock is derived from a genetically modified sunflower plant with a high oleic content. The same additive system is used for both formulations. The properties of these two fully formulated vegetable-based UTTO oils were compared with a commercially available mineral-based UTTO oil, a fast biodegradable synthetic-based UTTO oil and a synthetic ester-based gear oil (see Table 1).

The test UTTO oils have a kinematic viscosity between 9 mm²/s and 11 mm²/s at 100°C. This viscosity offers sufficient thickness to promote good gear protection and is still suitable for the hydraulic system. The synthetic ester G has a viscosity two ISO grades higher than other test oils and is suitable as a gear oil only.

The main difference between the vegetable base stocks for R and S formulation lies in fatty acids content (see Table 2). The high-oleic sunflower base stock is derived from a genetically altered plant and possesses a significantly higher content of oleic acid than rapeseed oil. Due to the higher saturation, the high-oleic sunflower oil has better oxidation stability than the rapeseed oil.

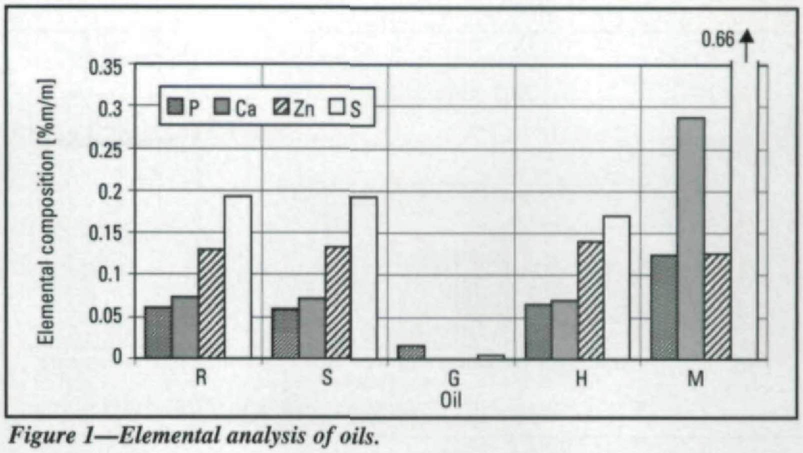

Figure 1—Elemental analysis of oils.

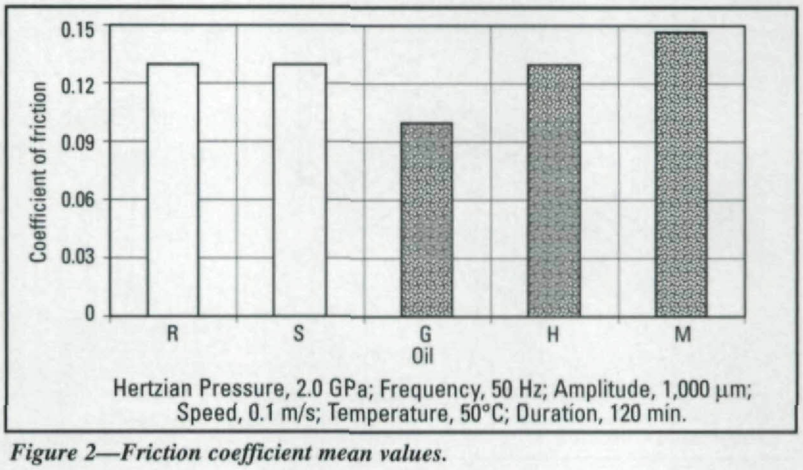

Figure 2—Friction coefficient mean values.

Elemental analysis of additives. Spectrometry via ED-XRF (energy disperse X-ray fluorescence) has been used to obtain the elemental composition of additives for the test oils (see Figure 1). The elemental composition of additives is quite similar for the formulated vegetable-based UTTO oils R and S and the reference synthetic ester-based UTTO oil labeled H. The mineral UTTO oil labeled M contains a significantly higher level of calcium and sulfur than any other test oil. The synthetic ester-based gear oil labeled G shows a low amount of additive concentration compared with the UTTO test oils.

