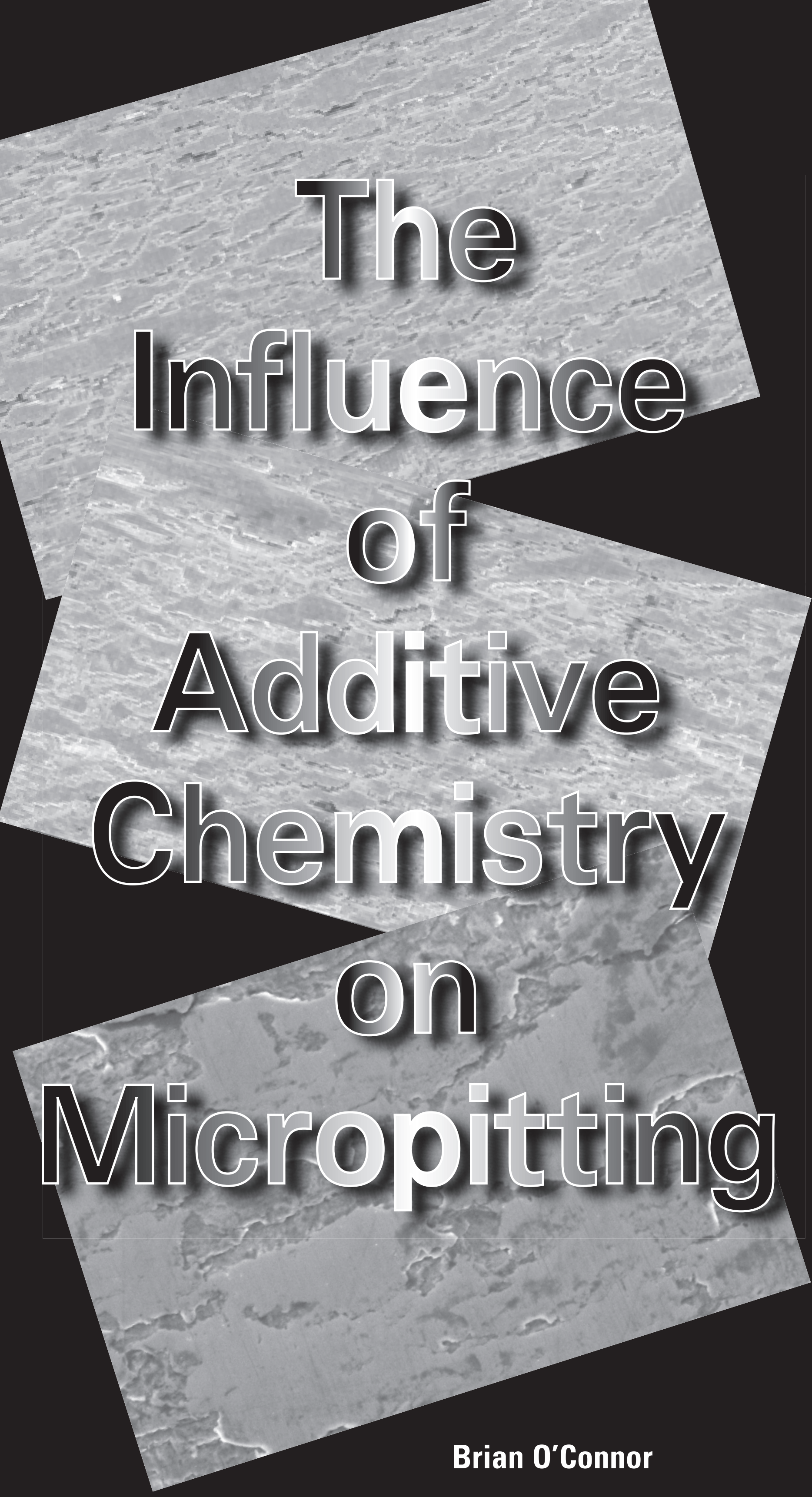
The Influence of Additive Chemistry on Micropitting



Brian O'Connor

Brian O'Connor *is a senior research scientist in the R&D division at Lubrizol Corp. of Wickliffe, OH. He has been with the company since 1970 in various technical and managerial positions. He specializes in various aspects of lubrication, tribology, engineering and development in support of the company's industrial and automotive gear applications.*

Introduction

Micropitting is a form of surface fatigue that appears to be benign, but can cause significant problems in drivetrains. It is not a new issue, but more recently, micropitting has been receiving increased attention as a serious mode of failure in many large industrial drives and also some automatic drives. Micropitting has become a significant issue in the wind turbine industry as turbine outputs have increased. What was thought to be harmless discoloration (gray staining) of the gear teeth is now recognized as a damage mode that can impact gear tooth accuracy, leading to increased noise and vibration and reduced gear life. The phenomenon has been studied from several perspectives, including kinematics, surface finish, metallurgy and lubrication (Refs. 1–5). The mechanisms behind micropitting are not completely understood, but it appears clear that it is affected by operating conditions, surface roughness and lubricant.

