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Technical Resources

08FTM10

AGMA Technical Paper

The Effect of Superfinishing on Gear Micropitting, Part II

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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

One of the most common failure mechanism of highly stressed case carburized gears is micropitting (gray staining). [1],[2],[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 previously presented in Part 1 of this paper.[4] Part II will present 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.

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500 Montgomery Street, Suite 350
Alexandria, Virginia, 22314

October, 2008

ISBN: 978-1-55589-940-0

The Effect of Superfinishing on Gear Micropitting Part II

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Introduction

It should be noted from the outset that the data presented in Part I and Part II of this paper was generated by independent laboratories. 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.

Part I of this paper 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.[4] This finding stresses the importance of surface finish for resisting the formation of micropitting.

Part II of 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 non-modified 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 (R_a). 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 large variety of applica-

tions 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-CI8.3190; 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.(FVA 54.1-IV *Test procedure for the investigation of the micropitting capacity of gear lubricants*).[5]

Experimental

Gear 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.[6], [7]. This process utilizes high density non-abrasive 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.

Table 1. Specifications are given for FZG C-type gears for use in micropitting testing according to FVA Information Sheet 54 [5]

Material	16 MnCr5 (DIN 17210)
Heat treatment	<ul style="list-style-type: none"> • Case carburized to 750 HV1 in the area of the tooth flank • Case depth: 0.8 – 1.0 mm (after grinding) • Core strength: 1000 – 1250 N/mm² • The zone close to the surface has no residual austenite content visible in the microscope (<20%).
Gear quality	5 according to DIN 3962, $f_{fm} \leq 5 \mu\text{m}$ 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	$R_a = 0.5 \pm 0.1 \mu\text{m}$ measured in the involute direction

Figure 1 shows scanning electron microscope (SEM) images at 1000X of a typical ground surface with an R_a of approximately $0.25 \mu\text{m}$ (top image) and a superfinished surface with an $R_a < 0.05 \mu\text{m}$ (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 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).

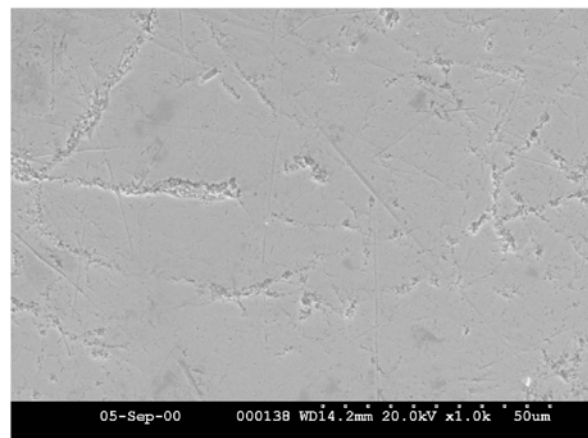
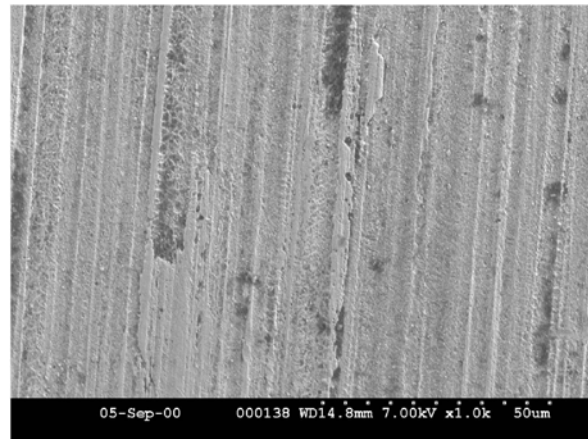


Figure 1. SEM images of a ground surface (top) and a superfinished surface (bottom)

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/mm ²	Cycle duration, hours	Failure criteria
Load stage test	5	795.1	16	$f_{fm} > 7.5 \mu\text{m}$
	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	$f_{fm} > 20 \mu\text{m}$
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	
	10	1547.3	80	

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:

1. f_{fm} , average profile form deviation, in μm ,
2. GF, micropitting area of gear flank, in %, and
3. W, weight loss of gear, in mg.

Failure was defined by the average profile deviation (f_{fm}). For the load stage test failure occurred when f_{fm} exceeded $7.5 \mu\text{m}$. For the endurance test failure occurred when f_{fm} exceeded $20 \mu\text{m}$ (see Table 3).