Preselection Experiments and Test Results

SRV test results. The coefficient of friction measurements have been performed on an SRV high frequency test device. SRV stands for the German words "Schwingung" (oscillation), "Reibung" (friction) and "Verschleiss" (wear). The device produces linear oscillating motion of a ball on a flat specimen under boundary lubricating conditions. A thin layer of lubricant is spread over the flat specimen before each test. On the SRV test rig, just the friction coefficient at

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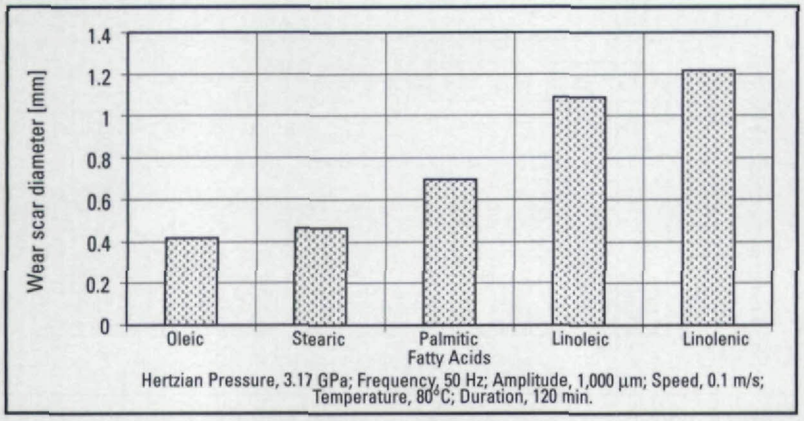

Figure 3—Antiwear properties of fatty acids.

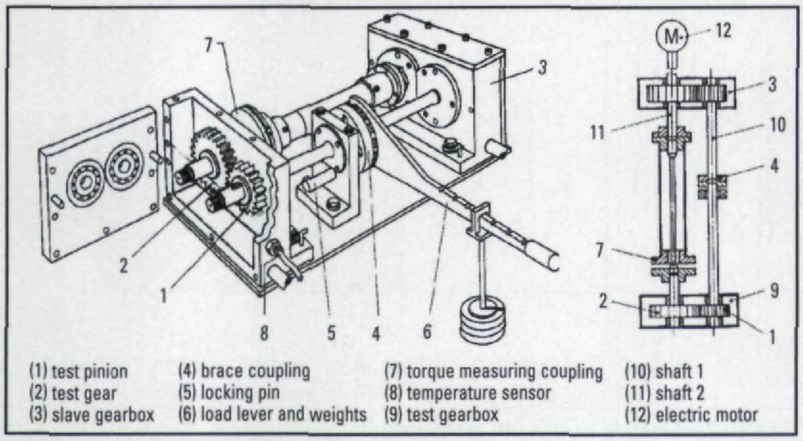

Figure 4—Schematic section of the FZG gear test rig.

sliding motion was measured. The test rig configuration and the test specimens are described in DIN 51 834 T2 (Ref. 5).

Figure 2 shows the results of friction coefficient measurement of the test oils. The mineral-based UTTO oil M shows the highest value of average friction coefficient. The biodegradable oils exhibit less friction, especially the test oil G. Biodegradable UTTO oils with similar elemental compositions of additives—R, S, and H—obtain almost the same value for friction coefficient.

Five different fatty acids contained in the vegetable oils were tested on the SRV test device to demonstrate their antiwear properties (see Fig. 3). The oleic fatty acid proved to have the best antiwear properties at the selected parameters. Antiwear properties and good oxidation stability make the oleic fatty acid the most desired fatty acid in the vegetable lubricant oil formulation.

FZG test results. The FZG gear test rig is commonly used to evaluate scuffing load capacity, pitting resistance and slow-speed, high-load wear resistance. Experiments are based on a failure of a standard gear set, lubricated with the test oil under specific test conditions, using the test rig illustrated in Figure 4 (Refs. 6–7).

