Gear Oil Micropitting Evaluation

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Introduction

During the last decade, industrial gear manufacturers, particularly in Europe, began to require documentation of micropitting performance before approving a gear oil for use in their equipment. The development of micropitting resistant lubricants has been limited both by a lack of understanding of the mechanism by which certain lubricant chemistry promotes micropitting and by a lack of readily available testing for evaluation of the micropitting resistance of lubricants. This paper reports results of two types of testing: (1) the use of a roller disk machine to conduct small scale laboratory studies of the effects of individual additives and combinations of additives on micropitting and (2) a helical gear test used to study micropitting performance of formulated gear oils.

Table 1—Factors Influencing Micropitting and Suggested Remedies.

Influencing Factor	Suggested Remedy
Gear Surface Roughness	Reduce to 0.3μm
Reduce Austenite Level	Retained Austenite
Lubricant Viscosity	Use Highest Practical Viscosity
Coefficient of Friction	Reduce the Coefficient of Friction
Speed	Run at High Speed (for a thicker EHL film)
Oil Temperature	Reduce Oil Temperature
Lubricant Additive Chemistry	Use Properly Selected Additives

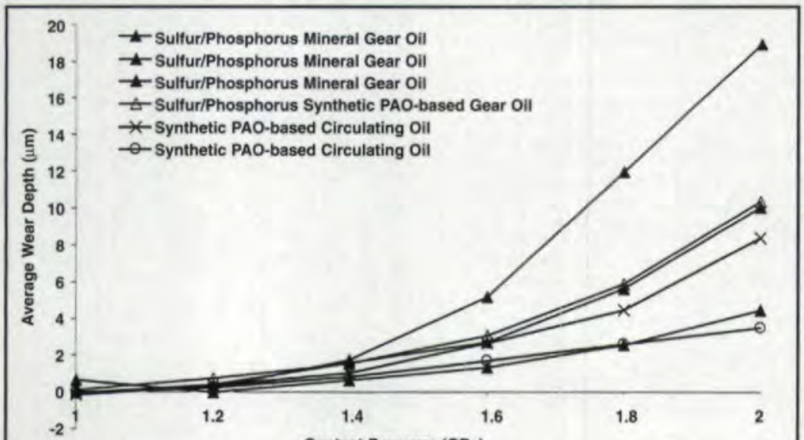

Fig. 1—Plot showing the progression of micropitting wear during Roller Disk machine experiments for various ISO VG 100 industrial gear and circulating lubricants.

Background

Micropitting is an unexpectedly high rolling contact fatigue wear phenomenon that is observed in combined rolling and sliding contacts operating under Elastohydrodynamic Lubrication (EHL) or mixed EHL/Boundary Lubrication conditions. Besides operating conditions such as temperature, load, speed, sliding and specific film thickness, the chemical composition of a lubricant has been found to strongly influence this wear phenomenon. Typically, the failure may start during the first 10^5 to 10^6 stress cycles with the generation of numerous surface cracks. The cracks propagate at a shallow angle to the surface forming micropits with characteristic dimensions of approximately 10μm. The micropits coalesce to produce a continuous fractured surface with a characteristic dull matte appearance that is variously called gray staining, frosting or micropitting when it is applied to gears. Micropitting is the preferred term. The terms peeling or general superficial spalling have also been used to describe this failure mode when it occurs on rolling element bearings. Micropitting is generally, but not necessarily exclusively, a problem associated with heavily loaded case hardened gears.

Unlike macropitting, micropitting is difficult to see, particularly under the conditions of field inspections. In the laboratory, with a clean gear mounted under a microscope with good directional lighting, micropitting takes on the appearance of etched glass. In the field, the tooth surface must be illuminated from various angles to see if the characteristic matte areas can be revealed.

