

Gear Oil Micropitting Evaluation

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American Gear Manufacturers Association



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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

As micropitting of gears has become increasingly recognized as a cause of gearbox failures, gear manufacturers have begun to require documentation of gear oil micropitting performance. The German FVA Procedure No. 54, currently the only industry recognized test, has limited availability and takes several months to complete. A laboratory test has been developed using a roller disk machine to simulate micropitting of gears. This test was instrumental in the development of new micropitting resistant gear oils. A helical gear test was developed using specially designed gears running on a four square test rig to further document micropitting performance prior to field testing the new oils.

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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.

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 $10\mu\text{m}$. The micropits coalesce to produce a continuous fractured surface with a characteristic dull matte appearance variously called gray staining, frosting or micropitting when applied to gears. Micropitting is the preferred term. The terms peeling or general superficial spalling have 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. Also, it has been observed that micropitting will often track local high spots in the surface topography of the gears which will be associated with local 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 and 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.¹

Micropitting Tests

The factors that influence micropitting have been reported² along with suggestions for preventing the problem as tabulated below:

Influencing Factor

Gear surface roughness
Reduce austenite level

Suggested Remedy

Reduce to $0.3\mu\text{m}$
Retained austenite

Lubricant viscosity	Use highest practical visc
Coefficient of friction	Reduce the coeff of friction
Speed	Run at high speed (to produce thicker EHL film)
Oil temperature	Reduce oil temperature
Lubricant additive chemistry	Use properly selected additives

The selection of properly additized lubricants is the most difficult parameter to determine. Ueno, et al³ found in their testing that anti-scuffing 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, 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 not available 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 Norbart⁴ 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:

- 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 resulted in a moderate reduction in micropitting damage versus virtual elimination of micropitting with polished surfaces giving a specific film thickness of 5.62.

- Micropitting is drastically reduced at low non-zero 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 provide 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 un-additized 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 in some way acts to reduce micropitting damage. However, it must be kept in mind that 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 micropitting area on test gears. Information about the gears and test conditions may be found in Table 1 and Figure 5. The test oils are listed in Table 2.

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.

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 micropitting to areas that have previously been damaged by micropitting.

The second test was conducting 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 were as follows:

Surface Finish, μ m., rms. (Oil B)		
	<u>Before</u>	<u>After</u>
Pinion	0.51	0.23
Gear	0.47	0.23

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 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 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 taken during the test for anomalies present at the start which were not related to micropitting and 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, but 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 follows:

Surface Finish, μ m., rms. (Oil C test)		
	<u>Before</u>	<u>After</u>
Pinion	0.64-0.76	0.20-0.25
Gear	0.64-0.76	0.20-0.25

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 the gears with the 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 and the changes in appearance of the worn surfaces posed additional problems for the illumination/imaging system. Individual gear teeth showed different localized levels of micropitting as well as 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.