The load-carrying capacity of lubricants was investigated by using the standard FZG A/8.3/90 test procedure. The test oil is subjected to a load, increasing by stages, until the scuffing failure criterion has been reached. Twenty millimeters of tooth scuffing indicate a test failure. The failure load stage is reported as a result (Ref. 6–7).

Investigations of the pitting resistance were performed on the FZG gear test rig in the standard pitting test C/8.3/90. After a two-hour run-in at load stage 6 (135.3 Nm), the test is run at load stage 9 (302 Nm) until the failure criterion is recorded. The number of pinion load cycles when the critical damage of the tooth flanks occur is reported as a result (Ref. 8).

UTTO oils are intended to lubricate transmissions and gearboxes of the tractors. In such systems, high temperatures, high loads and low speeds are very common conditions. The primary mode of failure observed with the spiral bevel gearing is scuffing, while the planetary units encounter normal abrasive wear. There are a number of methods to evaluate scuffing, but the primary concern of this investigation is to simulate normal rubbing wear of the planetary gears. In the slow-speed, high-load wear test, the C-type gears were used to reduce the sliding velocity and consequently the probability of scuffing. The test procedure is divided into two stages. The test gears are weighed before and after each stage and the weight loss associated with wear is recorded as a result which indicates the lubricant antiwear performance (Ref. 9–10).

The main FZG test conditions are summarized in Table 3.

The results of the FZG tests are summarized in Table 4. The best results on the FZG test rig were obtained with the synthetic ester-based oil G, which has a viscosity that's two ISO grades higher than other oils.

The results of scuffing load capacity for UTTO oils show better scuffing resistance for the formulated high-oleic sunflower-based oil S, which passed the 11th load stage while the other vegetable-based formulation R and reference UTTO oils passed the 10th load stage. Generally, UTTO oils exhibit a scuffing load stage between 9 and 11; therefore all tested oils meet these requirements (Ref. 11).

The results of pitting investigations show superior pitting resistance of the vegetable- and the synthetic esters-based oils, compared with the mineral-based UTTO oil. The high-oleic sunflower oil S showed very good pitting performance among the formulated UTTO oils.

The results of slow-speed, high-load wear investigations indicate no significant difference in wear rates among the UTTO oils. All test oils show low wear rates in a slow-speed, high-load FZG test.

On the basis of the FZG test results, we selected the formulated high-oleic sunflower-based formulation S for further investigations.

Table 3—FZG Test Conditions.					
Parameters	Unit	Scuffing	Pitting	Wear	
				Stage I	Stage II
Test gears type		A	C	C	
Load stage		*	9	10	
Gear torque	Nm	*	302	372.6	372.6
Circumferential speed	m/s	8.3	8.3	0.35	0.20
Pinion rotational speed	rpm	2,170	2,170	93	53
Running time	hour	1/4–one stage	until failure	20	30
Sump temperature	°C	90, at start	90	121	
* ... incrementally increased load.					

Table 4—FZG Test Results.			
Oil	Scuffing A/8.3/90 (FZG load stage)	Pitting C/8.3/90 (cycles of pinion)	Slow speed wear C/0.35–0.25/120 (weight loss in mg)
R	10	13.96 10^6	11/14[1)]
S	11	26.75 10^6	19/22[1)]
G	>12	30.00* 10^6	
H	10	15.66 10^6	
M	10	7.70 10^6	13/13[1)]

* ... pitting test was stopped, but critical failure did not occur.
1) ... Stage I/Stage II.

Helical Gear Test

Helical gear test rig. A helical gear test rig was used in order to demonstrate viscosity stability, antiwear properties, oxidation resistance and seal compatibility of the formulated high-oleic sunflower-based UTTO oil labeled S in controlled laboratory conditions. Through periodic sampling of the lubricant and used oil analysis, the condition of the test oil and parts of the gearbox were determined.

