04msec 79

Horsepower Retention by ISF (Isotropic Superfinishing) of Automotive Racing Components

William P. Nebiolo
REM Chemicals, Inc.
Southington, CT

ABSTRACT

Automotive power and drivetrain components typically transfer the energy from fuel combustions through a series of metal-to-metal mechanical components. Typical examples of metal-to-metal components include bearings, camshafts rotation and gear teeth in a transmission or differential.

The normal manufacturing steps for bearings and camshafts typically include various machining operations that normally end with a final grinding step. For economical reasons, automotive transmission and differential gears are usually lapped to generate the final surface finish. A careful examination of the as manufactured surface of these components reveals a polishing pattern associated with the final grinding or lapping step used to finish the component. Typically the pattern is visible as parallel rows of micro-asperity peaks and valleys.

In operation these mechanical components work by engaging their complementary partners. As such, bearings roll in races, gear teeth roll and slide against other gear teeth and camshafts engage cam followers. The presence of the micro-asperity peaks and valleys on the surface of these components reduces the actual available area of metal-to-metal contact. This results in frictional heat generation and a loss of engine horsepower.

This paper will examine the use of the ISF Process to improve the micro surface of automotive metal-to-metal contact surfaces. Evidence will be presented demonstrating how the improved micro surface of ISF processed parts retains horsepower, increases component durability and reduces operating temperature.

INTRODUCTION

Traditionally, automotive engine parts such as camshafts, rocker arms and valve springs, drivetrain parts such as transmission gears, shifting linkages and splines, differential parts such as rings and pinions, and universally mounted components such as bearings operate by rolling, sliding or pushing against their complementary partners.

Several OEM manufacturing steps are required to produce these components. These include, but are not limited to various combinations of forging, blanking, cold heading, and machining, hobbing and hardening operations such as thru-hardening, induction hardening, case hardening, nitriding, etc.[7, 8]

OEM FINISHING

OEM manufacturers will typically employ a final grinding operation to remove heat treatment warping, generate the final dimensions/geometry and achieve the ultimate surface finish. Automotive gears are typically lapped for economy reasons. See Photo 1.

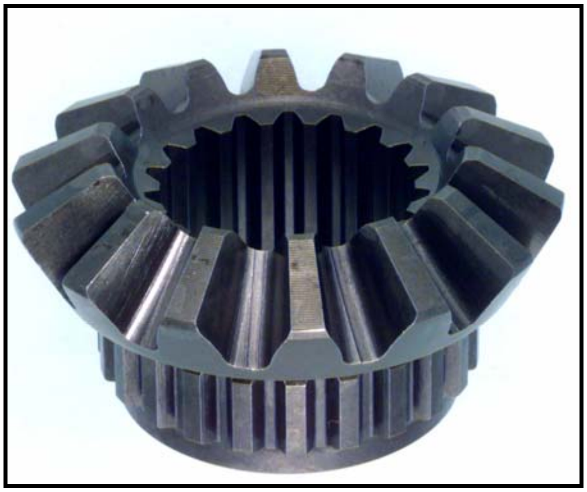


Photo 1; Shows a beveled spur gear from an OEM that is ready for installation. Note, grind lines are clearly visible on the flanks of the gear teeth.[7, 8]

An examination of the surface of any of these parts will reveal a unidirectional, microscopic, surface pattern consisting of parallel rows of asperity peaks and valleys. The directional pattern of the parallel rows corresponds to the direction of the final grinding or machining operation used to finish the component.[7, 8, 12, 13] See Photo 2.

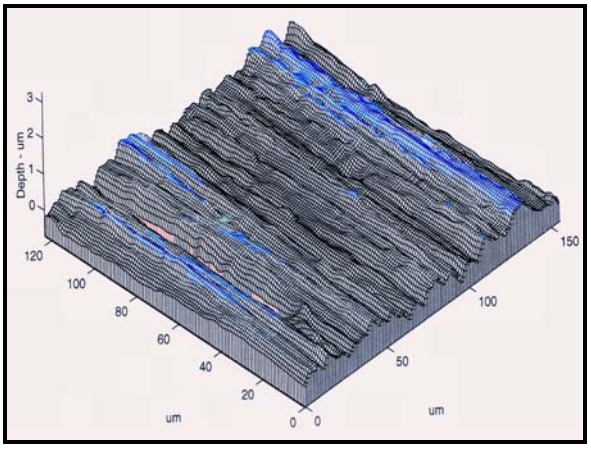


Photo 2; Shows a 3-dimensional, magnified view of a section of the surface of a gear tooth. The tooth had been ground to a final surface finish of R_a = 35 µin./0.9 µm. Note the parallel rows of surface asperities corresponding to the directional pattern of the final grinding or machining operation.[7, 8, 9, 12, and 13]

THE ISF SURFACE

It has been reported[1, 2, 3, 7, 8, 9, 12, 13, 14] that metal-to-metal contact areas, if refined by