Micropitting may occur almost anywhere on the gear tooth. However, research shows that micropitting is most likely to occur at local areas of high load, or areas associated with higher sliding during the gear tooth contact cycle. For this reason, micropitting is often found in the addendum and dedendum of the tooth profile and at the edge of the gear tooth if the gears are misaligned. It has also been observed that micropitting often tracks local high spots in the surface topography associated with high stresses.

The progression of micropitting may eventually result in macropitting. If pits form they often display a characteristic arrowhead or fan shape, with the pointed end at the edge of the micropitted area. There are also reported cases where the micropitting progresses up to a point and stops, sometimes described as a form of running-in or stress relief. Although it may appear innocuous, such loss of metal from the gear surface causes loss of gear accuracy, increased vibration, noise and other related problems. The metal particles released into the oil may be too small to be picked up by commonly used filters, but large enough to damage tooth and bearing surfaces (Ref. 1).

Micropitting Tests

The factors that are reported to influence micropitting (Ref. 2), along with suggestions for preventing the problem, are shown in Table 1.

The selection of properly additized lubricants is the most difficult parameter to determine. Ueno, et a1. (Ref. 3) found in their testing that antiscuffing additives (often referred to as EP additives) in a GL-5 type lubricant caused micropitting to increase. Certain specification tests, such as the Timken OK Load Test, Four Ball EP Test and the FZG Scuffing Test require the use of such anti-scuffing additives.

There is no globally accepted test for determining the effect of the lubricant on gear micropitting. However, the test reported in the FVA (Forschungsvereinigung Antriebstechnik, the German Research Association for Drive Technology) Information Sheet No. 54/I-IV has gained widespread acceptance among gear builders and customers. In this test, the failure is determined by the degree to which micropitting causes a deviation from the original gear involute profile. If involute measurement equipment is unavailable, the micropitting can be tracked using a combination of micropitting area and weight loss, which is compared with tables and pictures characteristic of reference lubricants with different levels of micropitting protection.

Experimental Roller Disk Program

The FVA micropitting gear procedure can be used to screen the performance of various lubricant options. However, disk machines offer a more flexible platform on which to conduct tests to evaluate the influence of various operational and lubrication parameters on micropitting. Webster and Norbart (Ref. 4) have described the development of a roller disk test procedure that successfully reproduced many of the aspects of micropitting observed in gear testing. Significant findings from this preliminary work were:

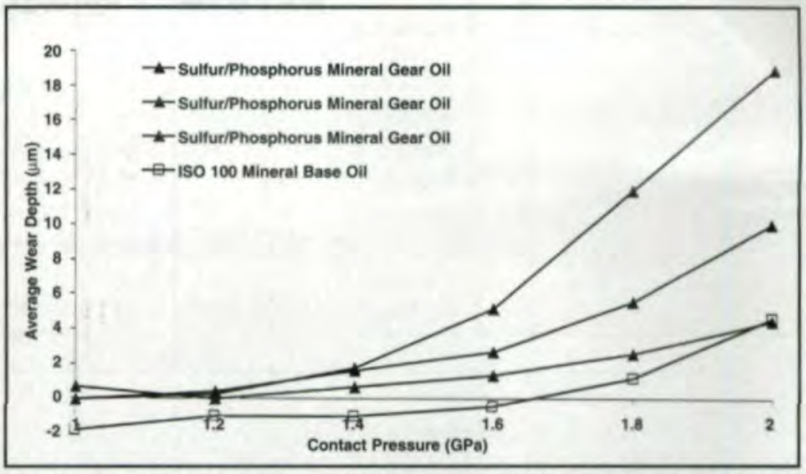

Fig. 2—Average wear depth results from Roller Disk tests show the effect of removing additives from an ISO VG 100 sulfur-phosphorus gear oil.

Table 2—Gear Design and Operational Variables for Helical Gear Micropitting Tests.