Lubricant studies have generally been limited to evaluating different commercial fluids in the marketplace or simplistic systems put together with available additives (Refs. 6–7). From this, some broad conclusions have been drawn, mostly suggesting that higher viscosities are more effective at reducing micropitting. This is helpful, but the problem of micropitting has not been studied in depth from the perspective of the chemical additive system. This work begins to address that issue and focuses on the impact various additive chemistries have on the micropitting form of damage. Typically, the additive is not well documented because of the proprietary nature of many of the components used. Nonetheless, the additive is an integral part of the lubricant formulation and is responsible for protecting gear and bearing surfaces from scuffing, catastrophic wear and corrosion in addition to minimizing oxidative degradation, minimizing foaming, and enabling water separation in many applications. The chemical additive system can then be a complex mixture of several different components, each used to provide a different performance function.

Management Summary

Gear micropitting has been a highly visible issue in selected applications in recent years, most notably in large wind turbine transmissions. Various industry groups have addressed the problem from their own areas of expertise. This has included evaluation of the gear design characteristics, surface finishing, the use of special coatings and lubrication. A common approach to improve the lubrication has been to increase the viscosity and create thicker films, which, in turn, reduce the amount of surface asperity interaction. Another approach from the lubricant side has been to alter the additive chemistry to effect a change in the wear properties of the system.

This paper discusses the potential effects observed for different antiwear and EP chemistry on the micropitting of cylindrical gears. Tests were conducted in an FZG test rig, which has been used by the industry as a guide for general gear performance. Fluids were examined in a series of experimental designs, which served as the iterative process leading toward an optimized additive system. The results show that the EP, or antiscuff, agent was the most effective component at reducing the level of micropitting.

They must also be compatible with each other and not diminish performance in areas outside their intended use. Thus, it becomes a careful balancing act to provide a broad functional system for the typical industrial application. When a new performance issue, such as micropitting, is introduced, the lubricant and its additive system must be re-examined to determine how its various components impact and help alleviate the problem.

As mentioned, one approach to improve micropitting performance through the lubricant is simply to increase its viscosity. This should increase the effective film thickness in the contact and reduce the amount of asperity contact, that is, increase the lambda ratio (film thickness to surface roughness ratio). This has been demonstrated to be an effective approach in some cases, but, in others, additive effects can still override the higher viscosity (Refs. 4, 8). Higher viscosity can also contribute to increased churning losses and reduced energy efficiency. This begins to have an impact on the economics of wind turbines in that there is less power being delivered to the grid due to increased losses in the transmission. Another approach would be to look at altering the additive chemistry while maintaining or reducing the viscosity of the fluid.

A typical industrial gear additive package consists of a number of individual components, each designed to provide a specific performance function. Many of these components are polar compounds, which absorb or react with the metal surfaces they are trying to protect. Examples would include antiwear (AW) agents, extreme pressure (EP) or antiscuff agents and corrosion inhibitors. There are at least two types of corrosion inhibitors—one for preventing rust of ferrous components and the other for the prevention of corrosion of non-ferrous surfaces, such as copper or copper-based alloy components. The copper-based alloy components are usually referred to as metal deactivators or metal passivators (MP). Other compounds used for control of oxidative degradation, deposit control, foam inhibition and demulsibility act more through interactions in the bulk field.

For the purpose of this study, a generic industrial gear additive system was created that basically took the most common components used to meet a basic set of performance requirements such as those outlined in AGMA 9005-E02 (Ref. 9). This package comprises an antiwear agent, EP agent, metal passivator, rust inhibitor, demulsifier, deposit control agent, friction modifier and foam inhibitor. The study began with the premise that the micropitting would likely be influenced by those components that reacted with the metal surface. This included the antiwear and the EP components of this formulation. In addition, experience has shown that the deactivator or metal passivator component can be very surface active and, in some cases, interfere with the primary function of the antiwear agent or the EP agent or both, and so this component was included in the assessment. Thus, the variables would be the AW, EP and MP, while the balance of components remained constant in the experiments. Additional studies followed where the changes were limited to varying only the antiwear and later only the EP agent, all other components being held constant. It became clear from these experiments that the EP agent had a greater effect than the antiwear agents. Further, there was evidence in the performance of the formulation with respect to micropitting performance.

Experimental

Despite the growing importance and performance implications of micropitting as a damage mode on gear drivetrains, there are no standardized tests available to the lubricant industry. Thus, part of the effort here was to develop a screening method that would reproduce the micropitting phenomenon and have relevance to the application of interest. The equipment used in these studies is the standard FZG four-square rig with the method evolving from a brief study involving different combinations of speeds and loads (torques). The gears are the standard "C" profile FZG gears generally used in pitting evaluations with this test rig. The lubricants are based on generic industrial gear oil and encompass the typical key components that are used in commercial formulations today.

