SAE TECHNICAL PAPER SERIES

2002-01-1391

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Reprinted From: Advances in Surface Engineering (SP–1705)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

SAE International Off-Highway Congress co-located with CONEXPO-CON/AGG
Las Vegas, Nevada
March 19-21, 2002

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760 Web: www.sae.org

ISSN 0148-7191

Printed in USA

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ABSTRACT

An Isotropic Superfinish (ISF) is produced by a patented chemically accelerated vibratory finishing process using non-abrasive media that is capable of surface finishing hundreds of parts per hour. Rolling/Sliding Contact Fatigue testing shows that this commercial technology virtually eliminates contact fatigue (pitting) in gear test specimens. Bending fatigue is also improved. Gears finished by this method will operate at higher power densities for much longer life cycles when compared to traditionally finished gears. Studies have confirmed that this process is metallurgically safe for both through hardened and carburized alloy steels. ISF can achieve an R_a < 0.038 µm (1.5 µin.) while maintaining an AGMA Q13 gear dimensions. Rolling/Sliding Contact Fatigue, single tooth bending fatigue, and rotating bending fatigue test results are presented.

INTRODUCTION

NEEDS OF THE HEAVY EQUIPMENT INDUSTRY

In today's marketplace, designers of off-road equipment, tractors, dozers, earthmovers, farm machinery, military equipment and the like must be cost and performance conscious. New designs must result in equipment that is more durable at ever increasing power densities and at competitive pricing.

Although this paper will focus primarily on gears, the results are applicable to many other metal-to-metal contact surfaces such as bearings and cams, and other parts that experience continuous bending or torsional flexing such as axles and shafts. The two major failure modes of gears used in heavy equipment are contact fatigue (pitting) and bending fatigue. The effect of an Isotropic Superfinish (ISF) on these failure modes is discussed in this paper.

PREVIOUS STUDIES

For many years now, major research efforts sought to reduce gear failure caused by contact fatigue and bending fatigue. New alloys, heat treatments, machining, grinding, honing, and coatings were developed for this purpose. Surprisingly though, the impact of the effect of surface finish on gear performance is still rather cloudy and controversial, even among experts in the field. The controversy probably stems from contradictory test results, erroneous assumptions concerning surface topography, and the difficulties involved in reproducibly surface finishing hard carburized surfaces without introducing other anomalies.

CONTACT FATIGUE

There is a generally accepted theory in the gear industry that a "very smooth" surface is detrimental to contact fatigue. It is theorized that a "very smooth" surface is unable to retain a lubricant film between metal-to-metal contacts and results in contact fatigue failure. Therefore, it has been proposed by some that the ideal surface for gear flanks is one that has smooth plateaus with microscopic indentations that can retain lubricant and provide relief for the contact micro-movement of the surface under sliding pressure. The best technique to generate such a surface is to first shot peen the gear flanks followed by a polishing step to remove surface peaks. One such example of this is given in the Society of Automotive Engineers, Inc. (SAE) Manual on Shot Peening which states: "Where good surface finish is required for fatigue resistance, the normal peened finish is better than the smoothest unpeened finish. In many cases such a peened surface also proves to be better for other reasons, for instance, where the peening impressions retain a lubricant."[1] On the other hand, some researchers have shown that superfinishing gears to a near mirror-like surface can significantly increase the surface fatigue lives of gears even without shot peening.[2, 3] This paper will discuss the effect of superfinishing on contact fatigue for high hardness carburized specimens.[*]

BENDING FATIGUE

It is commonly accepted that the bending life of properly shot-peened gears in the root fillet is 1.5 to 2 times the life of unpeened gears[4]. For fine pitch gearing (above 20 DP) the angle of shot impingement is difficult to control and can actually introduce damaging tensile stresses. Is there a way to avoid shot peening altogether by removing the consequences of surface stress raisers from residual machining marks or intergranular oxidation that occurs during heat treat? For low and intermediate hardness ranges of steel, it has been shown[5] that bending fatigue strength is very dependent on the surface condition. Fatigue strength increases significantly for highly polished surfaces in contrast with fine-ground or commercially polished ones. This paper will determine the effect of superfinishing on bending fatigue for high hardness carburized gears and specimens, and gives comparisons to lapping and shot peening.

TRADITIONAL FINISHING

Perhaps in the past, attempts to correlate surface finish to performance were blurred because the surface finish was characterized by selecting a few of many surface parameters such as R_a, R_z, and R_{max}. Surfaces were considered identical as long as these few parameters were approximately equal for each. Now in hindsight, it seems evident that each method of surface finishing creates its own unique surface with sometimes widely different performance results.