Experimental data

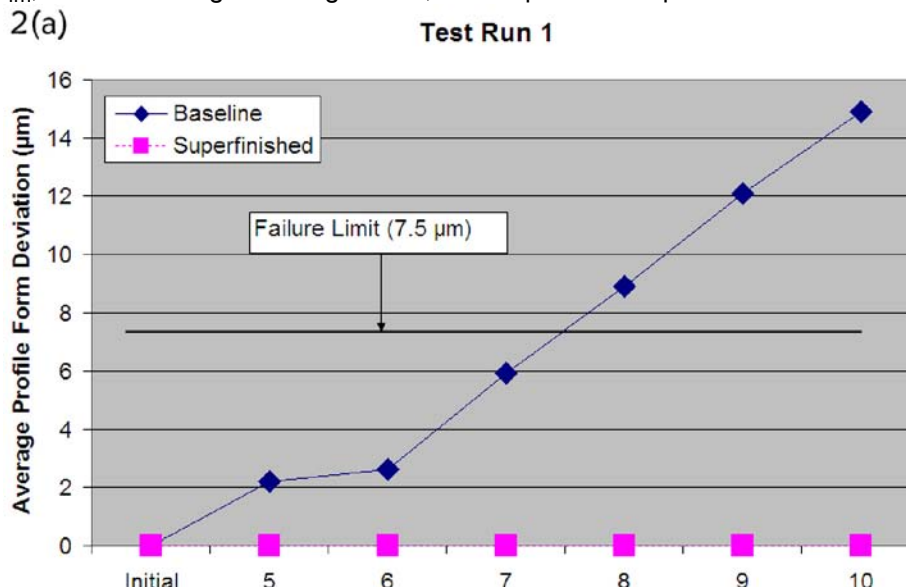
Test run 1

The results of f_{fm} , 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 f_{fm} was approximately $8.5 \mu\text{m}$. 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 f_{fm} , 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 their absence on the superfinished pinion.



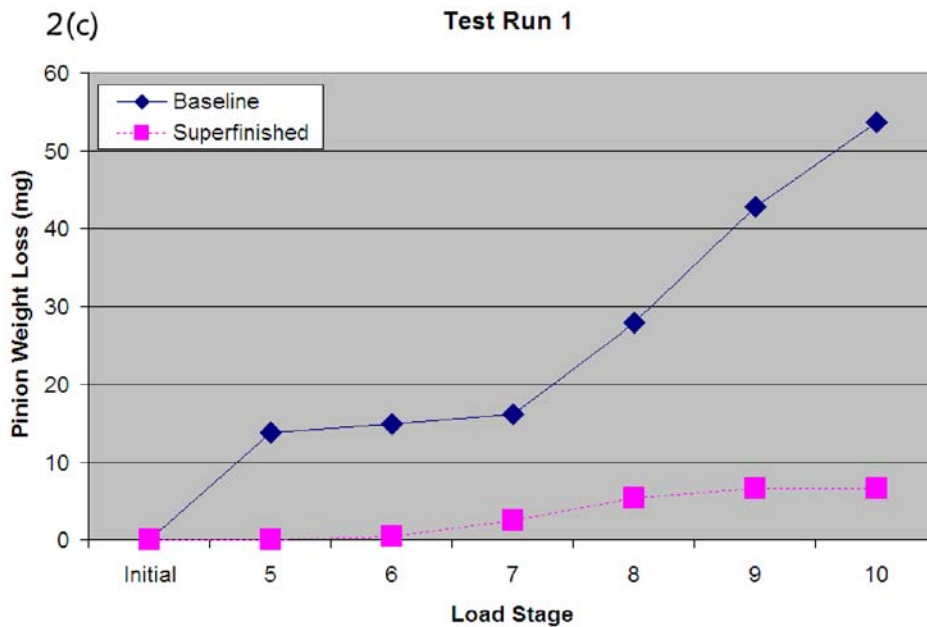
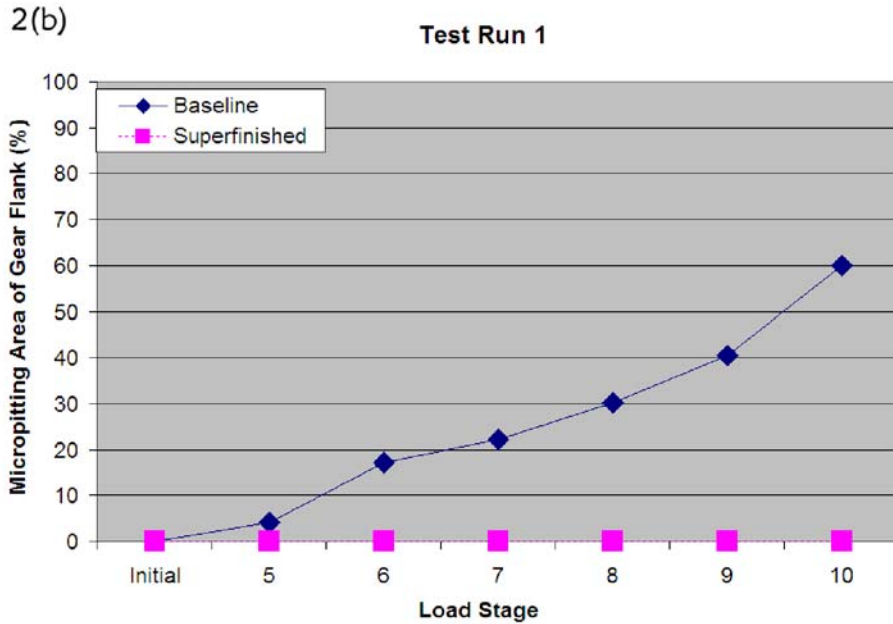