Test Rig. The FZG test rig is well known in the oil industry for measuring the scuffing load capacity of many types of fluids and is the basis for several test standards (Refs. 10–12). The FZG tester is a recirculating-power, four-square configuration rig. The basic test rig has been demonstrated to have sufficient versatility to evaluate a variety of wear modes, such as low speed wear, scuffing, pitting and micropitting (Ref. 13).

The principal parts of the rig include a

Table 1—Blends for Matrix 1: ISO VG 32 Mineral Base.								
Oil Code	A1	A2	A3	A4	A5	A6	A7	A8
Additive*								
AW–1	+	+	+	+	0	0	0	0
EP– 1	+	+	0	0	+	+	0	0
MP	+	0	+	0	+	0	+	0
	*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
KV 40°C[cSt]	30.2	30.3	30.3	30.3	30.2	30.3	30.2	30.4
Elemental								
P	338	338	338	338	0	0	0	0
S	7,451	7,451	3,179	3,179	7,062	7,063	2,790	2,791
N	218	155	218	156	126	63	126	64
Note: A "+" symbol indicates normal level and a "0" symbol indicates not present.								

test gearbox, a slave gearbox, a load clutch and a torsional shaft. Power is supplied by a variable speed 5.7 kW DC motor with an effective speed range from 50–3,000 rpm. The rig is designed to evaluate parallel-axis cylindrical gearing (primarily spur gears) having a center distance of 91.5 mm. The standard torsional shaft (23 mm diameter) will permit torques to at least 550 Nm on the test gears. The gears are loaded by applying torsion to a shaft through a slip clutch by means of weights or a scanner device. The locking bolts on the clutch ensure the torsional load is maintained during the running period.

Test Gears. The evaluations discussed here were conducted using two standardized test gears available for the FZG rig. One is known as the "C" profile and the other is identified as the "C-GF". These gears are typically used for pitting and micropitting evaluations, respectively, in the FZG rig. Both gear types are case carburized 16MnCr5 steel with a tooth width of 14 mm. The primary difference is in the finish, with the "C" type gears having an average roughness value of Ra = 0.30 +/– 0.05 µm and the "C–GF" gears typically with an Ra value = 0.50 +/– 0.10 µm. These gears do not have any tip relief or lead modification, as might be found in typical automotive or industrial applications, but they still serve as a useful test tool for relative comparison within their known limitations.

Test Methods. Although no officially sanctioned test method exists, the most widely accepted method for micropitting performance today is described in the FVA Information Sheet 54/I–IV (Ref. 11). This is basically a summary of the testing protocol used by Schoennenbeck in the early 1980s in his studies of micropitting (graufleckigkeit) at the Technical Univesity of Munich (Ref. 4). This is a very long and tedious test method and requires special gear checking equipment to measure the profile deviation along the involute of the tooth. Many test laboratories do not have the special equipment required to carry out the profile deviation measurement. There is, however, a general relationship between weight loss and profile deviation that we have used in our internal screen testing. Care must be maintained to minimize macropitting, as this can distort the response.

In order to evaluate a relatively large number of lubricant modifications in a timely and cost-effective manner, a screening procedure was developed from a short study of different operating conditions. The objective was to minimize the onset of macropitting while maximizing the wear that would occur from just a micropitting mode of damage. From previous experience, it is known that macropitting would occur with torques greater than 302 Nm (standard load stage 9) applied to the rig. Most industrial lubricants were capable of running for at least 100 hours before macropitting would occur. The operating condition study involved comparing the response of a single reference fluid using two speed variables (cycling multispeed vs. constant speed) and two torque variables (sequential step load vs. constant load) in a simple 2 x 2 matrix. The results showed that the maximum wear without significant macropitting was achieved with the constant speed, constant load combination of operating conditions. This is similar to the screening method used by Thiessen (Ref. 14). Thus, for the evaluations presented here, the test conditions used were: pitchline velocity = 6.25 m/s; pinion torque = 300 Nm, and duration = 72 hours. Type "C" profile gears were used in the screening method presented here. Also, in these experiments, the temperature was intentionally not controlled but rather allowed to seek its own equilibrium. Since many applications do not control the lubricant temperature, this was also applied to the experiments. It is an attempt to get closer to actual practice and affords some additional information about the thermal characteristics of the lubricant under test. At the end of each test, the gear is rated for area damaged by micropitting (averaged over 16 pinion teeth), macropitting (sum total over 16 pinion teeth) and wear by weight loss observed for the pinion and gear.

Following the screening evaluations, testing was conducted with a modified test matrix in the test known as the FVA 54/I micropitting test (Ref. 15). This is a two-part test conducted in a standard FZG test rig using jet spray lubrication. The first phase of the test involves a series of six, 16-hour increasing step load stages. At the end of each 16-hour stage, the gears are measured for profile deviation. The criteria for acceptability is ≤ 7.5 µm average profile deviation over three teeth on the gear set. The second part of the test is the durability phase and consists of a series of 80-hour stage runs at constant load. After each 80-hour stage, the gears are checked for profile deviation. In this phase, the criteria is ≤ 22.5 µm average profile deviation for acceptable performance. The test is then rated on a load stage achieved in part one, and the length of testing is achieved in part two. An overall rating with respect to the micropitting performance is assigned based on load stage, durability life and general condition of the gears.

