The Basics of Surface Engineering by Isotropic Superfinishing (ISF) Using a Traditional Vibratory Finishing Bowl

Abstract

Certain machined, engineered components are functionally operative because they interact with their complementary partners to transmit energy/motion. Examples of engineered items that transmit energy/motion are bearings or gears. These engineered items transmit energy/motion by rolling, sliding, rotating or engaging their complementary partners.

As a function of their operational efficiency the metal-to-metal contact location of the complementary partners becomes an area of great engineering concern, since this contact point is a probable area of parasitic frictional resistance. As such, the finish of the metal-to-metal contact areas becomes a critical variable in the efficiency equation related to energy or motion transfer.

Typically machined parts that have been subsequently polished to improve their final surface finish will have under magnification a unidirectional surface pattern that corresponds to the direction of polishing. Although the resulting polished surface is improved versus its original machined condition, the presence of the polishing line asperities minimizes metal-to-metal contact between complementary components because component contact is actually asperity peak-to-asperity peak.

Vibratory bowls are commonly used in metal finishing for generic deburring. By utilizing non-abrasive, high density media in conjunction with an Isotropic Superfinishing (ISF) chemistry the surfaces of the complementary components can be superfinished to an isotropic or random finish. This improved surface increases energy/motion transfer efficiency in the metal-to-metal contact area by reducing friction and providing an additional number of engineering advantages.

This paper will review the technique used to generate the improved isotropic surface finish and will additionally review some of the engineering advantages that can be imparted to metal-to-metal contact surfaces.

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Traditionally Finishing Operations

Grinding is the traditional, final, metal finishing operation done to engineered metal-to-metal contact surfaces such as roller bearings or AGMA Class 12 or higher gears.[7, 8] See Image 1.

Image 1; Image shows teeth of a helical gear being ground.

A microscopic examination of components prepared using a final grinding operation reveals a surface with a final unidirectional pattern that corresponds to the direction of the final grinding operation.[7, 8, 9] (Image 2.)

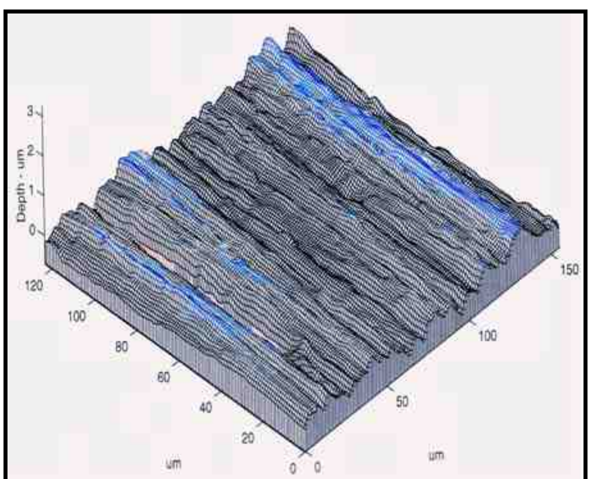


Image 2; A magnified view of a ground surface.[7, 8, 9] Note the unidirectional parallel rows of asperities corresponding to the final direction of the grinding operation.

Grinding with successively finer grinding wheels is expensive, repetitious and ineffective because it simply results in a surface that has more, closer-spaced rows of shorter height asperities.

The ISF Surface

It has been reported that metal-to-metal contact areas, if refined by ISF (Isotropic Superfinishing, a specific type of chemically accelerated vibratory finishing process), will have a resultant isotropic surface. [1, 3, 7, 8, 9, 12, 13] An isotropic surface is a surface that does not have a unidirectional pattern but rather, is random and non-directional in its final condition.[9, 14] See Image 3.

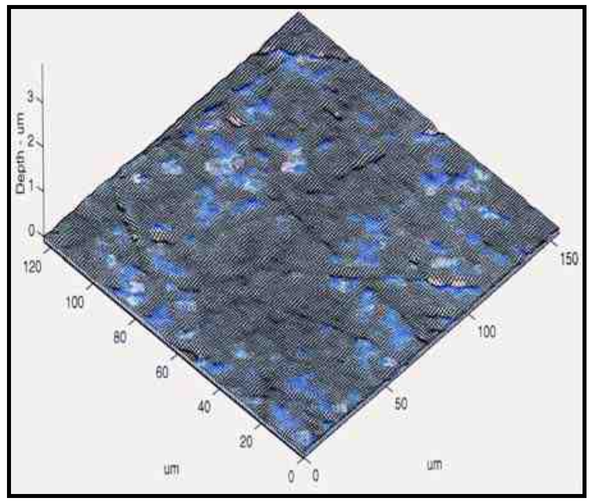


Image 3; A magnified view of an isotropically prepared surface.[7, 8, 9] Note, the parallel rows of asperity peaks as seen in Image 2 are non-existent and the final surface is smoother and random with no directional pattern.