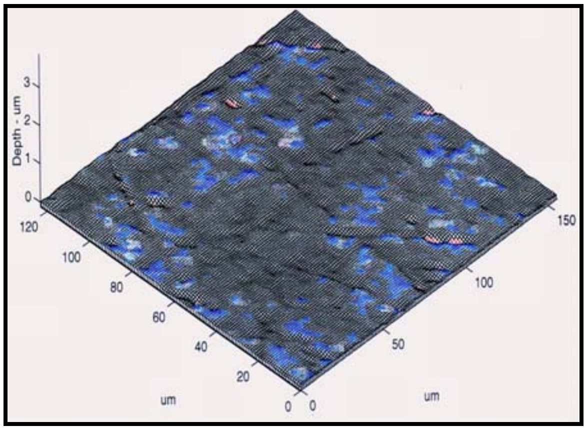


Photo 3; Shows a 3-dimensional, magnified view of an isotropic surface finish R_a = 1.5 µin./0.04 µm. The surface has been produced by chemically accelerated vibratory finishing. Note the elimination of the unidirectional surface asperities, grinding/machining lines, when compared to Photo #2.[7, 8, 9, 12, 13]

Chemically accelerated vibratory finishing[1, 5, 6, 7, 8, 10, 12, 13, 14] have a resultant Isotropic Superfinish. An isotropic surface is a surface that has a random, non-directional surface finish.[7, 8, 13] See Photo 3.

METAL-TO-METAL CONTACT TRADITIONAL SURFACES VS. ISF SURFACES

When placed into operation for the first time, camshaft lobes, gear teeth, bearings, rear end rings and pinions, etc. generate a contact, or wear pattern on their complementary partners.[2, 8, 9, 10, 12, 13, 14]

If the components are traditionally finished, the percentage of actual metal-to-metal contact between the two complementary partners is minimal because initially contact is only peak-to-peak.[8, 14] This contact pattern, concentrates all the surface contact stress associated with the two parts functioning against one another into a few isolated locations.[8, 14]

On the other hand, parts that have been finished with the ISF process have an improved metal-to-metal contact pattern.[8, 14] Since the asperity peaks have been removed from the complementary components the resultant surface is smoother. Contact stress in any one location is reduced, [8, 14] because the smoother finish spreads the stress across a wide surface area.

GENERATING THE ISF FINISH

According to the techniques described elsewhere, [1, 5, 6, 7, 8, 12, 13] asperity refinement occurs in a chemically accelerated vibratory finishing process. The camshafts, valve springs, gears, bearings, rings and pinions, etc. to be refined are placed into a vibratory machine containing a high-density, non-abrasive, ceramic media.[6] See Photos 4 and 5. The chemically accelerated vibratory finishing process consists of two steps that are conducted sequentially within the same vibratory machine.

Photo 4; Shows a traditional vibratory bowl. Ideal for processing short stubby parts such as gears, rocker arms, valve springs and bearings.

Photo 5; Shows a traditional vibratory tub. Ideal for processing long parts such as splines, camshafts, crankshafts, drive shafts and pinions.

During the initial refinement step, a chemistry is added to the vibratory machine.[1, 5, 7, 8, 12] Independent testing has shown that this chemistry will not generate hydrogen embrittlement within the steel parts.[4] The chemistry reacts with the surface of the part to produce a soft, conversion coating.[1, 5, 7, 8, 12] As the part rolls in the vibratory machine, the conversion coating is wiped from the peaks by the weight of the non-abrasive, high density ceramic media exposing unreacted, underlying metal.

The peaks, being elevated, are wiped preferentially.[7, 8, 12, 13] Since the wiped coating was formed by reacting with the steel’s surface; coating removal results in a lowering of the peak.

The recessed valleys between the peaks are untouched by the media, leaving the coating intact and the valleys untouched.[7, 8, 12, 13] The coating reforms on lowered peak to propagate final peak removal.[7, 8, 12, 13] In rapid order, the peaks are wiped thereby generating the improved micro-finish.[7, 8, 12, 13]