Test Lubricants. Lubricants used for many wind turbine applications today are typically ISO 320 viscosity grade. Since the objective of these studies was to identify potential additive response, a lower viscosity lubricant was chosen to increase the probability of asperity contact and accentuate the influence the additive may have on micropitting performance. The initial studies were done with a mineral base blend meeting the ISO VG 32 characteristics. Later studies were done with mineral base fluids meeting the ISO 150 viscosity grade to address other issues and will be reported on in the future.

For the ISO VG 32 blend, the base oil was a solvent-refined 150 neutral oil meeting the characteristics of an API Group I Stock (Ref. 16). The additive was noncommercial but designed to be representative of a typical industrial gear additive formulation meeting the requirements of AGMA 9005-E02 (formerly 9005-D94) (Ref. 9). Although the primary interest was in the antiwear (AW), antiscuff (EP) and metal passivator (MP) components, it is important to work with an otherwise complete package to determine if interactions may occur that might not be observed when evaluating isolated components. The balance of the additive package consisted of a dispersant for deposit control, demulsifier for water shedding capability, rust inhibitor and foam inhibitor.

In the first group of experiments, the focus was on the AW, EP and MP components. These were either present at their conventional treatment levels or at zero levels. A simple three factor-two level factorial design was created to evaluate the main effects and potential interactions of these components as outlined in Table 1. The physical and basic characteristics are provided in the table. As a follow up to those experiments, a series of evaluations were conducted where only the antiwear agent or the EP agent was varied to ascertain the response of different chemistries for the same performance function. The general characteristics for the alternate antiwear and EP blends are described in Table 2. The alternate antiwear and EP components were chosen to provide a range of different chemical functional groups or activity levels. They are generically described in Table 3.

Table 2—Blends for Antiwear and EP Studies.

Oil Code	A1	AW2	AW3	AW4	EP2	EP3	EP4
Additive*							
AW–1	+				+	+	+
AW–2		+					
AW–3			+				
AW–4				+			
EP–1	+	+	+	+			
EP–2					+		
EP–3						+	
EP–4							+
MP	+	+	+	+	+	+	+
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
KV at 40°C [cSt]	30.2	30.3	29.9	30.1	29.4	29.8	30.7
Elements							
P [ppm]	338	340	340	340	338	338	338
S [ppm]	7,451	7,046	7,050	7,048	7,454	7,453	7,446
N [ppm]	218	289	285	126	218	221	982

Table 3—Description of Antiwear and EP Chemical Components.

Component	Chemical Description	Function
AW–1	Medium-chain alkyl dithiophosphoric acid ester, amine salt	Antiwear (8.5% P)
AW–2	Long-chain alkyl phosphoric acid ester, amine salt	Antiwear/friction modifier (5.0% P)
AW–3	Medium-chain-length alkyl phosphoric acid ester, amine salt	Antiwear (7.7% P)
AW–4	Long-chain alkyl phosphite	Antiwear/friction modifier (5.8% P)
EP–1	Alkyl disulfide	Antiscuff (43% S)
EP–2	Alkyl polysulfide	Antiscuff (45% S)
EP–3	Alkyl polysulfide	Antiscuff/cutting agent (54% S)
EP–4	Experimental mono- and disulfide	Antiscuff/antioxidant (40% S)

Results and Discussion

As a first approximation, a simple 2^3 factoral design was evaluated to determine if the chosen variables were contributing to the micropitting mode of damage. The variables addressed in this matrix were the antiwear (AW), antiscuff (EP) and the metal passivator (MP). These were thought to be among the more surface-active components with reaction potential with the surface. To increase the emphasis on the effect coming from the additive system, a very light viscosity grade was chosen in order to maximize the surface asperity interaction. The nominal roughness value for the "C" profile FZG gears used in the early studies was approximately 0.3 μm. Using

Table 4—Results with Matrix 1.								
Oil Code	A1	A2	A3	A4	A5	A6	A7	A8
Base Fluid	ISO VG 32 (100% Solvent Refined 150 N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor. A "+" symbol indicates standard treat level, and a "–" symbol indicates not present.								
FZG Micropit Screen Test								
Micropit area [mm²]	17.9	23.4	24.4	24.8	18.7	9.1	N/A	N/A
Macropit area [mm²]	0	0	0.2	52.4	0	8.9	N/A	N/A
Weight Loss [mg]	22	29	37	102	49	47	12,309	4,562
Tmax [°C]	107.4	115.6	111.9	125.1	108.9	103.2	148.6	143.5
Tavg [°C]	103.5	110.6	106.2	116.7	100.7	98.9	119.0	107.7