<u>Metal-to-Metal Contact</u>
Traditional Surfaces vs. ISF Surfaces

When placed into operation for the first time, components that have been prepared using a traditional grinding operation have a minimal area of initial metal-to-metal contact because this initial contact is actually asperity peak-to-asperity peak.[2, 10] Such complementary patterns concentrate contact stress into a few isolated locations of asperity to asperity contact.[2, 10]

Parts that have been isotropically prepared have an improved metal-to-metal contact pattern, since the asperities have been removed from the complementary components. The final surface is smoother and contact stress in any one location is reduced since it is now diffused over a wider area due to the improved contact pattern.[8]

Generating the ISF Finish

Using techniques described earlier [1, 5, 6, 7, 8, 12, 13] ISF is produced using a chemically accelerated vibratory finishing process. The parts to be isotropically finished are placed into a vibratory unit containing high-density, non-abrasive media.[6] (Images 4 and 5.)

Image 4; Shows a traditional vibe bowl with parts/media separation deck. Ideal for processing short stubby parts such as gears, tappets and bearings.

Photo 5; Shows a traditional vibratory tub. Ideal for processing long skinny parts such as splined-shafts, camshafts, crankshafts, pinion shafts, spars, etc.

The chemically accelerated vibratory finishing process consists of two steps that are conducted sequentially within the same vibratory machine.

Image 6; Image of a differential pinion in traditional as ground finish. Note grind lines on the gear teeth.

During the initial ISF processing step, a refinement chemistry is added to the vibratory unit.[1, 5, 7, 8, 12, 13] Independent testing has confirmed that the chemistry doesn't generate hydrogen embrittlement on steel.[4]

This chemistry reacts with the surface of the part to produce a soft, conversion coating.[1, 5, 7, 8, 12, 13] (See image 7.)

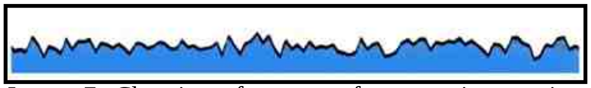


Image 7; Chemistry forms a soft conversion coating on the surface of the part.

As the part rolls in the vibratory unit, the conversion coating is wiped from the peaks of the asperities by the weight of the high-density non-abrasive media. This exposes unreacted, underlying steel from the now partially leveled asperity.[6] (See image 8.)

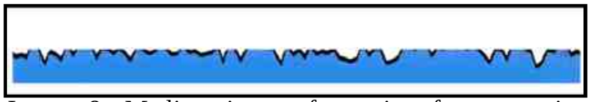


Image 8; Media wipes soft coating from asperity peaks exposing clean steel beneath.

The peaks, being elevated, are wiped preferentially.[7, 8, 12, 13] The recessed valleys between the peaks can not initially be contacted by the media, leaving the coating intact and the valleys untouched.[7, 8, 12, 13] The coating reforms on the partially lowered peaks to propagate peak refinement.[7, 8, 12, 13] (See image 9.)

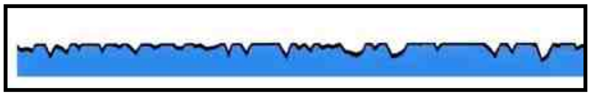


Image 9; Coating reforms on lowered asperities to propagate surface leveling.

In rapid order, the asperities are leveled to the basis level of the component's surface thereby generating the improved ISF.[7, 8, 12, 13] (See image 10.)

Image 10; Asperities leveled generating the ISF.

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 unit.[7, 8, 12, 13] The burnish neutralizes and removes any residual conversion coating remaining on the parts from the refinement step and yields, on hardened steel parts, a mirror-like, final finish.[7, 8, 12, 13] (See Image 11.)

Image 11; ISF surface after burnish step.