Figure 2. Measurements of test run 1 (load stage test) (a) f_{fm} , (b) GF, (c) W on the baseline and superfinished pinions

Test run 2

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

The results of f_{fm} , 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 f_{fm} was approximately $8.5 \mu\text{m}$. 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 base line pinion exceeded the $20\text{-}\mu\text{m}$ failure limit during the third 80-hour cycle at load stage 10 with a f_{fm} of approximately $20.2 \mu\text{m}$. By the conclusion of testing, f_{fm} , GF and W reached $28 \mu\text{m}$, 80%, and 128 mg, respectively.

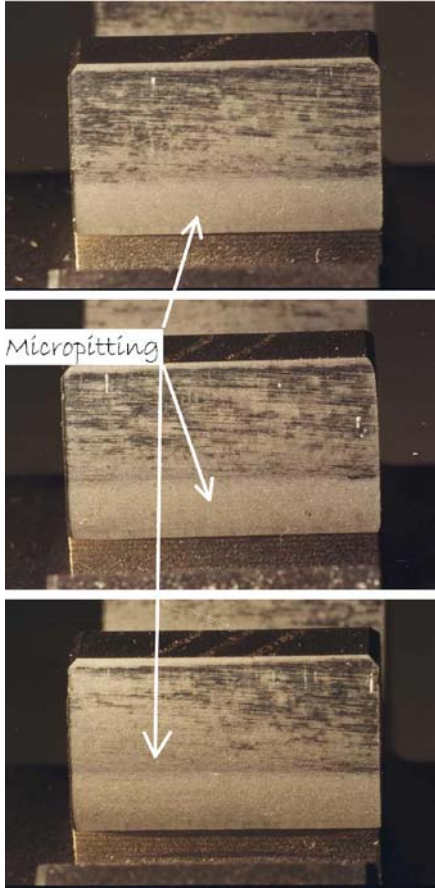


Figure 3. Pictures of three teeth on the baseline pinion after the completion of load stage 10 of test run 1 show micropitting on approximately 60% of the tooth flank