The helical gear test rig is schematically shown on Figure 5. The AC drive motor with frequency regulation runs a test gear-unit which is lubricated with the formulated high-oleic sunflower-based UTTO oil S. For load simulation, as a brake, the DC generator and electric heaters are used. The DIN CK60 pinion and DIN CK45 gear, case hardened to 60–62 HRC and not undercut, were used during the test. These helical gears had face widths of 30 mm, normal modules of 2.5 mm, and the drive pinion had 31 teeth meshing in a 1:1.5 ratio. The test rig was run continuously 12 hours per day at a constant load of approximately 60 Nm of torque. The oil temperature was maintained in the range of 78–82°C. A pair of helical gears was rotated until the lubricant deteriorated.

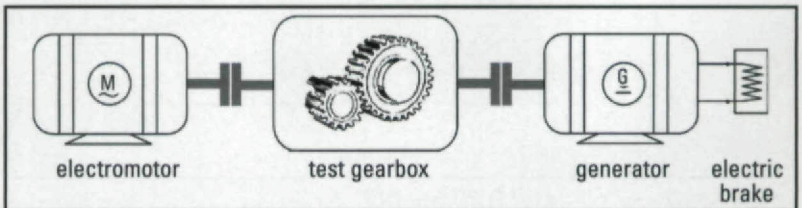

Figure 5—Schematic diagram of the helical gear test rig.

Oxidation of lubricants is normally measured by total acid number (TAN) and viscosity increase. New oils have an initial TAN, therefore the increase over the initial value measures oxidation. If the TAN exceeds 2.0 mg KOH/g over the original value, the oil should be changed. (The unit "mg KOH/g" is the quantity in milligrams of potassium hydroxide (KOH) needed to neutralize the acid constituents in one gram of lubrication oil.) A strong indicator of oil degradation is also its increase in viscosity. Normally a 20% increase in viscosity is a warning that the oil is reaching the end of its useful life.

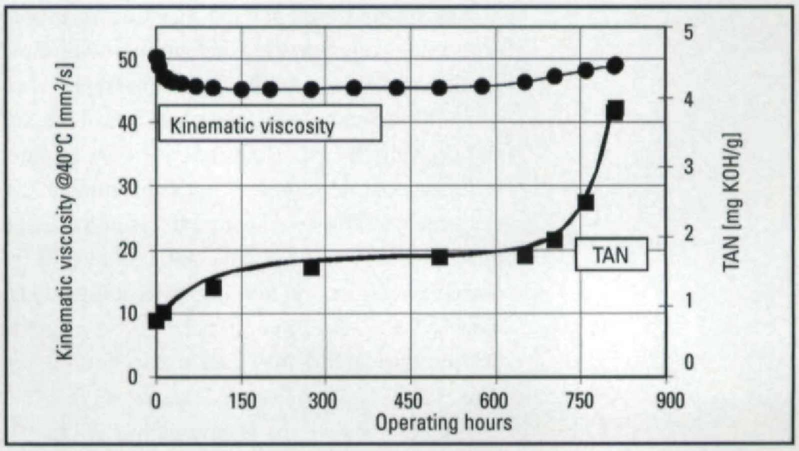

Figure 6—Trend values for viscosity and TAN.

Oil condition. The top line on the graph in Figure 6 represents kinematic viscosity of the high-oleic sunflower-based UTTO oil S, measured at 40°C. After initial shear-down, the viscosity is stable until 600 working hours, when a slight increase is observed. The bottom TAN line shows three distinct sections: initial increase is followed by a stable value until the sudden rise at 650 operating hours, which indicates the oil deterioration.

Gearbox condition. Oil in the gearbox could be a very useful condition monitoring media. If we can separate the debris from the oil, we can identify and track an abnormal wear condition without tearing down the equipment. Wear particles contained in the lubricating oil carry detailed and important information about the condition of the oil-wetted components in the gearbox. If no excessive wear is observed, then this indicates that the effective lubrication in the gearbox is maintained