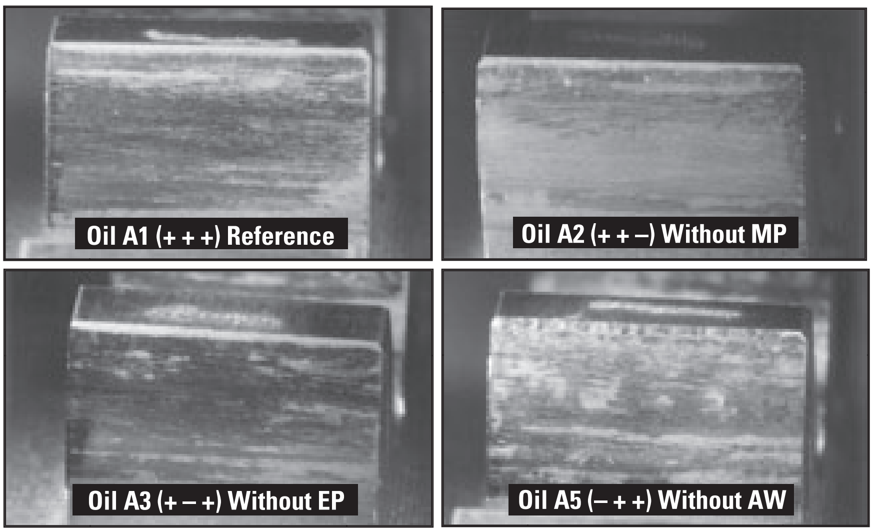


Figure 1—Comparison of micropitting damage from FZG Micropit Screen Test – Matrix 1.

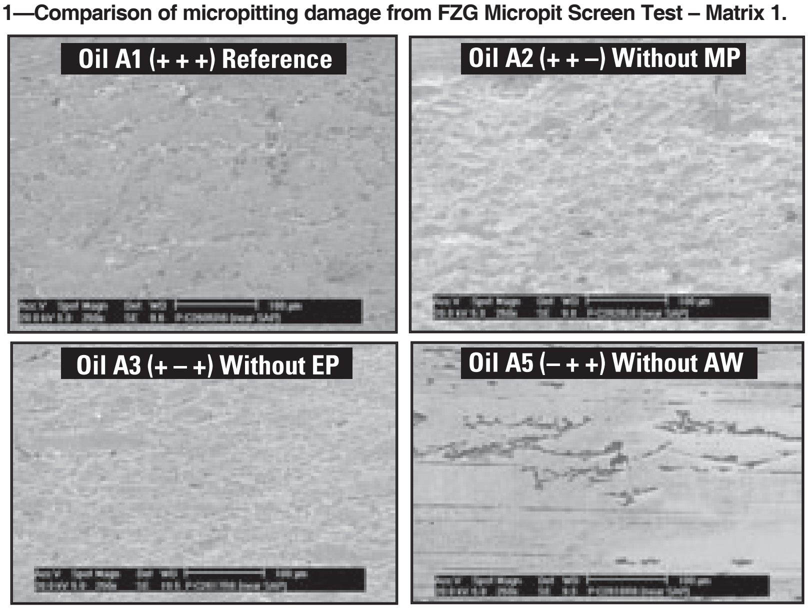


Figure 2—Influence of Main Effect Components (AW, EP, MP) on micropitting from Matrix 1 (all micrographs taken approx. 2 mm above SAP).

the Dowson-Higginson formula for film thickness in EHD line contact situations shown in Equation 1, it was clear that the typical ISO VG 320 viscosity used in many industrial applications would provide a very thick film and limit the possible additive interaction with the surfaces (Ref. 17).

$$h_{min} = 2.65 * \frac{R * G^{0.54} * U^{0.7}}{W^{0.13}} \quad (1)$$

Where:
h_{min} = minimum film thickness
R = reduced radius of curvature for the mating components
G = dimensionless materials parameter
U = dimensionless velocity parameter
W = dimensionless load parameter

It was desired to reduce the lambda ratio to well below 1.00 to provide an adequate forum for the additive interaction with the surfaces. Based on the calculations for the minimum film thickness using the Dowson-Higginson equation above and the typical surface roughness of the gears, an ISO VG 32 blend should provide a lambda ratio of approximately 0.6.

The results of the first test matrix are summarized in Table 4. A complete mathematical analysis of the results could not be carried out due to the severe wear encountered with the two tests run without the antiwear and EP components (blends A7 and A8). This clearly points out the value of these components in a loaded sliding contact. Because of the extremely high wear, the gears could not be rated for micropitting damage. The remaining six tests did provide some direction. The results suggest that there are likely interactions between the EP agent and the antiwear and metal passivator, which detract from performance. If one compares oil A6 (EP agent only) to either oil A2 (the comparable blend with the antiwear present) or to oil A5 (the comparable blend with the metal passivator present), both cases result in more micropitting.