One such example of this is the surface finish created by the "Abral" process. This is a proprietary mechanical superfinishing procedure that consists of immersing parts in an abrasive mixture of water, aluminum oxide powder and small zinc chips. The parts are typically vibrated through three successively finer mixtures of aluminum oxide powder until a mirror-like finish is achieved. An R_a and R_z as low as 0.04 µm (1.7 µin.) and 0.04 µm (20 µin.), respectively, have been reported on gears. Its application to gears has been studied in depth,[3, 6, 7, 8, 9] where it has been shown that the surface it produces approaches a full elastohydrodynamic lubrication (EHL) mode of lubrication, and thus reduces friction, bulk temperature and pitting fatigue. One key surface attribute that has been overlooked with this process is its inability to reduce/remove undulations. The use of small zinc chips and abrasive powder does not have the ability to bridge across the asperities and thus will not remove surface waviness. It is theorized by the authors that it is these undulations that result in the short cycle life results at high contact stress loading presented later in this paper.

No matter how much care and vigilance is taken, conventional mechanical machining is a highly aggressive mechanical process. It always results in metallurgical damage, if even at the microscopic level because of the application of highly concentrated forces and the concomitant localized temperature generation. Such damage can include microcracks, the introduction of stress raisers, and thermally induced damage such as tempering. This results in reductions in the residual compressive stress and/or a loss of surface microhardness and material integrity.

The grinding process, for example, can temper the surface of a hardened gear, which in extreme cases is called grinding burn. Surface tempering is a very common occurrence that reduces a gear's wear and contact fatigue properties. Conventional mechanical machining always produces burrs and directional machine lines. These features are stress raisers that must be removed from critical working surfaces in order to reduce wear, contact fatigue, and/or bending fatigue failures.

A FRESH APPROACH

Perhaps a fresh approach is needed then, one that can reproducibly finish hard carburized surfaces with a mechanism radically different from traditional mechanical machining. This paper presents performance test results on specimens and gears finished with a patented chemically accelerated vibratory finishing process[10] referred to as the Isotropic Superfinish (ISF) process. This process has been described in detail elsewhere[11] and is briefly described below.

ISF is carried out in vibratory finishing bowls or tubs. A proprietary chemistry is used in the vibratory machine in conjunction with high-density, non-abrasive ceramic media. When introduced into the machine, this chemistry

[*] This is a revision of material presented in AGMA 01FTM7. The original material is printed with permission of the copyright holder, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314. Statements presented are those of the Authors and may not be represented as the position of the AMERICAN GEAR MANUFACTURERS ASSOCIATION.

produces a stable, soft conversion coating on the surface of the metal part(s). The rubbing motion across the part(s) developed by the machine and media effectively wipes the conversion coating off the "peaks" of the part's surfaces, but leaves the "valleys" untouched. (No metal removal occurs where media is unable to contact or rub.) The conversion coating is continually reformed and wiped off during this stage producing surface leveling. This mechanism is continued in the vibratory machine until the surfaces of the part(s) are free of asperities. At this point, the proprietary chemistry is rinsed from the machine with a neutral soap. The conversion coating is wiped off the part(s) one final time to produce the ISF. In this final step, no metal is removed and is commonly referred to as burnishing.

As described above, ISF is a non-aggressive process that is carried out at ambient conditions in a rust inhibited water-based chemistry. This unique surface leveling process generates a surface that exhibits a non-directional pattern that is theorized to give optimum lubrication properties. The final surface typically exhibits a roughness average (R_a) of 0.038 µm (1.5 µin.) and maximum individual peak-to-valley height (R_{max}) of 0.38 µm (15 µin.). The media size is such that undulations from the machining process are removed or significantly reduced.

RESULTS OF THIS STUDY

Remarkable performance improvements were observed in Rolling/Sliding Contact Fatigue (R/SCF) testing[12, 13]. This data predicts the ISF process will extend cycle life while at increasing operating loads. This eliminates the need for re-engineering existing gear systems to achieve higher power densities. Specimens superfinished with another supposedly "comparable" process had a shorter cycle life under much lower loading.

Comparison of single tooth bending fatigue results of ISF processed AGMA Q12 carburized gears showed an improvement over root-fillet honed baseline gears. In a separate study, comparison of rotating beam bending fatigue data of carburized ISF specimens shows significant improvements in cycle life over baseline and shot peened specimens.

ROLLING SLIDING CONTACT FATIGUE (R/SCF)

DESCRIPTION OF R/SCF TEST

Rolling/Sliding Contact Fatigue (R/SCF) testing was performed by the Gear Research Institute (GRI). Their test rig simulates the R/SCF experienced by a gear with the benefit of being able to adjust the operating speed, sliding ratio, contact stress load, lubricant temperature, lubricant flow and lubricant type. It has been widely used in industry for predicting wear and contact fatigue performance of gears for many years. Figure 1 shows a schematic diagram of the test apparatus with the load roller and specimen mounted in contact, as they would be during testing. The testing parameters are given in Table 1. The sliding ratio of 43% negative on the specimen is designed to be higher than that experienced by a typical gear in the dedendum area. This is done to facilitate a typical failure mode with minimal testing time and cost.

In this test, the specimens are placed in the R/SCF test equipment, brought up to temperature with the oil flowing to the contact surface and run through a gentle break-in cycle at lower contact stress loads. The contact stress is then increased to the desired load and the cycle count started. The testing is continued until one of the failure criterions is met. If failure is due to pitting, the test apparatus will automatically shut down due to the induced vibrations. If no failure is exhibited after a set number of cycles (run-out), the contact stress is increased and the cycle count starts over.

