The Effect of Superfinishing on Gear Micropitting

L. Winkelmann, O. El-Saeed and M. Bell

Management Summary

One of the most common failure mechanisms of highly stressed case-carburized gears is micropitting, or gray staining (Refs. 1–3). The standard FZG gear test (FVA Work Sheet 54) is generally used to determine the micropitting load capacity of gear lubricants. In recent years, FZG gear testing has also demonstrated its usefulness for evaluating the effect of superfinishing on increasing the micropitting load capacity of gears. Such studies, however, can only be afforded by major corporations or research consortiums, whereby the data is typically kept confidential. Results from the Technical University of Munich were presented in a previous technical article (see Ref. 4). This paper presents the results of Ruhr University Bochum. Both research groups concluded that superfinishing is one of the most powerful technologies for significantly increasing the load-carrying capacity of gear flanks.

Introduction

It should be noted from the outset that the data presented in this paper was generated by an independent laboratory. Superfinishing of the gears was the authors' sole contribution to these studies. The authors provided no input on the selection of the testing facilities, procedures or parameters. The conclusions listed at the end of this paper were solely those of the testing laboratory.

In a previous paper (Ref. 4), the authors discussed the FZG Brief Test of Gray Staining (BTGS), which was designed to quickly induce micropitting. It is an economical test in terms of cost and time to determine how lubricants, lubricant temperature, coatings and surface finishes influence micropitting. The BTGS showed that superfinishing significantly reduces micropitting, in comparison to baseline gears (Ref. 4).This finding stresses the importance of surface finish for resisting the formation of micropitting.

This paper discusses the results of a more intensive micropitting testing performed according to FVA-Information-Sheet 54/I-IV. The mineral oil used for lubrication was an ISO viscosity class 200, which contains a special additive (the nature of the additive is unknown to the authors) to reduce the micropitting carrying capacity. Baseline tests with a nonmodified standard FZG-C gear were carried out to demonstrate the micropitting properties of the oil. The test gears were standard FZG-C gears, which had the surface modified by superfinishing to a low roughness average (Ra). The pitch-line velocity during all testing was set to 8.3 m/s and the lubricant was injected at 60°C.

A brief summary of the test procedure taken from FVA-Information Sheet 54/I-IV is given below:

The micropitting test may be used to determine quantitatively the influence of lubricants (especially additives), the lubricant temperature and other influential factors on micropitting. The micropitting test differentiates between oils and thus facilitates the choice of a lubricant with sufficient micropitting load capacity.

The operating conditions (circumferential speed and lubricant temperature) may be suitably adapted for testing lubricants for a variety of applications in the micropitting test. To differentiate between the various test options, which are carried out according to the same test sequence, but with different test conditions, they are designated similarly to the FZG scuffing test by test gear type, circumferential speed and lubricant (inlet temperature in accordance with the selected test conditions (e.g., standard test: GT-Cl8.3190; GT = micropitting test).

The micropitting test consists of two parts. It comprises a load stage test followed by an endurance test. In the load stage test, the ability of the gear lubricant tribological system to resist micropitting is determined under specified operating conditions (lubricant temperature, circumferential speed) in the form of a failure load stage. The endurance test provides information on the progress of the damage after higher numbers of load cycles (Ref. 5).

Experimental Design

The gears used were the standard FZG-C type gears for micropitting testing. Table 1 gives the general data for these gears.

Baseline gears. Baseline gears were unmodified from the specifications given in the FVA Information Sheet 54.

Superfinished gears. A set of gears conforming to the specifications given in FVA Information sheet 54 were finished using chemically accelerated vibratory finishing as described in detail elsewhere (Refs. 6–7). This process utilizes high-density, nonabrasive media to enhance the performance of components that are subjected to metal-to-metal contact or bending fatigue. The Isotropic Superfinish (ISF) process generates a unique surface when compared to even the finest honing and lapping in that it has no directionality with a final surface roughness of 0.25 µm R_a or less. This ISF surface will be referred to as "superfinished" throughout this paper.

Figure 1 shows scanning electron microscope (SEM) images at 1,000X of a typical ground surface with an R_a of approximately 0.25 µm (top image) and a superfinished surface with an R_a < 0.05 µm (bottom image). Only slight scratches and small dents are visible amongst smooth plateaus of the superfinished surface.