		Gear	Pinion
Number of Teeth		55	25
Normal Pressure Angle (deg)		25	25
Pitch Diameter (m)		0.297	0.135
Outside Diameter (m)		0.304	0.148
Helix Angle (deg)	19.75		
AGMA Quality Number	13		
Center Distance (m)	0.216		
Surface Roughness (rms)	0.81 mm		
Surface Hardness (HRC)	58–60		
Gear Material (carburized to 0.1016–0.1270 cm deep)	4820 Steel		
Face Width (m)	0.0286		
Gear Speed (rpm)	1000		
Power (kW)	625		
Oil Temperature (°C)	82		
Torque	5966 Nm		
Oil Viscosity		**Mineral**	**Synthetic**
Kinematic Viscosity at 40°C (cS)		68	68
Kinematic Viscosity at 100°C (cS)		8.5	10.4
Film Thickness (Lambda)	0.5 (approx.)		

- Under rolling/sliding conditions, the slower moving surface is more prone to micropitting.
- Increasing the specific film thickness (i.e. ratio of lubricant film thickness to combined surface roughness) from 0.92 to 2.32 moderately reduced micropitting damage versus the virtual elimination of micropitting with polished surfaces giving a specific film thickness of 5.62.
- Micropitting is drastically reduced at low, non-zero

Table 3—Oils Used in the Helical Gear Test Program.

Oil	Type	FVA Test Result
A	Mineral EP	Medium
B	Mineral EP	High
C	Synthetic AW	High
D1	Synthetic EP	Medium
D2	Synthetic EP	Medium
D3	Synthetic EP	Medium
D4	Synthetic EP	Medium
H	Synthetic EP	High

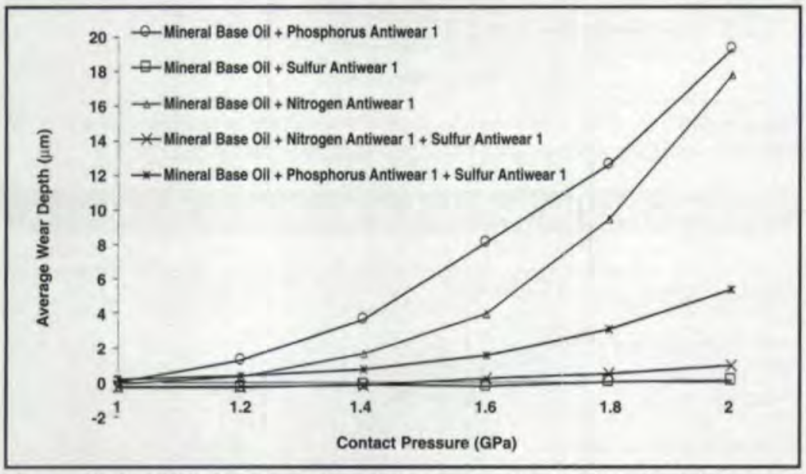

Fig. 3—Roller Disk Machine micropitting test results showing the influence of individual additive components from a typical ISO VG 150 sulfur-phosphorus-based gear oil package.

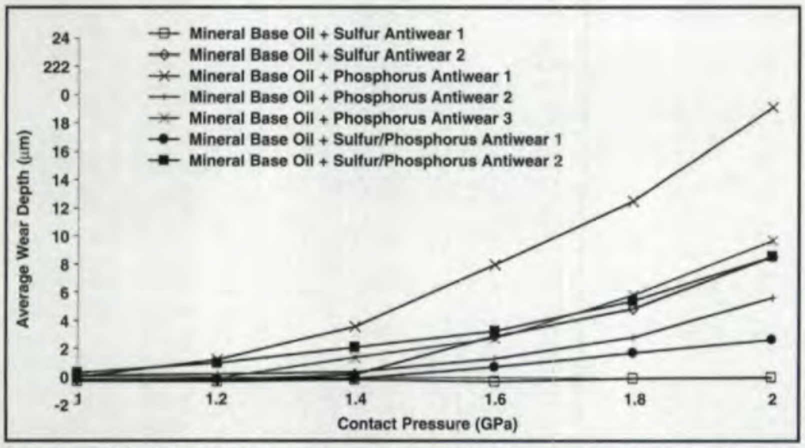

Fig. 4—Roller Disk Machine micropitting results for a range of alternative sulfur- and phosphorus-based antiwear additives blended into mineral base stocks.

slide to roll ratios (e.g. a slide to roll ratio of 0.0095).