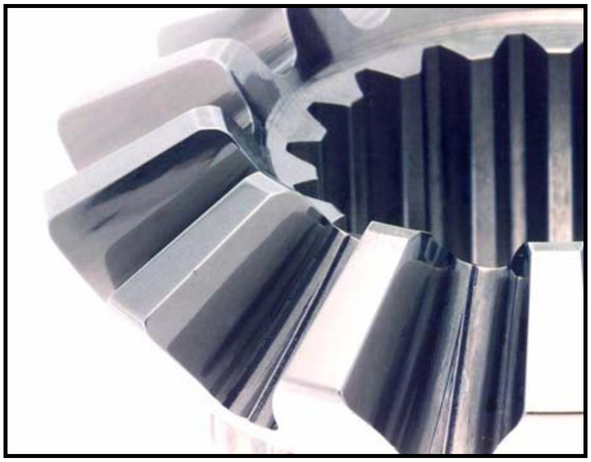
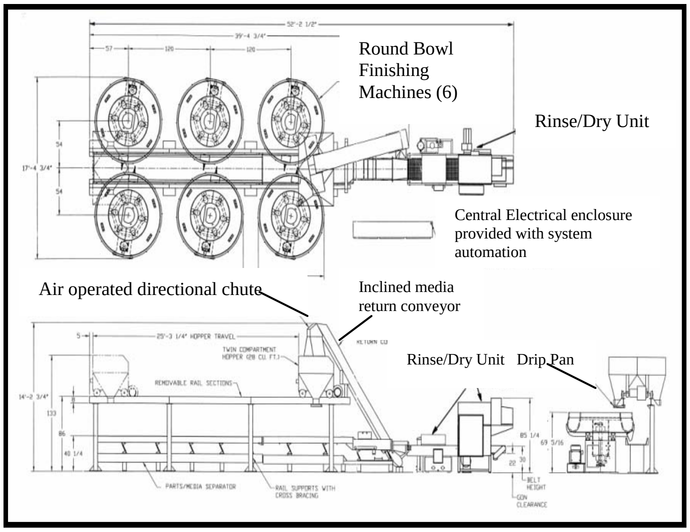


Photo 6; Shows a close-up of the teeth of the beveled spur gear shown in Photo 1. The gear was processed to achieve an isotropic finish by using the chemically accelerated vibratory finishing technique. The final surface finish was R_a = 1.5 µin./0.04µm. Note when compared to Photo 1, that all the grind line asperity peaks have been removed from the tooth flanks.

Once the asperities are removed and the improved micro-finish has been achieved, a mildly alkaline, soap-like burnish chemistry is added to the vibratory machine.[7, 8, 12, 13] The burnish neutralizes and removes any residual coating remaining on the parts from the refinement step and yields a mirror-like, final finish.[7, 8, 12, 13] See Photo 6.

In high volume, production operations, cost savings are realized through the ability to process parts in mass, thereby, achieving the superior ISF finish at per piece costs lower than conventional grinding, honing and lapping operations. See Schematic #1.

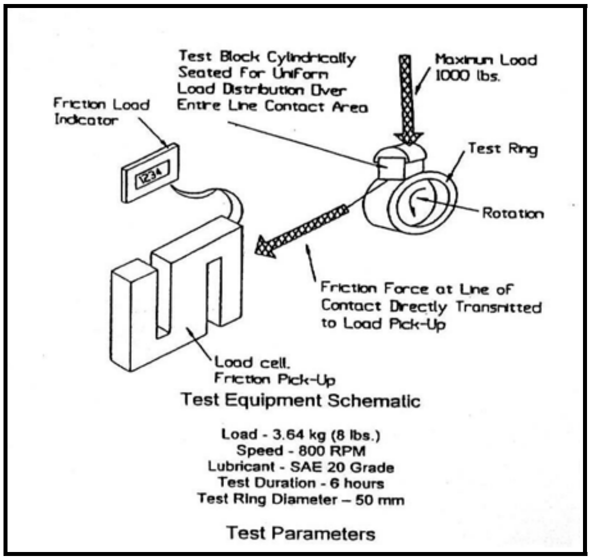


Schematic #1; Shows a 6 bowl, high volume ISF vibratory operation for an OEM manufacturer of planetary pinions. The operation is capable of generating 3,000 ISF finished pinions per hour or in JIT terms 1 pinion every 1.2 seconds.

HORSEPOWER LOSS AS DEMONSTRATED BY FRICTIONAL HEAT GENERATION

As noted earlier, engineered metal-to-metal contact surfaces such as camshafts, valve springs, transmission or quick change gears, bearings and rear end rings and pinions transfer energy by mechanical contact. This contact can be a rolling, sliding or pushing force against a complementary component. The asperity peaks on these surfaces introduces friction (i.e. inefficiency) into the mechanical transfer of engine horsepower resulting in horsepower loss most noticeable as heat.[3, 7, 8, 11, 12, 14]

In a recent evaluation, a major bearing manufacturer[9] monitored the performance features of two functional metal-to-metal contact surfaces by means of an ASTM D2714 and D2792 Block-on Ring test. See Schematic 2.



Schematic 2; a simplified schematic of the Block-on-Ring apparatus.

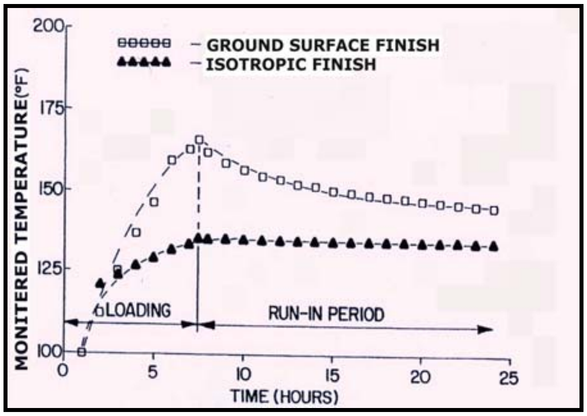
In the experiment, two steel blocks and rings were evaluated sequentially using the same test rig. During each evaluation, the sump temperature of the lubricant system was monitored as the ring was rotated at a constant 800 rpm.[9] the block was held on the rotating ring at a constant 8 lb (3.64 Kg) force.