The R_a of the baseline and superfinished gears were measured in

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Table 1—Specifications are given for FZG C-type gears for use in micropitting testing according to FVA Information Sheet 54 (Ref. 5)

Material	16 MnCr5 (DIN 17210)
Heat treatment	• Case carburized to 750 HV1 in the area of the tooth flank • Case depth: 0.8–1.0 mm (after grinding) • Core strength: 1,000–1,250 N/mm^2 • The zone close to the surface has no residual austenite content visible in the microscope (<20%).
Gear quality	5 according to DIN 3962, $ff_m \leq 5$ µm
	Pinion span: 34.779 mm (–0.11 to –0.135 mm) measured over 3 teeth
	Gear span: 35.252 mm (–0.11 to –0.135 mm) measured over 3 teeth
	Permissible R_w tolerance: each 0.01 mm
Roughness on tooth flanks	$R_a = 0.5 \pm 0.1$ µm measured in the involute direction

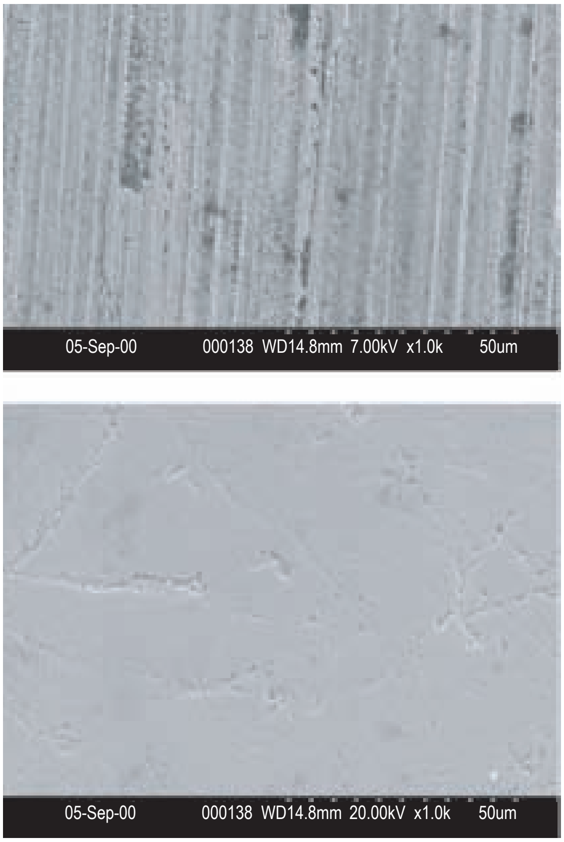

Figure 1—SEM images of a ground surface (top) and a superfinished surface (bottom).

the involute direction of the gear. The values are tabulated in Table 2.

Test rig. The test rig was the same as used in scuffing testing according to DIN 51 354 Part 1, but of reinforced construction and with spray lubrication.

Test runs description. Both the baseline gears and the superfinished gears underwent the following tests:

- Test run 1 was the load stage test in which the loading was increased every 16 hours, starting with load stage 5 and ending after load stage 10.
- Test run 2 consisted of a completed load stage test followed by an endurance test.

The endurance test starts with an 80-hour cycle at load stage 8, followed by five 80-hour cycles at load stage 10 (see Table 3).

After each 16-hour stage of the load stage test and every 80-hour cycle of the endurance test, the following inspection and measurements were made on the pinion:

- ff_m, average profile form deviation, in µm.
- *GF*, micropitting area of gear flank, in %.
- *W*, weight loss of gear, in mg.

Failure was defined by the average profile deviation (ff_m). For the load stage test, failure occurred when ff_m exceeded 7.5 µm. For the endurance test, failure occurred when ff_m exceeded 20 µm (see Table 3).

Experimental Data

Test run 1. The results of ff_m, *GF* and *W* are given in Figures 2a, 2b and 2c, for the baseline and superfinished gears, respectively. For the baseline gears, failure occurred at load stage 8, since ff_m was approximately 8.5 mm. By the end of load stage 8, approximately 30% of the gear tooth flank was covered with micropitting, which increased to 60% by the completion of test run 1 (load stage 10), with *W* at 54 mg.

The superfinished gears, however, showed no measurable variation for ff_m or *GF* at the end of load stage 10. Meanwhile, there was only approximately 8 mg of weight loss on the pinion.

Figures 3 and 4 show the presence of micropitting for the baseline pinion and its absence on the superfinished pinion.

Test run 2. Test run 2 consisted of a load stage test followed by an endurance test.