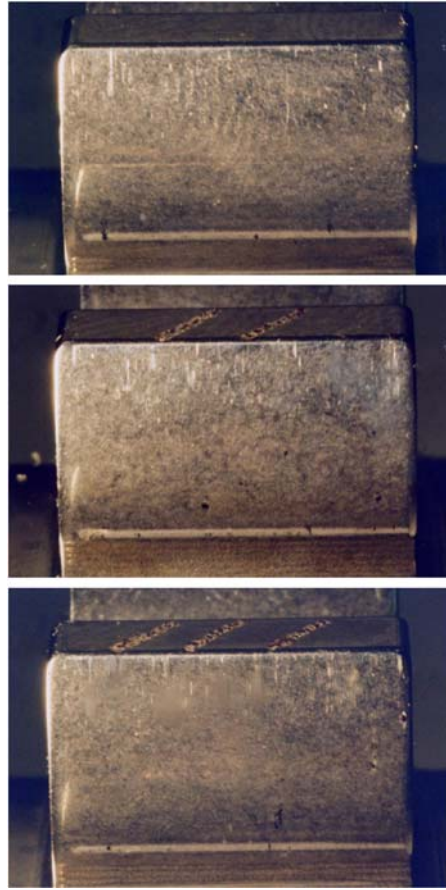
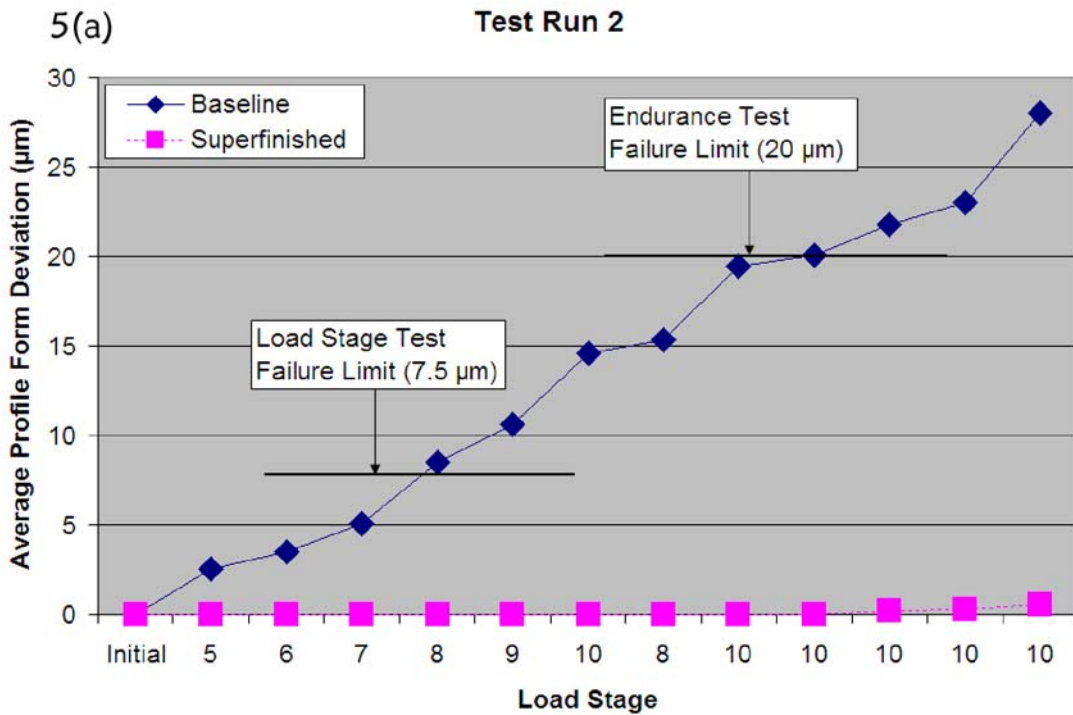


Figure 4. Images showing the lack of micropitting on the superfinished pinion following the completion of load stage 10 of test run 1 showing no micropitting on the tooth flanks