In the first evaluation; (the control standard test,) the block and ring specimens were finished using a grinding process to generate a 25µin/0.64µm surface finish. In the second evaluation the block and ring were ISF finished to remove surface asperities and generate the improved ISF finish. (See Table #1)

Sample I.D.	Test Surface R_a
Normal Ground Block	25 µin / 0.64 µm
Normal Ground Ring	29 µin / 0.75 µm
ISF Finished Block	2.3 µin / 0.06 µm
ISF Finished Ring	5.1 µin / 0.13 µm

Table #1; Block-on-Ring Test, specimen surface conditions.

Concomitant to the mechanical abrading of the asperities on the ground specimens, was a higher, monitored bearing temperature.[3, 7, 8, 11, 12, 14] Additionally, there was a definitive temperature spike 165°F/74°C, associated with the completion of the loading phase of the break-in cycle on the ground test specimens.[3, 7, 8, 11, 12, 14] Once the metal-to-metal contact surfaces of the ground specimens were broken-in; i.e. asperities removed, the monitored temperature dropped to a steady state operational temperature of 145°F/62°C. [3, 7, 8, 11, 12, 14] See Graph 1.



Graph 1; Superimposes the temperature curve for normally ground, control standard specimens with the temperature curve for the ISF specimens. Note the temperature spike for the ground specimens corresponding to asperity peak break-in and the absence of a spike for the ISF specimens[3, 7, 8, 11, 12, 14] also, note the lower, final operating temperature of the ISF specimens.

When the testing was repeated using the ISF finished specimens, it was noted immediately that there was a complete absence of the temperature spike, (i.e. no asperity peaks present therefore no break-in period required.) The ISF finished specimens showed a gradual rise to a steady-state temperature, 132°F/54°C. [3, 7, 8, 11, 12, 14]

When compared to the normally ground specimens this represents a 13°F/8°C difference in final operating temperature. It can be inferred from this experiment that the reduction in operational temperature at the metal-to-metal contact interface indicates a reduction in metal-to-metal friction thereby allowing this contact interface to retain horsepower that would ordinarily be lost to frictional heat generation.

LOADING EFFICIENCY IMPROVEMENT OF BEARING SYSTEMS BY THE ISF SUPERFINISH

A major manufacturer of industrial roller bearings recently performed an evaluation of its bearing sets under various loading levels.[11] The manufacturers' bearing sets consists of roller bearings and an inside and outside bearing race. The evaluation was performed to determine the extent of the possible benefit achieved by ISF finishing when applied to complete or partial bearing sets.

The company chose as its test specimens, a common bearing set from its traditional line of roller bearings. The testing was performed using three sets of roller bearings that were sequentially mounted in a pillow block.

Test engineers varied the applied load on the bearing sets in the pillow block. Beginning at 455 kg applied load, loading was increased to a maximum of 4,550 kg applied load. The applied load was adjusted upward in 455 kg increments.

In each evaluation the bearing sets were turned at a constant 2,400 rpm and only the applied load was varied. The pillow block was equipped with a thermocouple that allowed test engineers to monitor frictional heat generation at the roller/race interface.

Evaluation #1 served as a control standard, and consisted of the company's normally ground roller bearings coupled with normally ground inner and outer races.

In Evaluation #2 the rollers were ISF finished prior to being coupled with the traditionally ground inner and outer races.
Finally, in Evaluation #3, both the roller bearings and the races were ISF finished prior to testing. See Table #2.

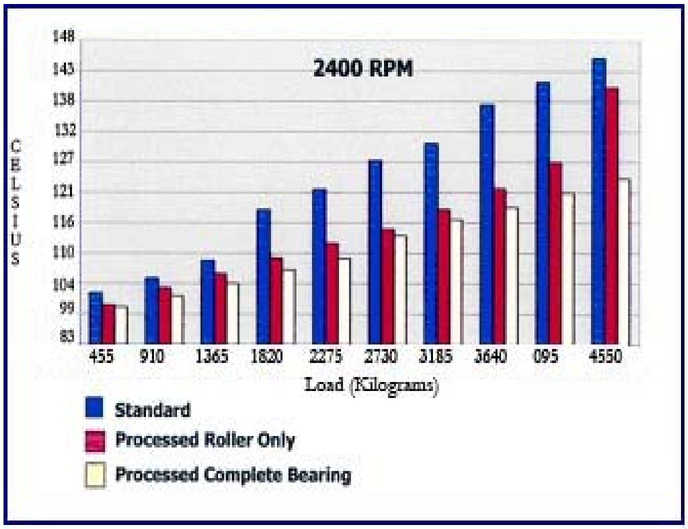


Table #2; Shows the combined results for all three evaluations.[11]

An examination of each loading level shows that the standard ground, roller/races, bearing set consistently had the highest operational temperature.