The variable load method as described in reference 4 has been used to investigate the effect of lubricant composition on micropitting. Figure 1 shows results obtained from the tests conducted using a series of ISO VG 100 industrial gear lubricants. The two sulfur-phosphorus gear oils contain the anti-wear and anti-scuffing additives required to provide Timken OK load results greater than 60 lbs. The synthetic PAO based circulating oil was formulated to provide FZG fail stage 11 scuffing protection but does not provide a high level of Timken OK load protection. Despite the scatter associated with the mineral gear oils, the results show that both the mineral and synthetic based gear oils yield similar results. The results for the synthetic PAO circulating oil suggest that the use of less aggressive anti-wear additive systems provides directional improvement in micropitting performance. The results from these gear oil tests compare well with results obtained with the same lubricants using the FVA micropitting gear test and suggest a good correlation between the roller disk machine and FVA test methods.

To further investigate the influence of additives on micropitting, a test was conducted on the unadditized mineral base oil used in the mineral gear oil test. The results are compared with the fully formulated gear oil in Figure 2. The onset of micropitting is delayed and the final result corresponds to the lowest of the three fully formulated gear oil results. This result confirms the significant impact that lubricant additives can have on micropitting.

Obviously, gear oils must contain additives to meet various performance and specification requirements, not the least of which is to provide protection against the severe form of adhesive wear known as scuffing that can occur in gear tooth contacts. Thus, the challenge of developing next generation gear lubricants is to arrive at a base stock and additive composition that balances the various performance needs against the requirement to obtain good micropitting protection.

In order to gain an understanding of the impact of different component technology, micropitting tests were conducted on different combinations of additives and base stocks. In a first series of tests, individual components and combinations typically found in conventional sulfur-phosphorus gear oils were tested in ISO VG 150 mineral base stock. The results shown in Figure 3 indicate that the sulfur based antiwear additive 1 does not promote micropitting. Comparing against the mineral base stock results from Figure 2, we find that it may even improve upon base, stock-only performance. Both the nitrogen and phosphorus antiwear additives showed a significant tendency to produce micropitting. The addition of the sulfur antiwear to either of these two resulted in a significant improvement in performance. From these results it was concluded that sulfur additive 1 acts in some way to reduce micropitting damage. However, results from mixtures are not necessarily the sum of the results gained on individual components so the benefit from the use of sulfur additive 1 may not be reproduced when combined with additional additive technology.

In a second series of tests, the performance of a range of alternative sulfur- and phosphorus-based antiwear additives were evaluated and the results are shown in Figure 4. In this case, we see that there is a variation in the response within a general category of additive. For example, sulfur additive 2 resulted in a greater degree of micropitting than found for sulfur additive 1. Similar variations are found for the phosphorus and mixed sulfur/phosphorus additives tested. The results show that there is a large variation in the micropitting performance of the anti-scuffing additives that can be used to formulate gear oils. This variation is, no doubt, a function of the individual additive chemistry and it would be dangerous to assume, based on our limited testing, that any one class of additive has an advantage over another.

Helical Gear Test Rig

Following the roller disk machine experiments, a program was embarked upon to develop a micropitting resistant gear oil. The formulation effort made use of the FVA test as the primary tool for the evaluation of micropitting performance. However, additional testing was also conducted on larger gears more representative of commercial industrial gears. A test program was developed using an available four square gear test rig. In a further development, an automated machine vision system was employed to provide accurate and repeatable measurement of the micropitting areas on the test gears. Information about the gears and test conditions may be found in Table 2 and Figure 5. The test oils are listed in Table 3.