The results of ff_m, *GF* and *W* are given in Figures 5a, 5b and 5c for the baseline and superfinished gears, respectively. For the baseline gears, failure again occurred at load stage 8, since ff_m was approximately 8.5 µm. By the end of load stage 8, approximately 28% of the gear tooth flank was covered with micropitting, which increased to 60% by the end of the load stage test with W at 57 mg.

In the endurance test, the baseline pinion exceeded the 20 µm failure limit during the third 80-hour cycle at load stage 10 with an ff_m of approximately 20.2 µm. By the conclusion of testing, ff_m, *GF* and *W* reached 28 µm, 80% and 128 mg, respectively.

The superfinished gears showed no measurable change for ff_m or *GF* at the end of the load stage test. There was only approximately 6 mg of weight loss on the pinion.

Figures 6 and 7 show the presence of micropitting for the baseline pinion and its absence on the superfinished pinion.

The thin (0.5 mm) gray mark on the superfinished pinion was attributed to the lack of tip relief on the mating gear and was not a manifestation of micropitting. A better view of the gray mark is shown in Figure 8, where it was investigated under a microscope.

Table 2—Listing of the R_a values for the baseline and superfinished FZG gears.

	Baseline gears		Superfinished gears	
	Test run 1 (µm)	Test run 2 (µm)	Test run 1 (µm))	Test run 2 (µm)
R_a1 of Pinion	0.52	0.51	0.13	0.12
R_a2 of Gear	0.44	0.42	0.07	0.07
$R_a = (R_a1 + R_a2)/2$	0.48	0.47	0.10	0.095

Table 3—Contact stresses, duration, and failure limits for load stage test and endurance test.

	Load stage	Contact stress, N/mm²	Cycle duration, hours	Failure criteria
Load stage test	5	795.1	16	$ff_m > 7.5$ µm
	6	945.1	16	
	7	1093.9	16	
	8	1244.9	16	
	9	1395.4	16	
	10	1547.3	16	
Endurance test	8	1244.9	80	$ff_m > 20$ µm
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	

Conclusions

The baseline gears had a lower resistance to micropitting.

- Profile form deviation was 28 µm by the end of the endurance test.
- Micropitting coverage was 60% at the end of the load stage test and 79% at the end of the endurance test.

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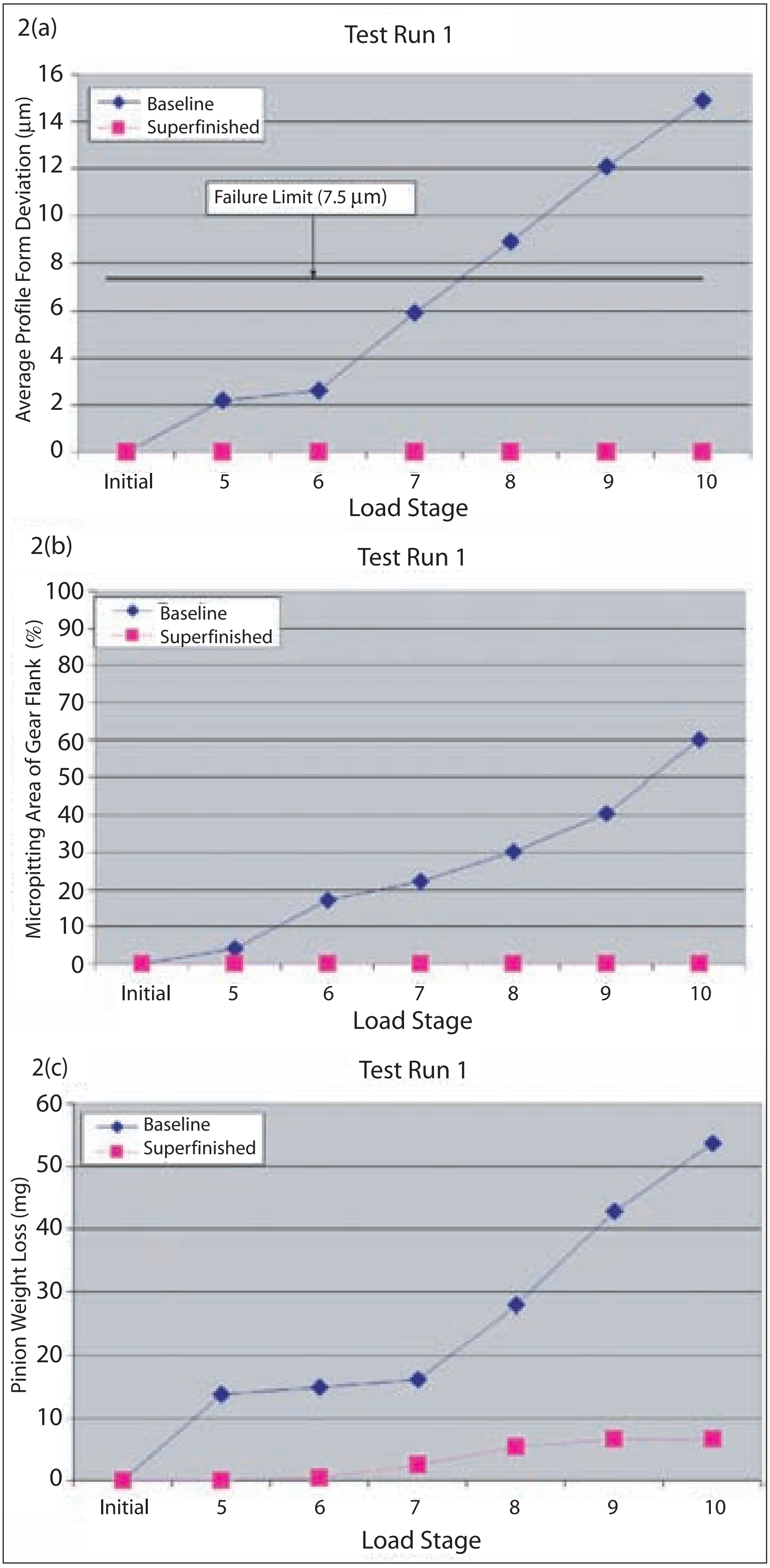