Sometimes, one must look beyond empirical results to see difference. If one compares oil A1, A2, A3, and A5, the average area of micropitting damage is similar, i.e. 17.9, 23.4, 24.4 and 18.7 mm^2 respectively. The typical visual assessment shown in Figure 1 confirms that these appear similar. However, as one examines the surfaces more closely, as in Figure 2, there is a distinct difference in the appearance of the micropitting damage for oil A5 compared to the other three. This change in appearance suggests that the antiwear component present in A1, A2, and A3 may be affecting performance in a negative fashion, since oil A5 was constructed without the antiwear component. The micropits on the surface of the gear run with oil A5 are larger in size, but the surface around them is much smoother, which suggests a possibly lower wear with increased running time, a point that was not examined in this study.

The previous exercise evaluated one antiwear agent and one EP agent in the matrix. The antiwear was a medium-chain-length alkyl dithiophosphoric acid ester and the EP was an alkyl disulfide. In two sets of evaluations, a series of simple substitution experiments were conducted to determine if the response (micropitting) would be altered if the chemical functionality were changed. There are still interactions to consider, but this limited work was a pilot to see if any effect could be observed. Using blend A1 from Matrix 1 as a baseline or reference, the alternate components were substituted on an equal chemical (phosphorus or sulfur) basis for the reference materials now dubbed as AW-1 and EP-1. A list of alternate components is shown in Table 3.

Two approaches are considered here to address the micropitting issue. One is to reduce the friction at the surface and thereby reduce the tangential stress acting on the asperities that form the micropits. The other approach is to actually induce a high rate of wear to rapidly remove the asperities and thus minimize the long-term damage from micropitting. The latter is considered more as a chemical break-in approach. If reduced friction is an important aspect in the mechanism of the micropitting formation, then the two long-chain alkyl phosphorus derivatives, AW-2 and AW-4, should help based on their performance in automotive applications. For the case involving high, chemically induced wear, the more active antiscuff components, EP-2 and EP-3, were chosen to accomplish this. These components are generally more active than the EP-1 baseline component and should provide a higher rate of wear, thereby reducing the surface roughness more rapidly. As part of the investigation, an antiwear component of similar alkyl chain length but different functionality (AW-3) and an experimental alkyl disulfide (EP-4) were also included simply to look at different chemical functional groups.

The results shown in Table 5 do not necessarily support either the reduced friction or increased wear approaches to reduce micropitting, at least for the components chosen. Of the two long-chain

Table 5—Results with Alternate Antiwear and EP Components.

Oil Code	A1	AW2	AW3	AW4	EP2	EP3	EP4
Base Fluid	ISO VG 32 (100% Solvent Refined 150 N)						
Additive*							
AW–1	+				+	+	+
AW–2		+					
AW–3			+				
AW–4				+			
AW–5							
EP–1	+	+	+	+			
EP–2					+		
EP–3						+	
EP–4							+
MP	+	+	+	+	+	+	+
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
Micropit area [mm^2]	17.9	30.9	12.6	12.4	38.8	39.4	6.9
Macropit area [mm^2]	0	7.5	0.6	27.4	0	0	4.9
Weight loss [mg]	22	41	40	48	52	60	28
Tmax [°C]	107.4	113.4	106.4	111.1	117.4	115.5	106.9
Tavg [°C]	103.5	108.2	100.9	103.6	114.5	111.0	103.7

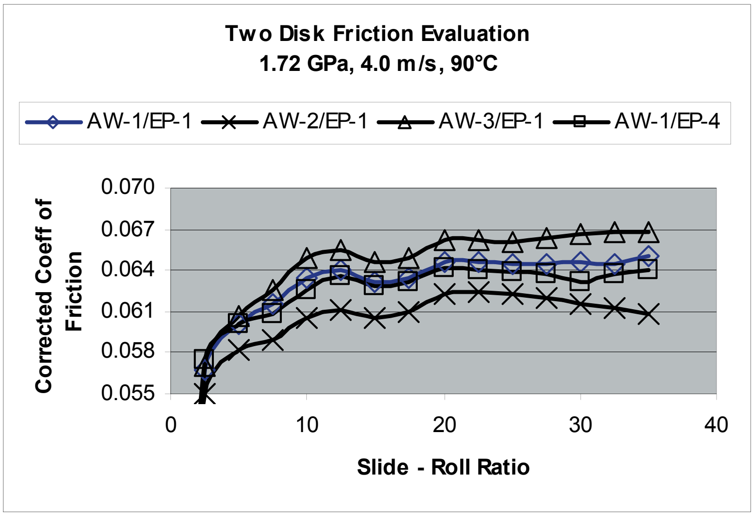


Figure 4—Two Disk Friction Response vs. Slide-Roll Ratio.