In high volume, production operations, cost savings are realized through the ability to process parts in mass, thereby achieving the superior ISF at per piece costs lower than conventional grinding, honing, lapping and buffing operations.[7, 8]

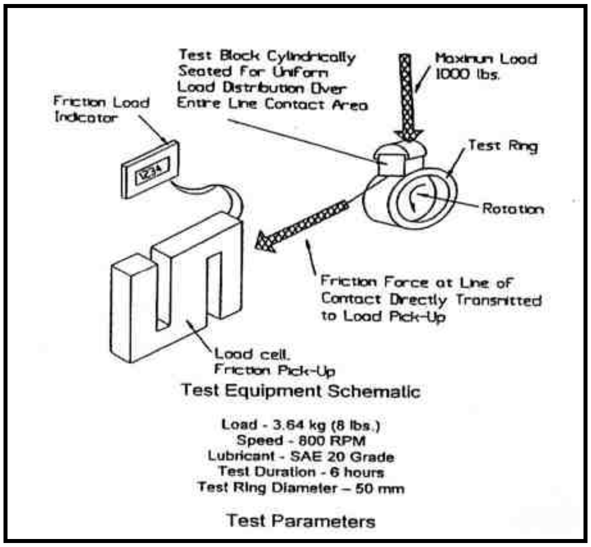
Image 12; Shows the same spiral differential pinion as shown in image 6. Note, grind line asperities have been removed leaving a smooth ISF.

Demonstrated Parasitic Frictional Heat Reduction

As noted earlier, engineered metal-to-metal contact surfaces such as gears and bearings transfer energy by mechanical contact. This contact can be a rolling, sliding or pushing force against a complementary component. The asperities on these surfaces introduce friction (i.e. inefficiency) into the mechanical transfer of energy resulting in energy loss which can most noticeably be monitored as heat generation.[3, 7, 8, 9]

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

The Block-on-Ring test rig holds a steel coupon, under constant load, against a rotating ring. The contact interface between the rotating ring and the loaded coupon then becomes an area of experimental interest.[9] (See Schematic 1.)



Schematic 1; A simplified schematic of the Block-on-Ring apparatus.[9]

In the experiment, a series of steel blocks and rings were evaluated sequentially. During each evaluation, the oil sump temperature was monitored as the ring was rotated at a constant 800 rpm.[9] The block was held on the rotating ring under a constant 1,000 lb. load.[9]

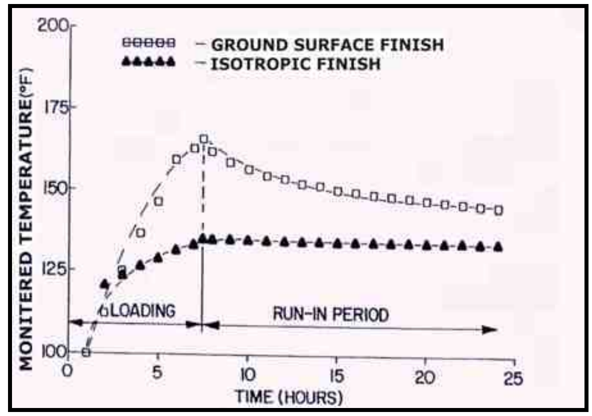
In the first set of evaluations the steel coupons were finished using the bearing manufacturer's traditional grinding process to generate a 25µin/0.64µm surface finish. These samples served as the experimental control standards.[9]

In the second set of evaluations the steel coupons were ISF prepared removing surface asperities and generating the improved ISF.[9] (See Table #1 below)

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 away of the asperities on the ground specimens, was a higher, monitored bearing temperature.[9] Additionally, there was a definitive temperature spike 165°F, associated with the completion of the loading phase of the break-in cycle on the ground test specimens.[9] 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[9] 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.[9] 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.[9]) The ISF Finished specimens showed a gradual rise to a steady-state temperature, 132°F. [9]

When compared to the normally ground specimens this represents a 13°F 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 energy that would ordinarily be lost to frictional heat generation.

Loading Efficiency Improvement of Bearing Systems by the ISF Superfinish

An evaluation of bearing sets under various loading levels by a second bearing manufacturer confirmed the temperature reduction.[8, 11, 12] Bearing sets evaluated consisted of roller bearings as well as inside and outside races. 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 1,000 lb. applied load, loading was increased to a maximum of 10,000 lb. applied load. The applied loaded was adjusted upward in 1,000 lb. increments.[8, 11, 12]

In each evaluation the bearing sets were rotated at a constant 2,400 rpm and only the applied load was varied. The pillow block was equipped with a thermocouple that to monitor frictional heat generation at the roller/cage interface.[8, 11, 12]

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.[8, 11, 12]

In Evaluation #2 the rollers were ISF finished prior to pairing with traditionally ground inner and outer races.[8, 11, 12]

Finally, in Evaluation #3, both the roller bearings and the races were ISF finished prior to testing.[8, 11, 12] (See Table #2.)