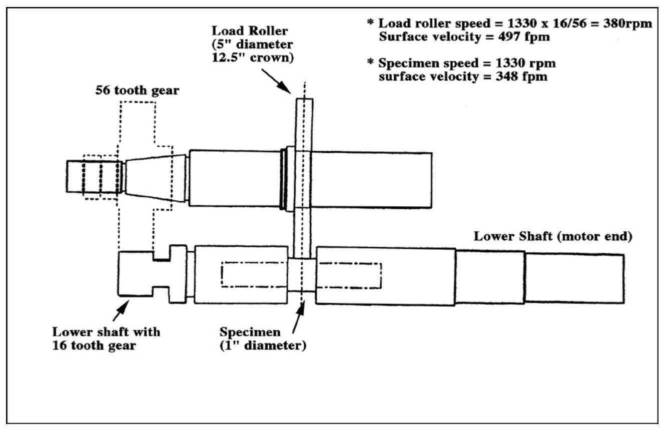


Figure 1: Schematic of Rolling/Sliding Contact Fatigue (R/SCF) test equipment (courtesy of GRI and AGMA from 01FTM7).

Specimen Operating Speed	1,330 RPM
Roll/Slide Ratio	43% negative sliding on specimen (pin)
Contact Surface Velocity	1.7 m/s (70 in./s)
Load Roller Contact Surface Velocity	2.5 m/s (100 in./s)
Lubricant	MOBIL Synthetic Jet Oil II (MIL L-23699C)
Lubricant Bulk Temperature	93 °C (200 °F)
Lubricant Filter	10 micron ceramic filament
Lubricant Change Interval	Approximately 1,200 hours
Failure Criterion	Surface origin pits approximately 4.8 mm (3/16 in.) wide

Table 1: Test parameters for the Rolling/Sliding Contact Fatigue (R/SCF) test (courtesy of AGMA from 01FTM7).

DESCRIPTION OF R/SCF SPECIMENS

A detailed description of the load roller and specimen is given in Table 2. All specimens and load rollers were previously normalized, quenched, tempered, finish machined with 0.0020 mm (0.008 inch) grind stock per side, carburized, sub critical annealed, copper plated 25 - 50 µm (0.001 - 0.002 in.) per side, hardened, cold treated, tempered, copper stripped, ground, honed, surface temper etch inspected, and magnetic particle inspected.

Three specimens (pin) and three load rollers (disc) were ISF processed for 2 hours to generate the typical asperity free condition. Profilometer tracings of the ground/honed [R_a = 0.25 µm (10.0 µin.)] (before processing) and ISF [R_a < 0.038 µm (1.5 µin.)] specimen surfaces are shown in Figure 2. The trace length is 1.5 mm (0.06 in.) with a gaussian filter of 0.25 mm (0.01 in.). The vertical scale is at 0.51 µm (20 µin.) per division for both tracings. Only two of the ISF sets were used in the R/SCF testing. One ISF set still remains untested and in storage.

Figure 3 shows photographs of an actual ISF load roller (disc) with a mirror-like surface and an R_a < 0.038 µm (1.5 µin.). Note the reflection of the grid lines from the graph paper under the load roller.

The contact surface of a ground/honed specimen and an ISF specimen were analyzed by scanning electron microscopy (SEM). Figure 4 shows the images of the surfaces at 1000X magnification. Note that the rows of directional asperities have been completely removed leaving an isotropic (non-directional) flat surface in its place. Also note the appearance of mechanical shearing damage from honing that is evident on the ground/honed specimen. This has been completely removed by the ISF process.

Specifications	**Specimen (Pin)**	**Load Roller (Disc)**
Material	AMS 6265 (SAE 9310H) Carburized, Ground, Honed	AMS 6265 (SAE 9310H) Carburized, Ground, Honed
Surface Hardness (HRC)	60 - 65	60 - 65
Case Depth (Effective 50 HRC) mm (in.)	0.51 – 0.64 (0.020-0.025)	0.51 – 0.64 (0.020-0.025)
Core Hardness (HRC)	34 - 41	34 - 41
Surface Finish R_a µm (µin.) (ground/honed)	0.25 – 0.41 (10 - 16)	0.25 – 0.41 (10 -16)
Test Surface Diameter mm (in.)	25.4 (1.0)	125 (5.0)
Test Surface Length mm (in.)	22.9 (0.9)	12.7 (0.5)
Crown Radius mm (in.)	None	320 (12.5)

Table 2: Description of specimen and load roller (courtesy of AGMA from 01FTM7).

The 3-D topography in µm of a typical ground surface and an ISF surface are compared in Figure 5. Note that the rows of parallel asperities have been completely removed, leaving a flat isotropic surface in its place.