The machine vision system is based on light scattering by rough surfaces, as shown in Figure 6. Unworn areas appear dark to the camera because most of the incident light is reflected away from the camera due to the low angle of incidence of the inspection lights. Any micropitted areas on a gear tooth scatter light, in all directions due to the irregular roughness of the surface. Some of the scattered light is captured by the camera, causing the area to appear white. In the absence of other surface features that may scatter light, this approach gives an accurate assessment of the surface affected by micropitting. It thus provides an automated inspection system for following the progression of micropitting while avoiding the need for removing the gears from their shafts.

After initial runs to determine optimum conditions, the first test was run using the second side of the test development gear set with a mineral oil, designated Oil A, that had been rated fail load stage 9, medium, in the FVA test. Observations were made at 100-hour increments. Images were recorded and the amount of micropitting wear was calculated at 100 and 300 hours. The micropitting was concentrated in the dedendum and at the edges of the teeth. At 327 hours, the rig automatically shut down due to vibration in the slave box. At this time two large pits and a crack were found in Pinion Tooth #1 and a smaller pit in Gear Tooth #3.

Table 4—Surface finish for Oil B.

Surface Finish, μm, rms.	Before	After
Pinion	0.51	0.23
Gear	0.47	0.23

Table 5—Surface finish for Oil C.

Surface Finish, μm, rms.	Before	After
Pinion	0.64–0.76	0.20–0.25
Gear	0.64–0.76	0.20–0.25

Table 6—Failure Modes and Hours to Failure.

Test	Test Duration	Cause
Oil D1	760 hours	Cracked tooth
Oil D2	36 hours	Broken tooth
Oil D3	30+ hours	Broken tooth
Oil D4	148 hours	Broken tooth
Oil H	534 hours	Broken tooth

The gear and pinion were analyzed to identify the type of damage and the cause of pitting. It was determined that the initiation of the failure was due to rolling contact fatigue, not adhesive wear. There was also evidence of movement and/or alignment problems with the gears. The photograph in Figure 7 shows a fan-shaped area starting in the micropitted area and terminating with macropits at the pitch line. This result appears to support field observations that have linked the onset of macropitting to areas that have previously been damaged by micropitting.

The second test was conducted using Oil B, for which a good rating in the FVA micropitting gear test had been obtained. This oil ran for the entire 1000 hours and had a much lower pinion micropitting rate compared to the previous test. Data for these two tests are graphically compared in Figure 8. Note the repeated pattern in the wear results, which exactly match the non-hunting tooth engagement pattern for the 25/55 pinion/gear tooth configuration. The nominal surface finishes recorded before and after the test are found in Table 4.

It was encouraging to find that the helical gear tests appeared to track the FVA test results. However, the small degree of micropitting resulted in anomalies in the machine vision measurement system that required improvements prior to starting the third test. A hard mount was fabricated to replace the universal fixture previously used

Fig. 5—Pictures showing the 55-tooth gear and 25-tooth pinion used in the helical gear testing.

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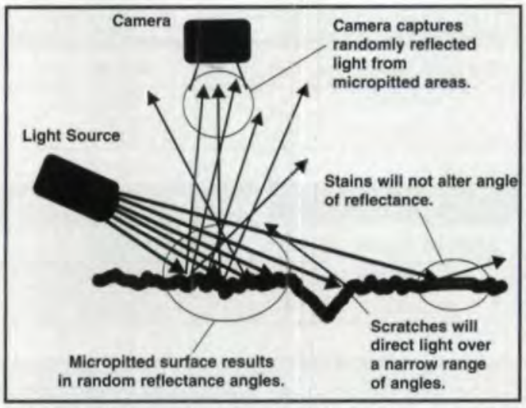

Fig. 6—Schematic showing the light-scattering characteristics from various surface features of the gear tooth under inspection.