Figure 2—Measurements of test run 1 (load stage test) (a) ff_m, (b) *GF*, (c) *W* on the baseline and superfinished pinions.

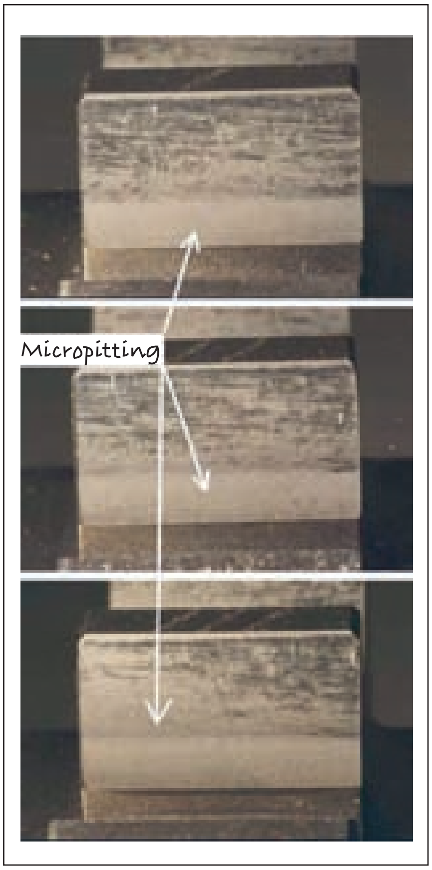

Figure 3—Pictures of three teeth on the baseline pinion after the completion of load stage 10 of test run 1 show micropitting on approximately 60% of the tooth flank.

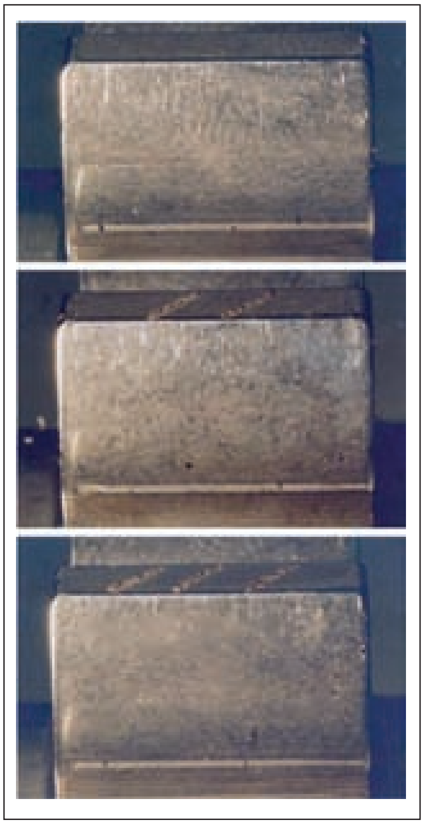

Figure 4—Images showing the lack of micropitting on the superfinished pinion following the completion of load stage 10 of test run 1 showing no micropitting on the tooth flanks.