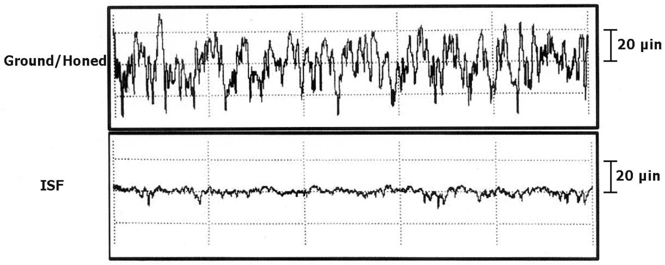


Figure 2: Profilometer readings of a ground/honed specimen and an ISF specimen (courtesy of AGMA from 01FTM7).

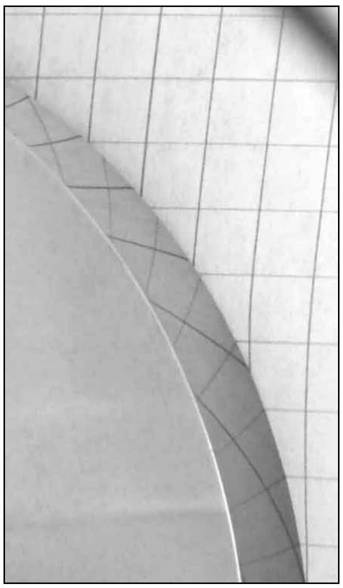


Figure 3: Image of a load roller after ISF showing the mirror-like surface finish (courtesy of AGMA from 01FTM7).

R/SCF TEST RESULTS

The Rolling/Sliding Contact Fatigue (R/SCF) results, listed in Table 3 show the virtual elimination of contact fatigue by ISF. Results for specimens superfinished with the “Abral” process are also given. This is a supposedly “comparable” process that gives a mirror-like surface and documented performance improvements.

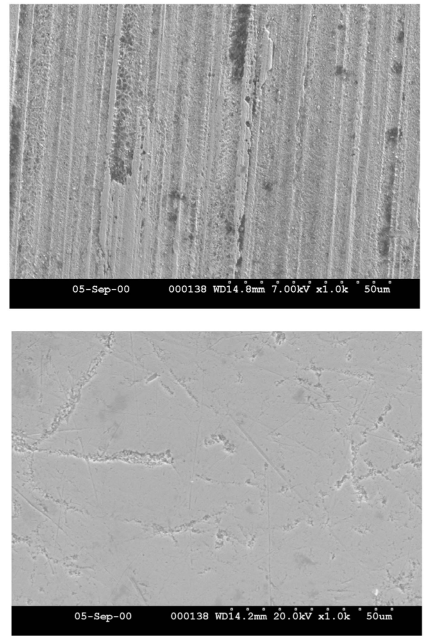


Figure 4: Scanning electron micrograph (1000X) of a ground/honed specimen (top) and an ISF surface (bottom) after processing (courtesy of AGMA from 01FTM7).

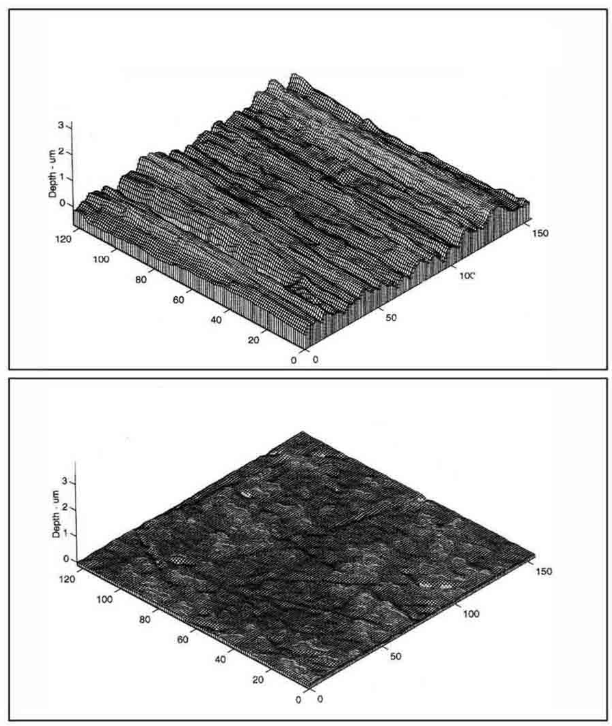


Figure 5: 3-D Topography of a typical ground surface (top) and an ISF surface (bottom) (courtesy of AGMA from 01FTM7).