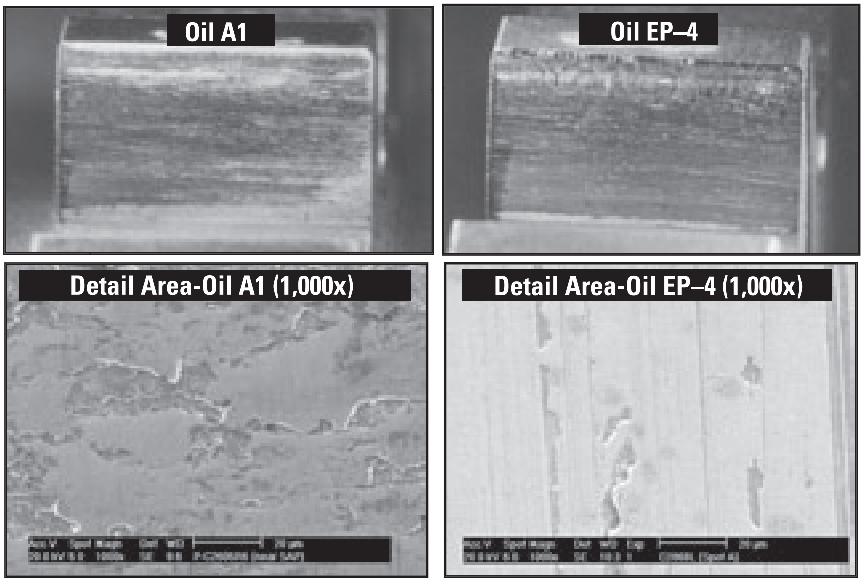


Figure 4—Comparison of micropitting damage from FZG Micropit Screen Test.

Table 6—Evaluation of Matrix 2.

Oil Code	A1	A2	B1	B2	A5	A6	B3	B4
Base Fluid	ISO VG 32 (100% Solvent Refined 150N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
EP–4	–	–	+	+	–	–	+	+
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.								
FZG Micropit Screen Test								
Micropit Area [mm²]	17.9	23.4	6.9	23.7	18.7	9.1	N/A	0.1
Macropit Area [mm²]	0.0	0.0	4.9	45.3	0.0	8.9	0.0	0.9
Weight Loss [mg]	22	29	28	93	49	47	248	17
Tmax [°C]	107.4	115.6	106.8	109.0	108.9	103.2	100.2	97.5
Tavg [°C]	103.5	110.6	103.7	105.7	100.7	98.9	95.0	94.5
Comment				Macropit fail			Severe wear—could not rate	

alkyl phosphorus compounds that were aimed at reducing friction, only the AW-4 material showed a reduction in micropitting. The medium-chain alkyl phosphoric acid ester, AW-3, also showed a similar reduction in micropitting. It is interesting to note that the other long-chain phosphoric acid ester (AW-2), which was expected to have a much lower surface friction, did not perform very well. Using a similar two-disk apparatus, the friction properties of selected alternate component blends were also examined. Figure 3 shows that the response of friction as a function of slide-roll ratio is very similar for these fluids regardless of their gear micropitting performance. This suggests that a different mechanism is controlling the micropitting response.

From the theory of increased wear, neither of the more active sulfur compounds, EP-2 or EP-3, performed as expected. In fact, their performance was detrimental with regard to micropitting protection. The experimental alkyl disulfide, however, provided a significant reduction in micropitting compared to the baseline EP–1 formulation. Figure 4 highlights the comparison between oil A1 and oil EP–4 in the critical region near the start of the active profile (SAP) on the pinion gear. There is clearly a difference in the amount of micropitting and the surface topography of these two runs. The original machine marks are still visible in the test with EP-4, whereas with A1, the surface in the same region is void of detail beyond the micropitted damage.

While the focus of this study was to examine and reduce the amount of micropitting formed through the lubricant, the alternative antiwear components that did show a benefit, AW-3 and AW-4, were found to have deficiencies elsewhere that limited their long-term use. Thus, the next iteration would only include further evaluation of the EP component, EP-4, which showed a benefit in the initial screening. Again, it was desired to look for interactive effects between the potential components of interest. A modified version of the first matrix was then set up and evaluated. In this case, the blends were first evaluated in the short screen test and then later by the FVA 54/I method.

The Matrix 2 design and results for the FZG screen test and full length FVA 54/I tests are shown in Tables 6 and 7, respectively. From the available data, one can examine trends with respect to the response of the main effects, i.e., the presence or absence of AW-1, use of EP-1 vs. EP-4, and the presence or absence of the MP. From the screen test results, we find that the presence of AW-1 in the formulation leads to higher amounts of micro- and macropitting and increased maximum and average oil temperatures during the testing. Component EP-1 resulted in higher levels of micropitting and higher oil temperatures than EP-4, but had less macropitting on average than EP-4. There was no real difference in the measured parameters when the metal passivator was present or not. If one examines the FVA 54/I test data in a similar fashion, it shows the antiwear component produces, on average, higher amounts of micropitting along with higher levels of profile deviation. This is consistent with the trends observed for the screen test. For the EP and metal passivator (MP) components, the FVA test did not show any notable separation for the profile deviation, which is the critical measurement of that test. It is interesting to note that despite the use of a very low viscosity base fluid (ISO VG 32), there were several cases of high micropit classification. This is encouraging from the standpoint that perhaps lighter fluids may be used in the future, if the additive system provides adequate protection.

Table 7—Evaluation of Matrix 2 by FVA 54/I Method.