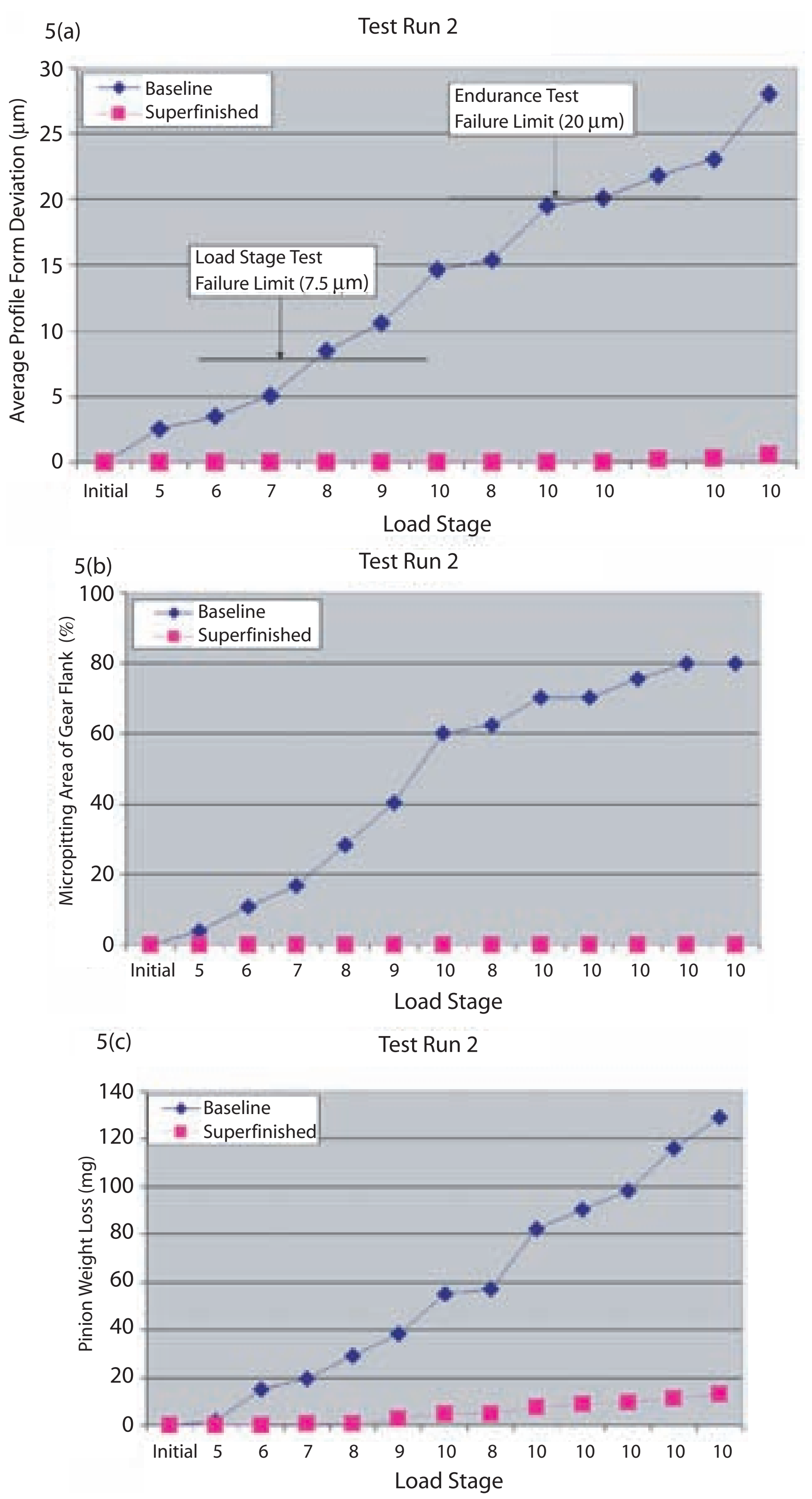

Figure 5—Measurements of test run 2 (load stage test) (a) ff_m, (b) *GF*, (c) *W* on the baseline and superfinished pinions.