Sample	Contact Stress N/mm^2 (ksi)	Test Duration (million cycles)	Failure Mode
Ground/Honed Baseline			
#1	2,760 (400)	3.6	Pitted
#2	2,760 (400)	4.2	Pitted
#3	2,760 (400)	3.5	Pitted
Abral #1	2,760 (400)	44.0	Pitted
Abral #2	2,930 (425)	1.0	Plastic Flow
ISF #1	2,760 (400)	20.0	**No Failure**
Same specimen and load roller sequentially tested at each stress level.	2,930 (425)	20.0	**No Failure**
	3,100 (450)	22.4	**No Failure**
Cumulative Result	2,760 – 3,100 (400 - 450)	62.4	**No Failure**
ISF #2	2,760 (400)	5.0*	**No Failure**
Same specimen and load roller sequentially tested at each stress level.	2,930 (425)	5.0*	**No Failure**
	3,100 (450)	20.0	**No Failure**
Cumulative Result	2,760 – 3,100 (400 – 450)	30.0	**No Failure**
*** Based on the results of ISF #1 specimen, the cycles at the first two load levels were shortened to 5 million cycles to reduce testing time and cost.**			

Table 3: Summary of Rolling/Sliding Contact (R/SCF) test data (courtesy of AGMA from 01FTM7).

CONCLUSIONS FROM R/SCF TESTING

- ISF specimens did not fail after running sequentially at three increasing contact stress loadings 2,760, 2,930, and 3,100 N/mm^2 (400, 425, and 450 ksi).
- ISF specimens were capable of carrying 12.5% higher contact stresses than the ground/honed specimens without failure.
- ISF specimens had a minimum cycle life at least 16 times that of ground/honed specimens at 2,760 N/mm^2 (400 ksi).
- ISF specimens had a minimum cycle life at least 42 times that of "Abral" processed specimens at 2,930 N/mm^2 (425 ksi). This demonstrates that ISF imparts unique surface properties that enhance performance over and above that by purely abrasive superfinishing processes.

SINGLE TOOTH BENDING FATIGUE (STBF)

DESCRIPTION OF TEST

The Pulsator tests used to determine the bending fatigue strength were carried out using an Instron 1603 resonant fatigue machine with the gears mounted on a special fixture (See Figure 6.) The teeth were loaded using a flat-faced steel anvil with the load applied at a diameter of 105 mm (4.080 in). The scale factor used to calculate the resulting stress was based on data supplied by the gear manufacturer.

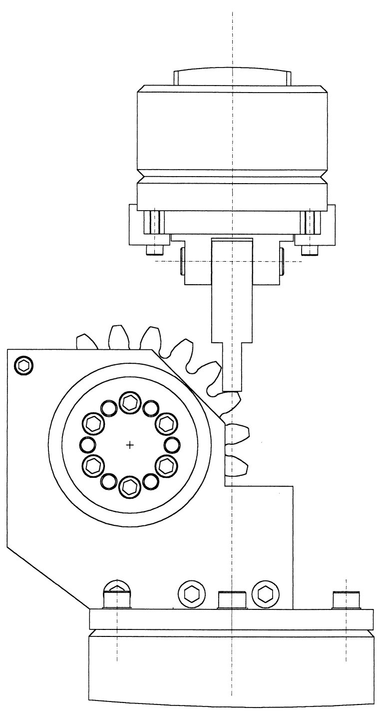


Figure 6: Schematic of pulsator test method for STBF.

A 12-step staircase endurance test was carried out on alternate teeth with a step size of about 3.7% of the mean strength. A minimum load was always applied to the teeth (about 7.5% of the mean strength). A non-failure was defined at ≥ 10 million cycles.

DESCRIPTION OF STBF TEST SPECIMENS

Four identical AGMA Q12 carburized gears were used in the study. Their description and specifications are summarized in Table 4.

Gear Description & Specifications	
Gear Type	Involute Spur External
Number of Teeth	24
Diametral Pitch	6
Pressure Angle	20º
Circular Pitch	13.30 mm (0.5236 in.)
Base Circle Diameter	95.47 mm (3.7587705 in.)
Material	Pyrowear® Alloy 53
Hardness (HRC)	60 HRC
Case Depth (Effective 50 HRC)	1.02 – 1.27 mm (0.040 – 0.050 in.)
Core Hardness	33 – 41 HRC
Tooth Flanks Shot Peened Intensity Coverage	 0.010A – 0.012A 200%
Honed Surface Roughness (Root Fillet Area)	0.076 – 0.13 µm (3 – 5 µin.)

Table 4: Gear description and specifications.

Two gears were randomly chosen from the set for surface finishing while the other two remained in the as received condition to be used as the baseline. The two selected gears were ISF processed for 2.5 hours resulting in the typical asperity free surface condition. The final surface finish on the ISF tooth flanks was an R_a ranging from 0.02 – 0.05 µm (0.8 to 2.0 µin.) compared to the baseline surface finish that ranged from 0.076 – 0.13 µm (3 – 5 µin.). Figure 7 is an image of one of the ISF gears.