Bearing sets in which only the rollers were ISF finished demonstrated cooler operating temperatures at every loading level. At the lower load levels of 455 – 1,365 kg, the temperature differential was modest. However as the loading was increased from the 1,820 kg level and up, the temperature differential between Evaluation #1 samples and Evaluation #2 was significant. Additionally, that differential was maintained throughout the balance of the loading variations.

At all load levels and most especially at the higher end loading level of 4,550 kg., Evaluation #3 bearing sets demonstrated the most significant temperature benefit.

The results of this experiment clearly suggest that the ISF finish is of significant benefit even if applied to select components in a metal-to-metal, friction inducing application. Additionally, the ISF finish can be of maximum benefit when applied to both, complementary metal-to-metal contact surfaces.

DYNAMOMETER TESTING DEMONSTRATES HORSEPOWER RETENTION

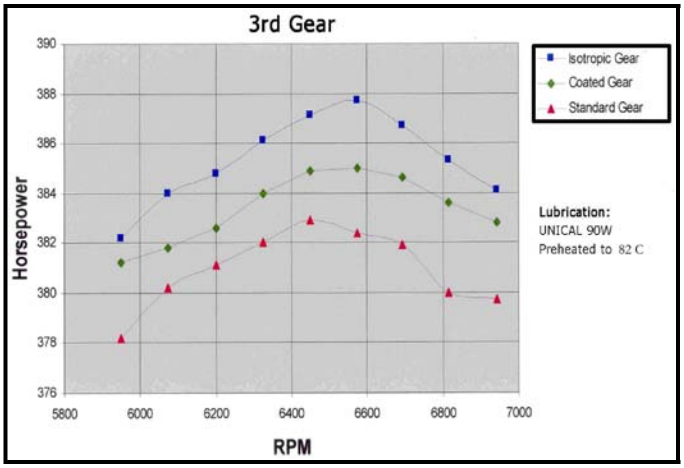
As an actual performance evaluation to determine if the experimental benefits of the ISF finish were legitimate, a series of dynamometer tests[12] were conducted using three Nextel Cup, T101 transmissions.

The testing was conducted sequentially on the same dynamometer stand. The transmissions were run using the same engine[12] and in each evaluation a horsepower curve for 3rd gear was plotted. During each test, the engine with the test transmission attached was preheated by idling until the transmission oil (Unocal 90W) reached a uniform 82°C.[12] Drive shaft angles were monitored to ensure a consistent angle was maintained for all evaluations.[12] Load was then applied and horsepower output was monitored.

Dynamometer evaluation #1 served as the baseline control standard. A T101 transmission was run as received from the OEM. The transmission was not disassembled, nor was it improved upon.

In evaluation #2, a second T101 transmission was disassembled and the individual components were removed. The components were then coated with a commercially available product valued as a friction reducing, performance enhancer. The transmission was then reassembled, attached to the engine and the second dynamometer test was conducted.[12]

In Evaluation #3, the transmission was completely dissembled. All components were then ISF finished. The transmission was then reassembled, attached to the engine and the third dynamometer test was conducted.[12] See graph #1.



Graph #2; Superimposes the resultant horsepower curves of 3rd gear, at specified rpm levels, for the tested T101 transmissions.[12] Note an approximate 1% horsepower retention with the ISF transmission.

Examination of the graph between the 6,400 and 6,600 rpm levels shows output levels of 383, 385 and 388 hp respectively for the as OEM supplied, coated and ISF gears.

The 5 hp difference between the as OEM supplied and ISF gears represents a 1.3% retention of horsepower that would have been lost had the gears not been ISF finished. Likewise, when compared to the coated gears there was nearly a 1% horsepower retention benefit due to ISF finishing. Since ISF is an actual refinement to the base metal there is no risk of coating loss via wear through, flaking or peeling.

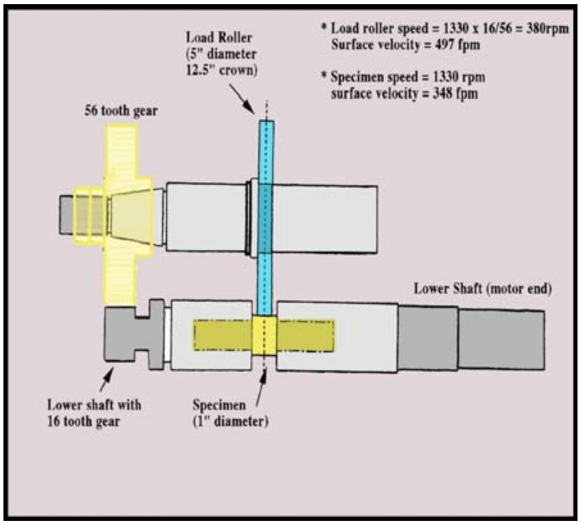
Component Durability Increase; Virtual Elimination of Contact Fatigue

It is a reasonable expectation that ISF will retain horsepower by reducing friction and will also increase a component's long term durability by eliminating contact fatigue, asperity stress risers and metallic debris in the lube system.