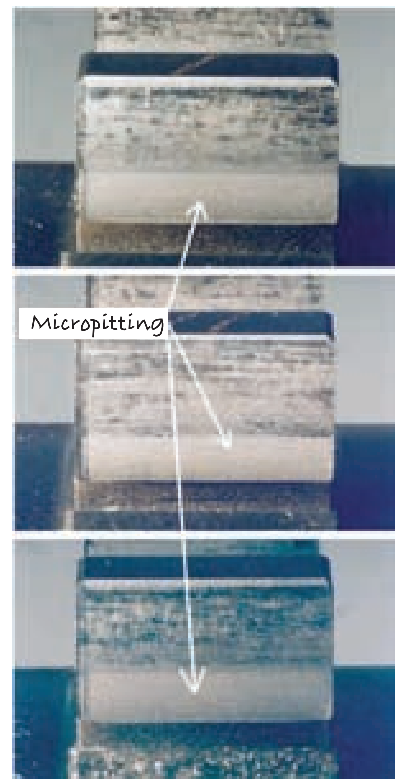

Figure 6—Three teeth on the baseline pinion after test run 2 showing 79% of the tooth flank covered in micropitting, with the band of the densest micropitting specified.

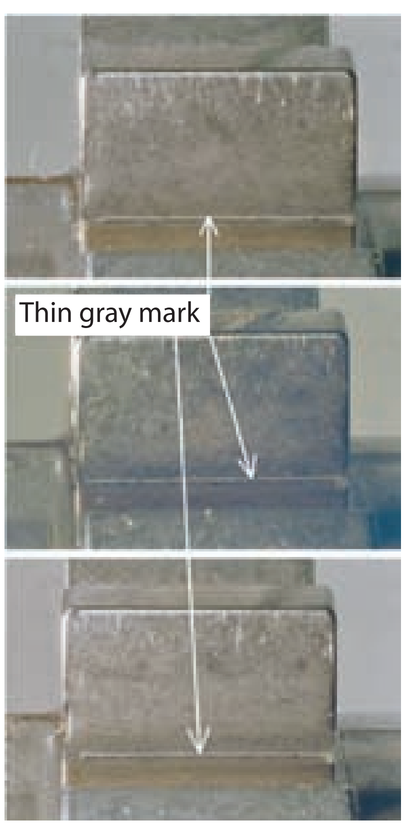

Figure 7—Picture of three teeth on the superfinished pinion after test run 2 (load stage test and endurance test) showing a thin gray mark that was attributed to the gears not having any tip relief. The gears show no micropitting.

- Weight loss was 38 mg after the load stage test, and 129 mg at the end of the endurance test.

The superfinished gears never showed micropitting nor reached any of the specified failure criteria.

- Profile form deviation was 0 µm at the end the load stage test and only 0.5 µm at the completion of the endurance test.
- Micropitting coverage at the end of both the load stage test and endurance test was nonexistent (0%).
- Weight loss was 6 mg after the load stage test, and 13 mg by the end of the endurance test.

These superfinishing results are remarkable despite the use of unfavorable oil, which showed damage at load stage 8 on the baseline gears.

Acknowledgments

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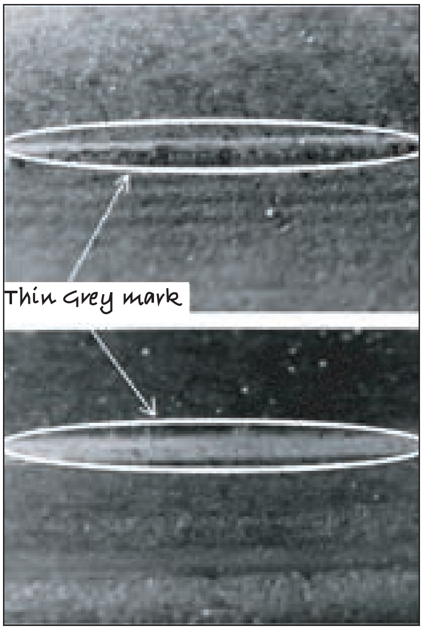

Figure 8—Microscope image of the thin gray mark of the dedendum circled on two flanks of the superfinished pinion. An investigation determined that this mark was not micropitting.

Lane Winkelmann *joined REM Chemicals, Inc. in 1996 as a senior research associate in the Research and Development Group. For the last three years, he has served as products manager. During his career, he has developed numerous products and processes for superfinishing a wide variety of alloys for both decorative and engineered surfaces. Winkelmann has co-authored several patents and has written and/or presented numerous papers on the use of superfinishing to improve gear performance. As a result of his accomplishments, this technology has been widely adopted by industries such as wind turbines, motorsports and aerospace. He received a bachelor's degree from Texas A&M University in 1991, and his master's degree at Tulane University in 2005.*

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