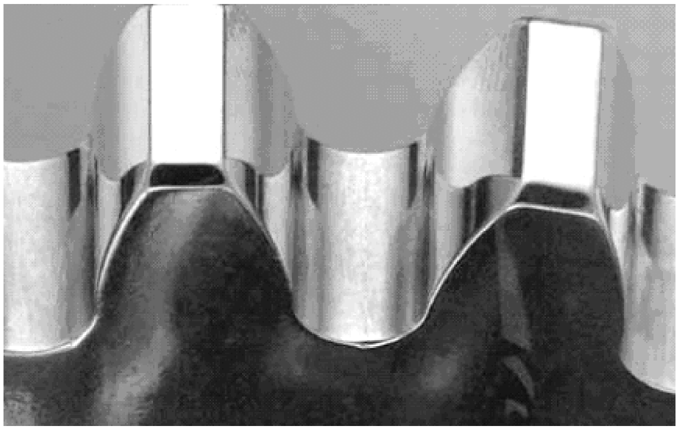


Figure 7: STBF test gear after ISF.

	N/mm² (ksi)	
	Mean	**Std. Dev**
Baseline #1	1,498 (217)	83 (12)
Baseline #2	1,355 (196)	114 (17)
Mean (Baseline)	1,427 (207)	100 (15)
ISF #1	1,498 (217)	32 (5)
ISF #2	1,522 (221)	114 (17)
Mean (ISF)	1,510 (219)	84 (13)

Table 5: Summary of Pulsator test results.

STBF TEST RESULTS

The mean bending fatigue strengths and their standard deviations were calculated per BS3518 and are given in Table 5. The ISF gears are on average 6% stronger than the baseline gears. Although some variation can be seen between gears, the average scatter in the test results (standard deviation) is similar for gears in each test condition. An alternative analysis method is to combine the test points from the gears into one data set rather than treating the gears as separate items. Combining the data from the two gears to give a larger sample size in each condition and reanalyzing produces the results listed in Table 6.

	Standard Gear	**ISF Gear**
Mean Strength	1444 N/mm² (209 ksi)	1498 N/mm² (217 ksi)
Standard Deviation (SD)	195 N/mm² (28 ksi)	76 N/mm² (11 ksi)
SD/Mean %	14%	5%

Table 6: Reanalysis of data after combining data.

Although there are only small differences in the fatigue strength of these gears, the results do indicate an improved STBF strength when the ISF process has been applied. This becomes a little more apparent if the data is reanalyzed to give 1% probability of failure as often used in gear design. For the combined data above, this would give strength of 996 N/mm² (144 ksi) for the baseline pair and 1,323 N/mm² (192 ksi) for the ISF gears.

It is worth noting that the baseline gears tested already have a good strength most likely introduced from the shot peening and honing. Testing of the baseline and ISF gears for retained austenite, residual compressive stress and microhardness demonstrated that there was essentially no change imparted by ISF processing. These results suggest that the only explanation to the increased bending fatigue strength is due to the improvement in surface finish. It is perhaps possible that the ISF process would have a more marked effect on a gear root in the as-heat treated condition where the starting surface condition is often not as ideal as the tested gears.

CONCLUSIONS FROM SINGLE TOOTH BENDING FATIGUE TESTS

- ISF processing does not adversely affect bending fatigue. Single tooth bending fatigue results show that this process does not cause intergranular attack or hydrogen embrittlement.
- ISF gears resulted in improving the bending fatigue life of already high quality AGMA Q12 carburized gears.
- For gears with a starting surface finish not as ideal as those tested here, it is expected that the ISF process will impart a more dramatic improvement to bending fatigue.

ROTATING BEAM BENDING FATIGUE (RBF)

DESCRIPTION OF RBF TEST

The testing was conducted on a Fatigue Dynamics Model RBF-200 rotating beam fatigue test machine. See Figure 8. Through a calibrated beam and weight system, the rotating beam fatigue test machine applies a constant load to the specimen over the duration of a test. When the specimen fractures, the machine automatically stops, and the number of cycles displayed on the counter is recorded.

All tests were run at a bending moment or calibrated beam reading of 25.4 N-m (225 in.-lb) or a bending stress at the minimum section of the test specimen of 1014 N/mm^2 (147 ksi). The rotating speed was kept at approximately 10,000 rpm.

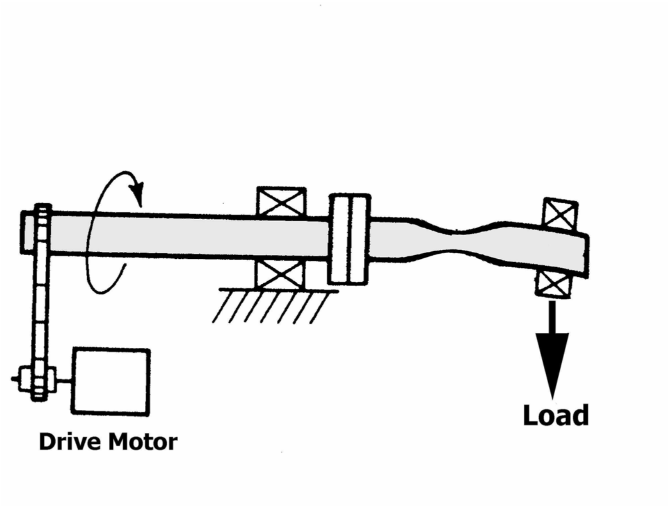


Figure 8: Fatigue Dynamics RBF-200.