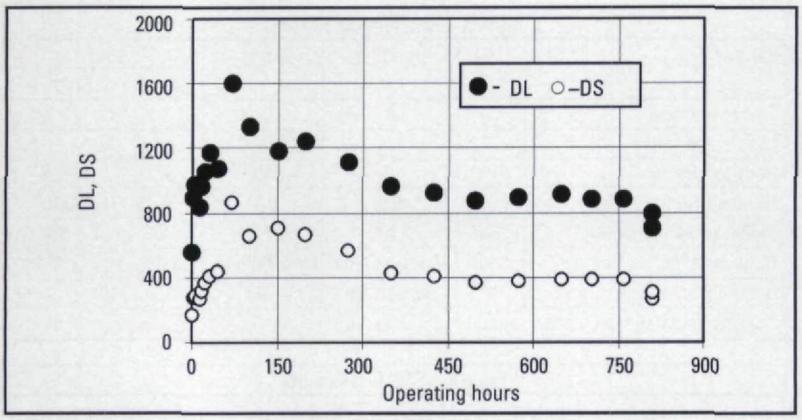

Figure 7—Quantitative ferrography readings.

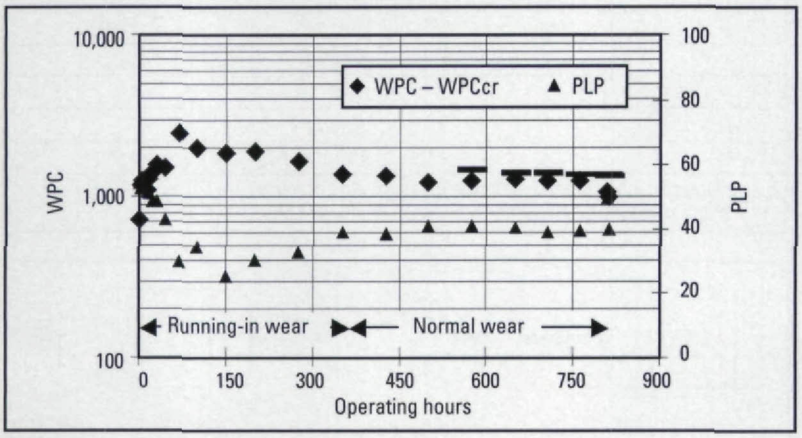

Figure 8—Trend values for WPC and PLP.

during the operation.

The method used for the quantitative evaluation of the wear particle concentration was direct reading (DR) ferrography. DR ferrography magnetically separates wear particles from lubricants and optically measures the relative concentration of ferrous particles present in the oil sample. The instrument is able to detect particles in the length range of 1–300 microns. The output of the DR ferrography consists of two digital readings, a DL (density large) for large particles (> 5 µm) and a DS (density small) for small particles (1–2 µm) (Ref. 12).

Figure 7 shows the measured values for DL and DS for high-oleic sunflower-based oil S as a function of operating time. These readings can be processed in several ways to allow easier identification of an abnormal wear mode. Two such ways are briefly described (Ref. 12):

Total Wear Particle Concentration (*WPC*)

$$WPC = DL + DS \quad (1)$$

Percentage of Large Particles (*PLP*)

$$PLP = [(DL - DS)/WPC]*100 \quad (2)$$

Although the magnitude of the *WPC* is important, the change from historical values is the indicator of machine wear condition. Quantitative ferrography is a trending tool and not a particle count. In normal operating conditions, a baseline of normal wear may be established and the average of *WPC* values can be calculated.

The average of Wear Particle Concentration value (WPC_{mean})

$$WPC_{mean} = 1/n\sum WPC^* \quad (3)$$

where WPC^* means that only normal wear data are summed (outliers are excluded).

The *WPC* value should not exceed the value of an alarm limit—the critical wear particle concentration that is based on the WPC_{mean} value and standard deviation of the normal samples (outliers are excluded).

The critical Wear Particle Concentration (WPC_{cr})

$$WPC_{cr} = WPC_{mean} + 2\sigma \quad (4)$$

where σ is a population's standard deviation.

The most informative method for DR results representation is a plot of *WPC* and *PLP* in the same graph, because an increase in both *WPC* and *PLP* is the best indication of an abnormal wear condition. Figure 8 shows the calculated values for *WPC* and *PLP*, which are plotted over time. The *WPC* value shows an initial sharp rise through a running-in process, during which the quantity of wear particles quickly increases and then settles to a lower value after 350 operating hours, when a normal wear period is beginning. The *WPC* and *PLP* values remain relatively constant in the normal running operation period, because the gearbox wear reaches a state of equilibrium in which the particle loss rate equals the particle production rate.