As an example consider the operational mode of automotive transmission and rear end gearing. Gears by their nature, undergo two primary modes of motion, rolling and sliding. Rolling motion is, as one would expect, the rolling of one gear against its complementary partner.

Sliding motion occurs when the flank of a gear tooth slides against the opposing flank of another gear tooth. Sliding occurs both as gear teeth engage and then again, as they disengage. Since this sliding action is a metal-to-metal contact phenomenon, it is here that ISF will benefit the gear by eliminating contact fatigue problems.

Recently, the Gear Research Institute (GRI) used a Rolling/Sliding Contact Fatigue (R/SCF) Test Rig[12, 13] to evaluate this very hypothesis. See Schematic #3.



Schematic #3; Schematic of the R/SCF test rig used by GRI to conduct its evaluations.[12, 13]

The GRI, R/SCF test rig utilizes a crowned, 5” diameter loading roller and a 1” diameter specimen pin.[12, 13] See Photo #7.

During R/SCF operation, the 1” specimen pin is secured to a rotating motor shaft. The shaft is in turn connected by two gears to the 5” diameter loading roller. The two components roll against one another during rig operation.

Photo #7; Shows a 1” diameter specimen pin on the lower left and a 5” loading roller on the upper right side of the photograph.

The loading roller and the specimen pin have different diameters and the rpm level of the motor shaft on the R/SCF Test Rig can be adjusted by the rig’s operator. These differences result in a phenomenon where the specimen pin becomes the sacrificial, friction-affected, sliding wear component.

During the GRI tests, the R/SCF test operator was able to produce a 43% negative sliding ratio on the specimen.[12, 13] whereas, a mid-20% range, is typical of normally paired gears. Adjusting the sliding ratio to an artificially high level facilitated having a failure mode on the 1” specimen pin in a minimal period of test time and at a minimal test rig run cost.[12, 13]

Once the rpm level of the R/SCF test rig was optimized, it was maintained as a constant throughout the evaluations. To facilitate specimen pin fatigue, the R/SCF test rig operator varied the stress load with which the 5” diameter contact roller was rolled against the 1” specimen pin.

Normal stress loading for the R/SCF test rig is 400 ksi. However to facilitate accelerated testing the stress loading can be varied upward. In this evaluation, the stress loads were increased upward in 25 ksi increments to 425 and 450 ksi respectively.

Two types of sample sets were evaluated during the R/SCF tests. The first evaluations were performed on 3 sets of rollers and pins. These rollers and pins were the baseline, control standard and were prepared to have a traditional ground/honed surface finish typical of the standard surface condition of gear tooth flanks as received from an original OEM manufacturer. See Table #3.

Sample I.D.	Test Surface R_a
Ground/honed set	16 µin./0.4 µm
ISF Finished Set	1.5 µin./0.04 µm

Table #3; Surface conditions of the R/SCF test specimens.

The second set of evaluations was performed on 2 sets of rollers and pins. These rollers and pins were ISF processed to generate the improved isotropic finish using the chemically accelerated vibratory finishing technique described earlier. See Table #3.

Prior to beginning the evaluation GRI defined the test's limitations and specimen performance to determine test completion. Success was determined to be cycle run out where cycle run out was defined as 20 million specimen pin rotations without a failure. Likewise, failure mode was defined as specimen pin pitting.

To facilitate testing the R/SCF test rig was equipped with a cycle counter to monitor the rotations. Additionally the R/SCF was equipped with a vibration monitor that would record the onset of pitting by the inception of specimen pin vibration and automatically shutdown the test rig to preserve the cycle count.

Sample I.D.	Stress in ksi	Millions of cycles	Failure Mode
Gd/hd #1	400	3.6	Pitted
Gd/hd #2	400	4.2	Pitted
Gd/hd #3	400	3.5	Pitted
ISF #1	400	20.0	None
ISF #1	425	20.0	None
ISF #1	450	22.4	None
#1 Sum	400-450	62.4	None
ISF #2	400	5.0*	None
ISF#2	425	5.0*	None
ISF #2	450	20.0	None
#2 Sum	400-450	30.0	None

Table #2; Tabulated results of R/SCF Testing [12, 13]
Where Gd/hd = ground/honed

* Note, after the extensive time it took to complete the full run outs at all three contact stress levels of ISF specimen set #1, it was decided that when testing ISF specimen set #2, the cycle count would be stopped after 5 million cycles at the lower contact stress levels of 400 and 425 ksi respectively to advance to the next highest stress loading level and to save time and reduce cost. The maximum 450 ksi stress loading level; however would be run to full run out.[12, 13]

In the first set of evaluations, the GRI R/SCF test rig operator was able to generate the typical failure mode of pitting, caused by the significant, applied sliding ratio on the control standard specimens. All three baseline standard samples failed in less than 5 million cycles at the lowest contact stress loading level of 400 ksi. In each case, the failure mode was by pitting.[12, 13]

Testing results of the ISF specimens were exemplary. In fact the ISF specimens could not be made to fail, even with the artificially high sliding ratio and the 450 ksi contact stress load.