DESCRIPTION OF TEST SPECIMENS

The dimensions of the test specimens are given in Figure 9.

Total Length:	102 mm (4.0 in.)
Diameter of Grip:	12.7 mm (0.500 in.)
Neck Diameter:	6.4 mm (0.250 in.)

Figure 9: RBF specimen dimensions.

The as-received specimen properties are given in Table 7.

Material	AISI 8620H
Test Region	Circumferential Lines $R_a \approx 0.73$ µm (29 µin.)
Heat Treat	Carbonitrided
Case Hardness	50 HRC
Effective Case Depth 50 HRC	0.51 mm (0.020 in.)
Core Hardness	40 HRC
Grip Areas	Centerless Ground

Table 7: Properties of as-received specimens.

Four different tests were conducted on test specimens as described in Table 8.

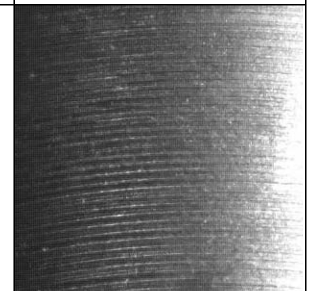
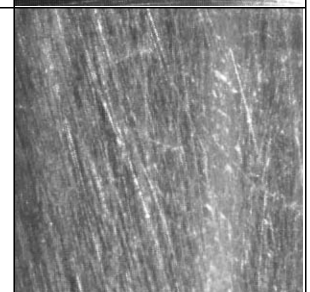
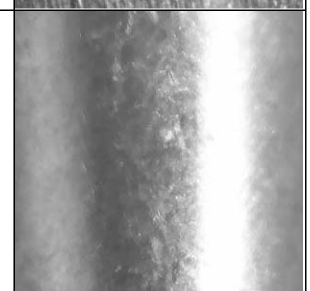
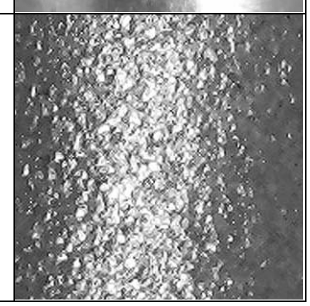
Test No.	Specimen Description	R_a µm (µin.)	R_{max} µm (µin.)	Surface Appearance
1	Baseline with circumferential machine lines.	0.73 (29)	5.0 (201)	
2	Machine line free by hand lapping in axial direction with 1500-grit final lap.	0.079 (3.2)	0.92 (37)	
3	ISF processed to line-free condition	0.055 (2.2)	0.43 (17)	
4	Shot peened using S230 hard shot (55 – 60 HRC) to 0.015A with 200% coverage.	2.2 (88)	16 (635)	

Table 8: Summary of specimens tested.

ROTATING BEAM FATIGUE TEST RESULTS

The results of the RBF tests are presented graphically in Figure 10.

CONCLUSIONS FROM ROTATING BEAM FATIGUE TESTING

- Test 1 demonstrates that typical fatigue performance can be expected when residual machine lines are in the circumferential direction.

- Test 2 shows that parts lapped in the axial direction extend the fatigue cycle life approximately 105 times that of the baseline circumferentially machined parts.

- Test 3 illustrates that ISF processed specimens have a fatigue cycle life at least as good as specimens lapped in the axial direction. These results again prove that the ISF process does not cause hydrogen embrittlement or other metallurgical damage.

- Test 4 shows that ISF processed specimens have a fatigue cycle life approximately six times that of shot peened specimens.

PREVIOUS ISF RESEARCH

Previous experience and research has demonstrated that the chemicals used in ISF processing are non-toxic and non-hazardous per 49CFR (Federal Hazardous Material Transportation Law). These chemicals have been supplied to a wide variety of industries for over 15 years without any health or safety incidents. The waste products from the ISF process are non-hazardous per the EPA but may require standard metals precipitation to meet local and state discharge regulations.

Prior research has concluded that the ISF process is metallurgically safe with respect to Intergranular Attack (IGA) and Hydrogen Embrittlement[11]. Previous metrology studies have concluded that material removal can be uniform and minimal (just enough to remove the surface imperfections)[11]. Precision AGMA Q13 gears entering the ISF process remain AGMA Q13 after ISF processing with surface finish improved typically from R_a 0.30 µm (12 µin.) to R_a 0.038 µm (1.5 µin.). Wear studies previously reported indicate a 94-95% reduction in wear that virtually eliminates this parameter as a design consideration for most gears[11, 14].

CURRENT & ADDITIONAL ISF RESEARCH

Interest in ISF processing has motivated additional research that is currently in progress or has been recently completed. Results from the following projects will be available in the near future:

- Single Tooth Bending Fatigue Testing of ISF gears versus traditionally ground gears.
- Noise reduction of ISF processed gear sets.
- Maximum permissible power densities of ISF processed gears and increased time between maintenance.
- Temperature studies as related to the reduction of oil reservoir capacity and the required oil cooling systems due to reduced parasitic frictional losses associated with ISF processed components in gearboxes or transmissions and the concomitant increases in fuel economy.
- R/SCF testing with a redesigned load roller radius to increase the contact stress load and facilitate failures of ISF specimens.
- Comparative performance in standardized scuffing resistance tests.