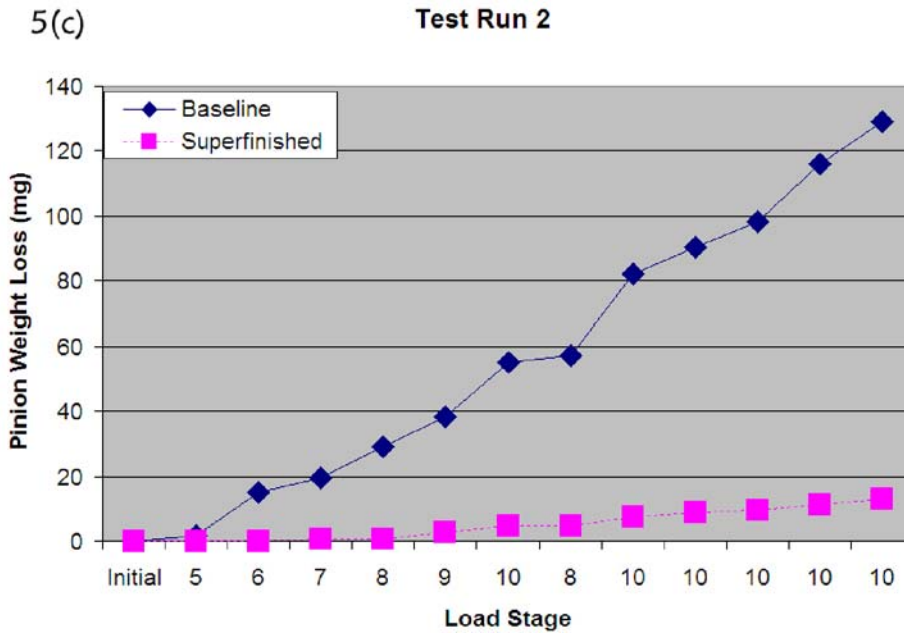
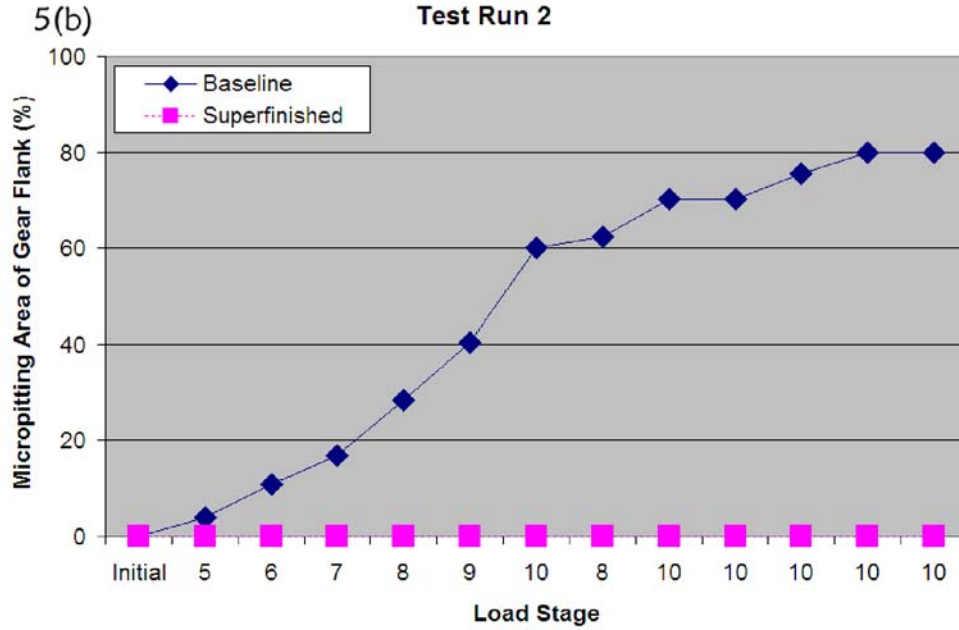


Figure 5. Measurements of test run 1 (load stage test) (a) f_{fm} , (b) GF, (c) W on the baseline and superfinished pinions

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

In sharp contrast to the baseline gears, the superfinished gears showed a negligible f_{fm} of $0.5 \mu\text{m}$, no mi-

cropping (GF of 0%), and a mere 13 mg W by the conclusion of Test Run 2.

Figure 6 and Figure 7 show the presence of micro-pitting for the baseline pinion and their absence on the superfinished pinion.

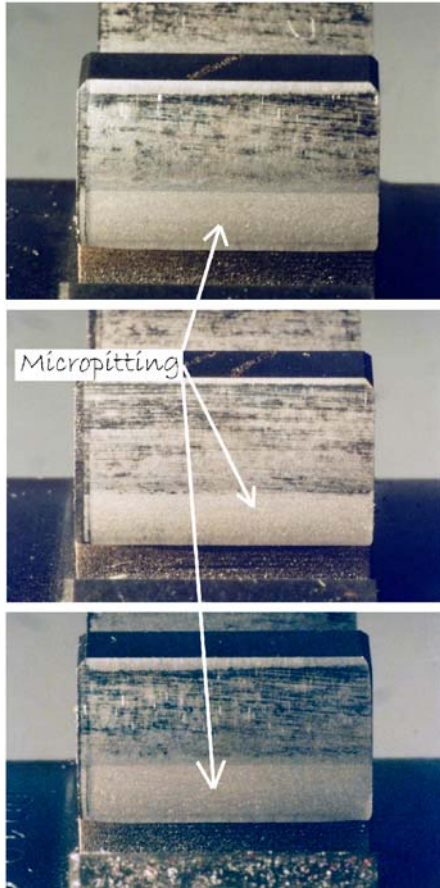


Figure 6. Three teeth on the baseline pinion after test run 2 showing 79% of the tooth flank covered in micropitting, with the band of the densest micropitting specified

The thin (0.5mm) 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.