Fig. 7—Pitted gear tooth from the helical gear tests on Oil A. Note that the pit appears to have started from within the micropitted area.

to locate the camera with respect to the gear under inspection. This eliminated the need to adjust the lighting to compensate for shifts in the location of the camera. Additionally, post processing vision algorithms, which use an adaptive rather than a fixed threshold to discriminate between worn and unworn areas of the gear tooth, were employed.

In the third test, the same procedure was employed using a synthetic oil, designated Oil C, that rated fail load Stage >10 high in the FVA test. A report file was generated containing the estimated percent micropitting relative to the total tooth contact area. A reference data set was recorded after run-in to be used to correct inspections made during the test for anomalies present at the start, which were not related to micropitting and which would not be expected to change during the test. Data for the 100-hour inspection period are not available due to a problem with the data acquisition system.

As expected, there was a very low level of micropitting wear. Since we have a quantitative measure of micropitting throughout the test, it is possible to estimate wear rate as a function of test time. In comparing Oil B with Oil C, we found that the progression of micropitting wear was quite different. In the case of Oil B, the rate was consistently low at 0.2%/100 hrs up to 700 hrs, at which point the rate increased sharply. Between 700 and 900 hours, the rate increased to 0.7%/100 hrs and between 900 and 1000 hours, the rate was 0.9%/100 hrs. The overall rate for the test was 0.5%/100 hrs. For Oil C, the overall rate was slightly greater at 0.61%/100 hrs, however, the greatest amount of wear occurred in the first 300 hours (1.57%/100 hrs) with a very low rate of wear, 0.17%/100 hrs, thereafter. For Oil C, the nominal surface finishes were recorded before and after the test as shown in Table 5.

The difference in micropitting wear rate was unexpected, since both oils had the same performance level in the FVA Test. However, it is interesting to note that the high initial rate found in the Oil C tests corresponds to gears with higher initial roughness. This result matches well with observations that gear tooth surface roughness has a significant impact on the initiation of micropitting.

The low level of micropitting, as well as the changes in appearance of the worn surfaces, posed additional problems for the illumination/imaging system. Individual gear teeth showed different localized levels of both micropitting and macropitting. Under these conditions, the intensity based feature recognition system was not always able to successfully separate brightness due to a micropitted area from the brightness of the non-micropitted portion of the tooth. One possible solution to this problem would be to replace the incandescent light with a laser based system. However, this upgrade has not been implemented.

The next run was made with Oil D, a synthetic oil that was rated fail load stage 9, medium, in the FVA test, using the second side of the gear set which had been used for Oil C. This oil had a similar progression of wear to that of Oil C with most of the wear occurring in the first 300 hrs and with very low incremental wear thereafter. The test was stopped at 760 hrs due to vibration caused by a cracked tooth. The surface finishes before and after testing were the same as for Oil C.

Figure 9 compares the results at 300 hours for the first set of test oils. The mineral oils are rated in the same order as the rating in the FVA test and the synthetic oils are not. These differences may well be related to manufacturing and surface finishing variations between the test gears.

A further series of tests were conducted using a new batch of test gears. The first of these tests was conducted with Oil D. From early observations it became clear that this test was yielding a different result from the first test using Oil D with the previous batch of test gears. Mild scuffing was observed on several of the pinion teeth after only a few hours of run-in. This test terminated after 36 hours with a broken tooth. A repeat of this test ended with a similar result. Following modifications to the torque system, a further repeat test was initiated (denoted as Oil D4). This test was terminated at 148 hours due to a broken tooth and also showed signs of mild scuffing. During this test it was observed that the unworn tooth area had taken on a mottled appearance. However, the vision system did successfully exclude these from the micropitted area. It was also noted that some of the initial micropitting was removed as the test progressed. The test was terminated at this point due to uncertainties in the validity of the micropitting measurement under these circumstances.