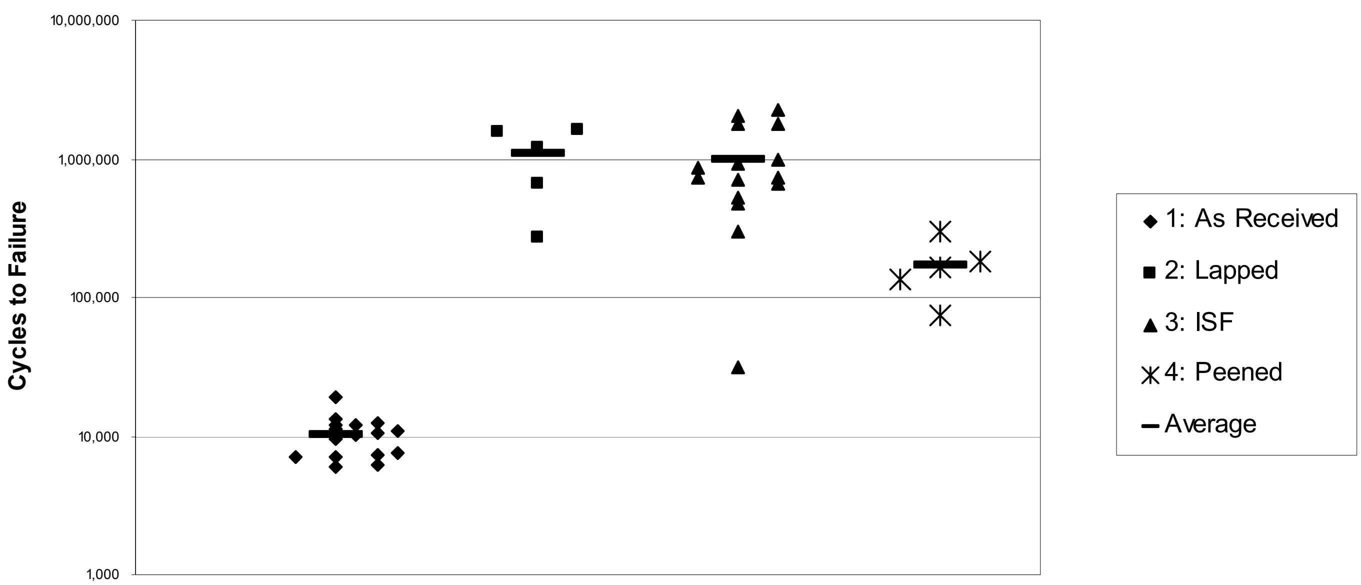


Figure 10: Rotating beam fatigue testing data.

SUMMARY

Research, testing and commercial use has concluded that ISF creates a super smooth surface and removes material repeatably and uniformly. ISF processing is metallurgically and environmentally safe.

R/SCF testing indicates that ISF processed components can successfully operate at increased contact stress loads of at least 12.5% while surviving at least 16 times longer than ground/honed components.

Single tooth bending testing indicates that ISF processing improves bending fatigue life by 6% of already high quality AGMA Q12 carburized gears and does not induce intergranular attack or hydrogen embrittlement. For gears with a starting surface finish not as ideal as those tested here, it is expected that the ISF process will impart a more dramatic improvement to bending fatigue.

Rotating beam fatigue testing indicates that ISF processed specimens have a fatigue cycle life at least as good as lapped specimens and approximately 105 times greater than the baseline specimens. ISF processed specimens also show approximately six times the fatigue cycle life of shot peened specimens. This data also proves there is no hydrogen embrittlement or other metallurgical damage due to the ISF process.

ACKNOWLEDGMENT

The Rolling/Sliding Contact Fatigue (R/SCF) testing discussed in this paper was performed under the Instrumented Factory for Gears (INFAC) Program at IIT Research Institute (IITRI), sponsored by the US Army Aviation and Missile Command (AMCOM) ManTech Program. Additional superfinish testing research on the Isotropic Superfinish (ISF) process is currently being conducted by IITRI and AMCOM, with US Army ManTech funding. This additional work is also sponsored by AMCOM, and is being conducted under the Power Transfer Systems Manufacturing (PTSM) Program.

- R/SCF testing was conducted in association with Rolls-Royce and Boeing.
- R/SCF testing was performed by the Gear Research Institute (GRI) at the Applied Research Laboratory of Pennsylvania State University.

ISF was conducted by REM Chemicals, Inc., Brenham, Texas, who also sponsored the following studies:

- Single Tooth Bending Fatigue (STBF) of ISF Gears by the Design Unit, Gear Technology Centre, University of Newcastle upon Tyne, U.K.
- Rotating Beam Bending Fatigue (RBF) testing by REM Chemicals, Inc., Research and Development Department.

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