It should be noted that the initial ISF roller and pin set ran for a total accumulated cycle count of 62.4 million cycles. This included 20 million cycles at 400 ksi, 20 million cycles at 425 ksi and 22.4 million cycles at 450 ksi before the test rig was shut down.[12, 13]

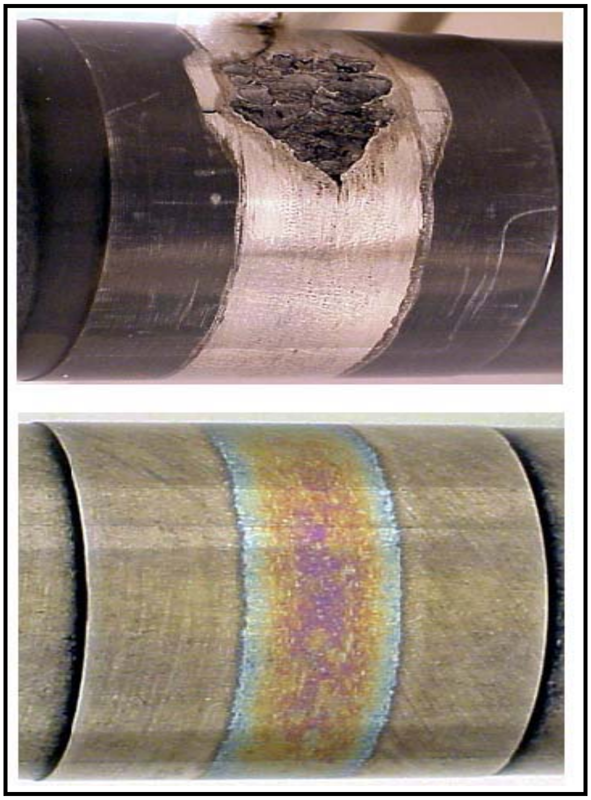


Photo #8; R/SCF test, pin specimen results
Top – Ground/honed specimen #3 with pitting failure mode after 3.5 million cycles at 400 ksi load level.
Bottom – ISF Processed specimen #1 after 62.4 million cycles. No failure, no pitting.

Testing was repeated with ISF specimen set #2 to determine if the favorable results were repeatable. The test was abbreviated to 5 million cycles at the 400 and 425 ksi stress loading levels so as to reach the maximum loading pressure of 450 ksi quicker.[12, 13] Five million cycles was chosen for the abbreviated, lower ksi loading, run out limit because it was itself, a longer cycle life than exhibited by any of the 3 sets of failed control standard, ground/honed specimens.

CONCLUSION

Grinding, honing and lapping are traditional surface finishing methods applied to automotive components such as camshafts, bearings, transmission gears and rear end rings and pinions.

Since these finishing techniques are mechanically applied to the component being finished they leave a consequential unidirectional pattern on the surface of the part. This pattern can easily be seen as parallel rows of asperity peaks and valleys.

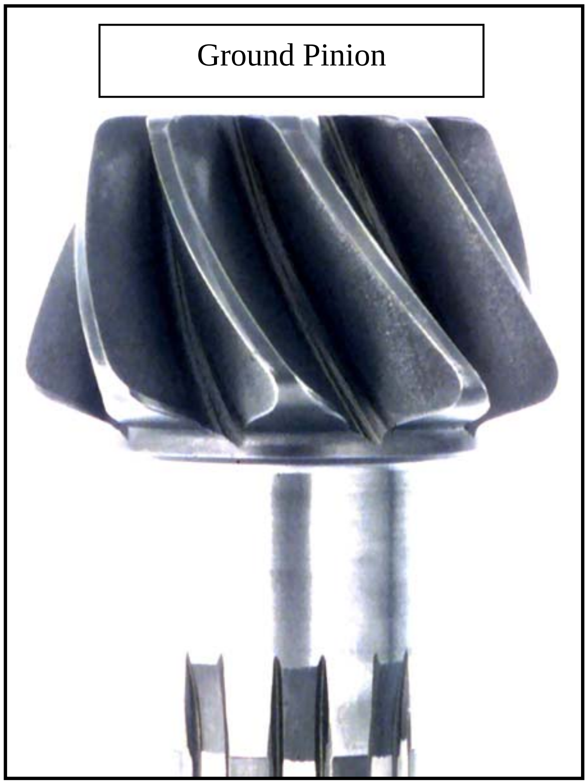


Photo #9; Shows pinion with traditionally ground gear teeth. Note, rows of asperity peaks.