Oil Code	A1	A2	B1	B2	A5	A6	B3	B4
Base Fluid	ISO VG 32 (100% Solvent Refined 150N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
EP–4	–	–	+	+	–	–	+	+
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.								
FVA 54/I Micropit Test								
Overall Rating	High	Middle	N/A	Low	High	Middle	Middle	High
Part 1: Step Load								
Fail LS	10	10	10*	9	>10	9	9	>10
Profile Dev. [μm]	11.1	9.0	7.5	8.7	2.7	8.0	8.0	7.5
Weight Loss [mg]	21	45	24	65	18	34	27	19
Part 2: Durability								
Duration [h]	480	320	N/A	160	160	240	160	240
Profile Dev. [μm]	19.0	22.5	N/A	22.5	14.3	18.4	22.5	21.0
Comment			*Scuff failure	Macropit fail	Macropit fail	Macropit fail		

Conclusion

The work presented in this study is part of a larger program to investigate and understand lubricant chemical response toward micropitting of gears. This initial work shows that the choice of additive chemistry can have an impact on performance. Additionally, it is clear that there are variations of performance within a given functional family. Therefore, it may not be prudent to arbitrarily declare a given functionality, such as antiwear or EP, as being more beneficial or detrimental over the other, owing to the many possible chemical types that fall within a given performance functional group. This work has also looked at friction and wear as factors in the micropitting process, but the results did not support the premises. Additional work is being undertaken to explore the mechanism involved.

This article was previously published by ASME at the 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference (DETC2003/PTG-48125). It is reprinted here with ASME's permission.

References

1. Olver, A.V. "Micropitting of Gear Teeth: Design Solutions," Aerotech '95, NEC Birmingham, October 1995, published by I Mech E, 1995.
2. Berthe, D., L. Flammand, D. Foucher and M. Godet. "Micropitting in Hertzian Contacts," *Trans ASME, J. Lubr. Technol.*, 102, 1980, pp. 478–489.
3. Shotter, B.A. "Micropitting: Its Characteristics and Implications on the Test Requirements of Gear Oils," *Performance and Testing of Gear Oils and Transmission Fluids*, Institute of Petroleum, 1981, pp. 53–60 and 320–323.
4. Schoennenbeck, G. "Einfluss der Schmiestoff auf die Zahnflankenermuedung (Graufleckigkeit und Gruebchenbildung) Hauptsaechlich im Umfansgeschwindigkeits bereich 1…9 m/s," Dissertation, Technische Universität Muenchen, 1984.
5. Hoeprich, M.R. "Analysis of Micropitting on Prototype Surface Fatigue Test Gears," American Gear Manufacturers Association Technical Paper No. 99FTM5, October 1999.
6. Errichello, R. "Selecting and Applying Lubricants to Avoid Micropitting of Gear Teeth," *Machinery Lubrication*, Nov.–Dec. 2002, pp. 30–36.
7. Cardis, A.B., and M.N. Webster. "Gear Oil Micropitting Evaluation," American Gear Manufacturers Association Technical Paper No. 99FTM4, October 1999.
8. O'Connor, B.M., and P.S. Greenfield. "Investigation of Lubricant Effects on Surface Fatigue Using an FZG Test Rig," Technische Akademie Esslingen 11th International Colloquium, Industrial and Automotive Lubrication, pp. 419–424, Jan. 13–15, 1998.
9. ANSI/AGMA 9005-E02, American National Standard—Industrial Gear Lubrication, AGMA 2002.
10. ISO Standard 14635-1, Gears–FZG test procedures Part 1: FZG test method A/8.3/90 for relative scuffing load carrying capacity for oils, International Standards Organization, Geneva, Switzerland, 2000.
11. CEC Method, L-07-A-95, Load Carrying Capacity Test for Transmission Lubricants, Coordinating European Council, London, U.K., 1995.
12. ASTM D-5182-97, Standard Test Method for Evaluation in the Scuffing Load Capacity of Oils (FZG Visual Method), American Society for Testing and Materials, West Conshohocken, PA, 1997.
13. Hoehn, B-R., P. Oster and K. Michaelis. "New Test Methods for the Evaluation of Wear, Scuffing and Pitting Capacity of Gear Lubricants," American Gear Manufacturers Assocation Technical Paper No. 98FTM8, October 1998.
14. Theissen, J. "Eignungsnachweise von Schmieroelen fuer Industriegetriebe," Technische Akademie Esslingen 11th International Colloquium, Industrial and Automotive Lubrication, pp. 383–392. Jan. 1998.
15. FVA Information Sheet 54/I–IV Micropitting, Forschungvereinigung Antriebstechnik e.V. Lyoner Strasse 18, D-60528 Frankfurt/Main, Germany, July 1993.
16. API Publication 1509, *Engine Oil Licensing and Certification System*, 15th Edition, American Petroleum Institute, April 2002.
17. Winer, W., and H. Chen. "Film Thickness, Contact Stress and Surface Temperatures," *Wear Control Handbook*, American Society of Mechanical Engineers, 1980, pp. 81–141.