Conclusions

1. The baseline gears had a lower resistance to micropitting.
 - a. Profile form deviation was 28 μm by the end of the endurance test.
 - b. Micropitting coverage at the end of the load stage test was 60% and 79% by the end of the endurance test.
 - c. Weight loss was 38 mg after the load stage test, and 129 mg by the end of the endurance test.

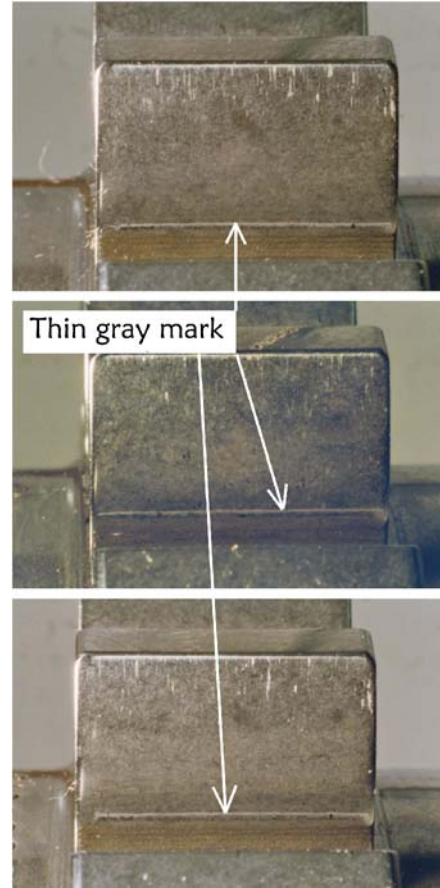


Figure 7. Picture of 3 teeth on the superfinished pinion after test run 2 (load stage test and endurance test) showing a thin gray mark that was attributed to the gears not having any tip relief. The gears show no micropitting

2. The superfinished gears never showed micropitting nor reached any of the specified failure criteria.
 - a. 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.
 - b. Micropitting coverage at the end of both the load stage test and endurance test was non-existent (0 %).
 - c. Weight loss was 6 mg after the load stage test, and 13 mg by the end of the endurance test.
3. The superfinishing results are remarkable despite the use of unfavorable oil which showed damage at load stage 8 on the baseline gears.

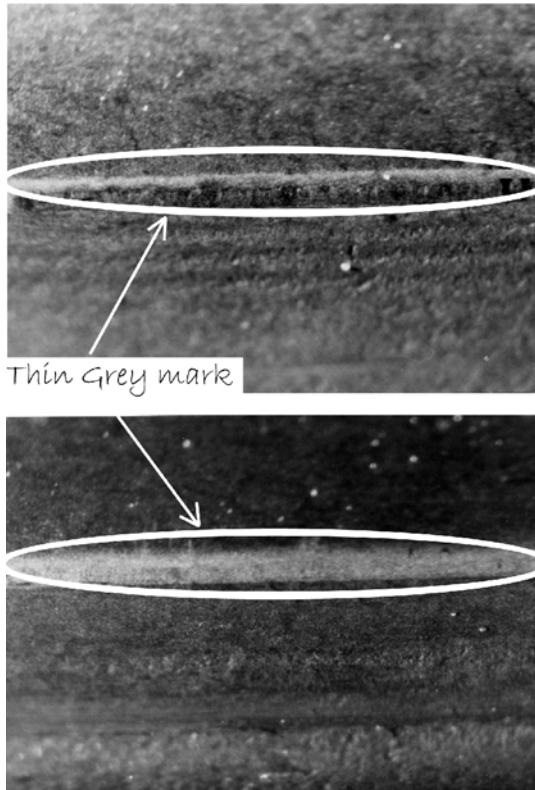


Figure 8. Microscope image of the thin gray mark of the dedendum circled on two flanks of the superfinished pinion. An investigation determined that this mark was not micropitting

Acknowledgements

The authors would like to thank Dipl.-Ing. G Lützig, and Prof. Dr.-Ing. W. Predki with the University of Bochum for performing the testing along with Winergy for their part in making this information available.

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