An alarm limit for severe wear WPC_{cr} can be calculated for the last six samples, because at least three data in the normal wear period are necessary to determine WPC_{mean} and a population's standard deviation σ before the WPC_{cr} for the first point can be calculated. All *WPC* values are beyond the alarm limit, therefore the gearbox operates in the normal wear mode. The test was ended when the test oil started to deteriorate and before the gear failures occurred.

To avoid leakage problems, seals used in a gearbox should be compatible with the test oil. Fluoroelastomer (Viton®) was used as a seal material for the test. The seals were inspected after the test and no change in the geometry was found.

Discussion

Two formulated vegetable-based UTTO oils, two synthetic esters, and a mineral UTTO oil were investigated with respect to their gear protection properties. The study has shown that the gear protection properties of the formulated vegetable-based oils are comparable with the corresponding mineral-based oil. However, the FZG investigations show significantly better results for pitting resistance for the vegetable-based oils and synthetic esters.

The vegetable-based oils and synthetic esters exhibit very good lubricity in boundary lubrication conditions, because the synthetic esters contain organic straight chain compounds with polar end groups—fatty acids (see Table 2). The polar nature of the biodegradable oils gives them a greater affinity for metal surfaces than nonpolar mineral oils. The need for antiwear additives is reduced. Therefore, with lower concentration of the additives, both the vegetable- and synthetic-based oils show lower friction coefficients than the mineral test oil (see Figs. 1–2).

The FZG test results indicate that oil viscosity has a strong influence on scuffing performance and pitting resistance (Ref. 13). The best results are obtained with the synthetic-based gear oil, which has a viscosity two ISO grades higher than the UTTO test oils. At the same time, this synthetic ester has the lowest concentration of additives. The gear oils are generally of higher viscosity than hydraulic oils, but UTTO oil is a multipurpose lubricant that has to meet both the gear protection and hydraulic system requirements.

Vegetable- and synthetic-based oils have excellent viscosity properties. Their viscosity indexes (VI) exceed 195, while the VI for mineral UTTO oil equals 150 (see Table 1). The higher VI allows for the formation of the thicker lubrication film and for better separation of the contact surfaces at working temperatures (Ref. 14–15). The UTTO oils are of the same ISO grade viscosity, but tests—especially for pitting resistance—show a great differentiation in the results. Besides the lubricant viscosity, the lubricant base stock has a great influence on pitting resistance, while the additive type and concentration have only a minor influence. The FZG pitting test conditions correspond to a Hertzian contact point pressure of 1.65 GPa, while contact pressure at the SRV test is 2.0 GPa. The pitting test results closely follow the SRV investigations. Measured friction coefficient (Figure 2), the fatty acid content (Table 2), and antiwear properties of fatty acids (Figure 3) determine the pitting performance. The higher number of cycles until failure is thus a function of the lower sliding friction at the point of contact and, consequently, lower tangential stresses on the surface, which can efficiently prevent fatigue failure associated with surface-initiated cracks (Ref. 16).

Summary

The vegetable-based UTTO oil formulations have the advantages of having a green source of oil and lower cost than a biodegradable synthetic UTTO oils. Agricultural equipment is ideally suited to use vegetable-based oil because the tractor is lubricated by oil derived from a plant growing in the field that has been cultivated by the same equipment.

The vegetable-based oil formulations exhibit low changes of viscosity with temperature. The viscosity index improvers can be used to enhance the viscosity index of mineral-based oils, but it is advantageous to have a high viscosity index "built into" the base oil molecule itself.

The tests show that the pitting resistance of vegetable- and synthetic ester-based UTTO oil formulations is significantly better compared with the mineral UTTO oil.

The investigations on the helical gear test rig have shown that the test high-oleic sunflower-based UTTO oil formulation derived from the genetically modified plant provides sufficient gearbox lubrication for 600 operation hours at a maintained oil temperature in the range of 78–82°C. ○

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