The presence of asperity peaks results in:

- poor metal-to-metal contact [7, 8, 12, 13]
- increased friction, promoted initially by peak-to-peak contact [8, 14]
- increased surface contact stresses isolated in the peak-to-peak contact locations [8, 14]
- Heat generation due to friction [11]
- Lose of engine horsepower transfer through these inefficiencies [12]
- Shortening of component life due to contact fatigue wear and pitting [12, 13]
- Metal debris in the lubricant recirculation system [12, 13]

Chemically accelerated vibratory finishing offers an efficient way to mass produce an ISF finish on metal-to-metal contact automotive components.[1, 5, 6, 7, 8, 12, 13] The ISF finish is non-directional and asperity free.[7, 8, 12, 13]

Photo #10; Pinion as seen in photo #9 after being chemically accelerated vibratory finished generating the ISF finish

The ISF finished part contains no contact fatigue initiation sites because the asperity peaks have been removed by the wiping action of the media during the chemically accelerated finishing process.[8, 14] Additionally, metallic debris is not present in the lube system since the asperities were removed prior to component installation.[8, 14]

An isotropic surface finish offers several advantages to the operation of the metal-to-metal contact surfaces of automotive parts:

- Efficient metal-to-metal contact[7, 8, 12, 13]
- Diffusion of contact stresses by the elimination of asperity peaks thereby spreading the stresses over a larger surface area[8, 14]
- Elimination of parasitic, frictional, heat generation[11]
- Retention of engine horsepower[8]
- Increase in component durability via a reduction on contact fatigue failure[12, 13]
- Elimination of metallic debris in the lubricant recirculation system[12, 13]

REFERENCES

1. J. Arvin, Arrow Gear, Manesh, A., Power Transfer System Manufacturing, Michaud, M., Sroka G., Winkelmann, L., REM Chemicals Inc, *Proc. AGMA Technical Conference*, 2002 “The Effect of Chemically Accelerated Vibratory Finishing on Gear Metrology”

2. R.D. Britton, Elcoate C.D., Alanou M.P., Evans H.P. & Snidle R.W., *Proc. STLE/ASME Tribology Conference;* Orlando, FL (1999) “Effect of Surface Finish on Gear Tooth Friction”

3. F.F.H. Hashimoto, Zhou R.S. & Howlett K.; U.S. Patent 5,503,481 (1996) “Bearing Surfaces with Isotropic Finish”

4. R.D. Kane & Maldonado J., InterCorr International, Inc., Report L99825GK (1999)

5. M. Michaud, Tirendi F., Zobbi R.G.; U.S. Patent 4,491,500 (1985) “Method for Refinement of Metal Surfaces”

6. M. Michaud, U.S. Patent 4,818,333 (1989) “Metal Surface Refinement Using Dense Alumina-Based Media”

7. W.P. Nebiolo, *Proc. of the 37th AESF Aerospace/Airline Plating & Metal Finishing Forum;* Portland, OR (2001) “Isotropic Finishing of Helicopter and Turboprop Gearbox Components.”

8. W.P. Nebiolo, *Proc. of the SAE/PRI Conference*, Indianapolis, IN; 2002 “The Reduction of Parasitic Friction in Automotive Gearbox and Drive Train Components by the Isotropic Superfinish”

9. H.P. Nixon, Cogdell J.D., *Proc. of the SAE International; 1998 Earthmoving Industry Conference and Exposition* Peoria, IL (1998) “Performance Evaluation of a Potential New Engineered Surface for Enhanced Concentrated Tribological Contacts”

10. R.W. Snidle, Evans H.P., Alanou M.P., “The Effect of Superfinishing on Gear Tooth Profile” Report 2284; contract N68171-96-C-9043 (1997)

11. Technical Bulletin, “Heat Generation Test Results for REM Processed Bearings versus Standard Spherical Roller Bearings,” REM Chemicals, Inc., Southington, CT

12. L. Winkelmann, Michaud M., Sroka, G., Swiglo, A.A., Mahan D.; *American Gear Manufacturers Association Meeting*, Detroit, MI, (2001) “Chemically Accelerated Vibratory Finishing for the Virtual Elimination of Wear and Pitting for Steel Gears.”

13. L. Winkelmann, Michaud M., Sroka, G., Swiglo A.A., *SAE International Off-Highway Congress*, Las Vegas, NV (2002) “Impact of Isotropic Superfinishing on Contact and Bending Fatigue of Carburized Steel”

14. Zhou R.S.; Hashimoto F.; *Proc. ATLE/ASME Tribology Conference;* Maui, HI (1994) “A New Rolling Contract Surface and “No-Run-In”