Following our disappointing experience using Oil D with the second batch of test gears, we elected to try a different oil. Oil H had been developed as a micropitting resistant oil based on the earlier Roller Disk Machine results and had achieved a high rating in the FVA test. In this test, significant micropitting (7.8%) appeared during run-in and the first 5 hours at the test load. An additional 7.0% had accumulated by the 100-hour inspection.

Thereafter, the micropitted area appeared to decrease in a similar fashion to that in the last test of Oil D. Once again the test was stopped because of a broken tooth, at which point micropitting covered 14.37% of the pinion active flank area. Table 6 summarizes the failure modes and hours to failure for the tests conducted on the second batch of gears.

Conclusions

Despite the mixed experience with the gear test, several instructive lessons were gained from the earlier roller disk machine experiments and the large-scale gear tests.

- Results from both the roller disk machine and the FVA gear test have confirmed that if all other variables are held constant, the composition of the gear oil has a direct influence on micropitting.
- Additives commonly used in gear oils to provide anti-scuffing performance can have a negative influence on micropitting.
- There is a wide variation in the micropitting performance of the anti-scuffing additives that can be used to formulate gear oils.
- An automated machine vision system can be applied to *in situ* gear inspections to track the progression of micropitting.
- Gear manufacture and finishing has a significant influence on micropitting, which highlights the need for close tolerances on these variables in order to obtain a consistent test.
- Batch to batch variations between gear sets suggest that it is good practice to plan any test series on one batch of gears. One gear set from the batch should be run with a reference oil.
- Variation in results between the helical gear and FVA tests confirms that micropitting responds to many gear manufacturing, operational and lubricant characteristics.
- Gear oils can be formulated using new additive systems balanced to meet the combination of providing anti-scuffing requirements while reducing the risk of micropitting. ○

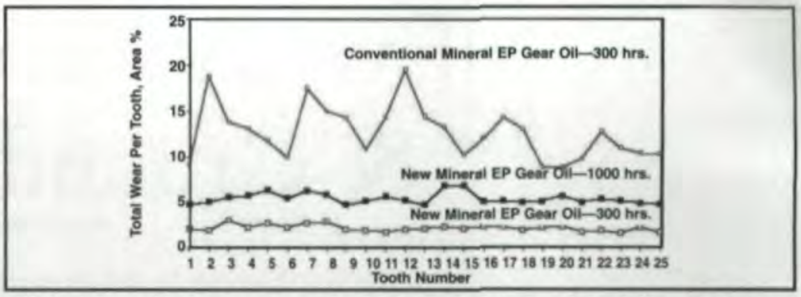

Fig. 8—Micropitted area measured on individual pinion teeth for different lubricants and test times. Note the repeated pattern observed for the conventional EP gear oil corresponds to gear contacts associated with the non-hunting 25/55 gear ratio.

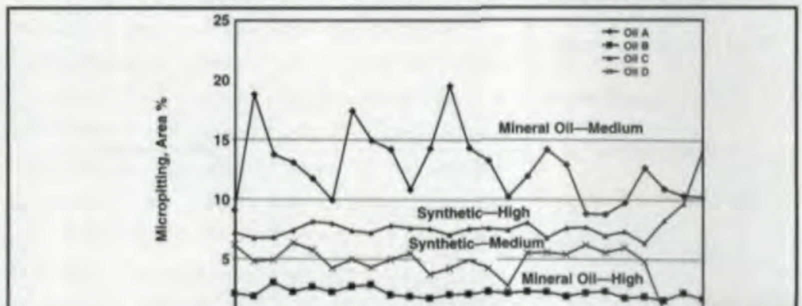

Fig. 9—Micropitted area at 300 hours for oils exhibiting different FVA gear test micropitting performance.

Acknowledgements

The authors would like to acknowledge the work of E. E. Shipley and R. W. Gamache of Mechanical Technology Incorporated (MTI) who were responsible for the helical gear testing and development of the machine vision system respectively. We would also like to dedicate this paper to our friend and colleague, E. E. Shipley, who sadly passed away soon after the completion of the large-scale gear test program.

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