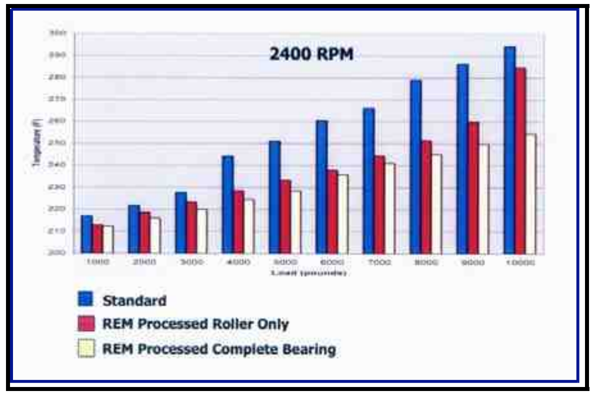


Table #2; Shows the combined results for all three evaluations.[8, 11, 12]

An examination at each loading level shows that the traditionally ground bearing sets consistently had the highest operational temperature.[8, 11, 12] (Blue columns Table #2.)

Bearing sets in which only the rollers were ISF finished demonstrated cooler operating temperatures at every loading level. At the lower load levels of 1,000–3,000 lbs, the temperature differential was modest. However as the loading was increased from the 4,000 lb. level and up, the temperature differential between the Evaluation #1 samples and the Evaluation #2 samples was significant. Additionally, that differential was maintained throughout the balance of the loading variations.[8, 11, 12] (See red columns, Table #2.)

At all load levels and most especially at the higher end loading level of 10,000 lbs, Evaluation #3 bearing sets demonstrated the most significant temperature benefit.[8, 11, 12] (See white columns, Table #2.)

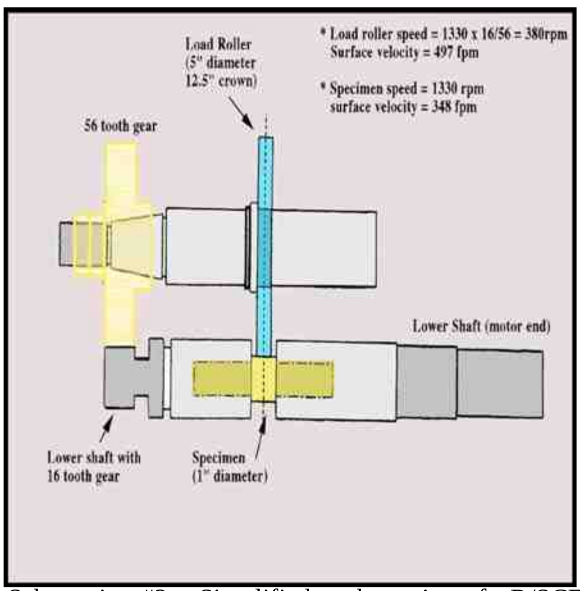
The results of this experiment demonstrate that the ISF Superfinish is a partial benefit even if applied to selected components in a metal-to-metal, friction induced application. Additionally, the ISF Superfinish can be of maximum benefit when applied to both, complementary metal contact surfaces.[8, 11, 12]

Component Durability Increase; Virtual Elimination of Contact Fatigue

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

As an example consider the operational mode of gear mesh. Gears by their nature, undergo two primary modes of motion, rolling and sliding. Rolling motion consists of one gear tooth rolling upon its complementary partner during mesh.

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



Schematic #2; Simplified schematic of R/SCF Rolling/Sliding Contact Fatigue Test Rig.[8, 13]

Recently, the Gear Research Institute (GRI) used a Rolling/Sliding Contact Fatigue (R/SCF) Test Rig[8, 13] to evaluate this very hypothesis. (See Schematic #2.) The R/SCF test rig utilizes a crowned, 5" diameter loading roller and a 1" diameter specimen pin.[8, 13] (See Image #13.)

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.

Image #13; Shows a 1" diameter specimen pin on the lower left and a 5" loading roller on the upper right side of the photograph.[8, 13]

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.[8]

During the GRI tests, the R/SCF test operator was able to produce a 43% negative sliding ratio on the specimen.[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.[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.[8, 13]

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.[13]

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.[8, 13] (See Table #3 below.)

R/SCF Sample Parameters

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.[8, 13]

The second set of evaluations was performed on two sets of rollers and pins. These rollers and pins were ISF finished to generate the improved isotropic surface using the chemically accelerated vibratory finishing technique described earlier.[8, 13] (See Table #3 above.)

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 at 20 million rotations of the pin without a failure defined as specimen pin pitting.[8]

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.[8]

R/SCF Test Results

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 #4; Tabulated results of R/SCF Testing [8, 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.[8, 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.[8, 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 for another test project.[8, 13]

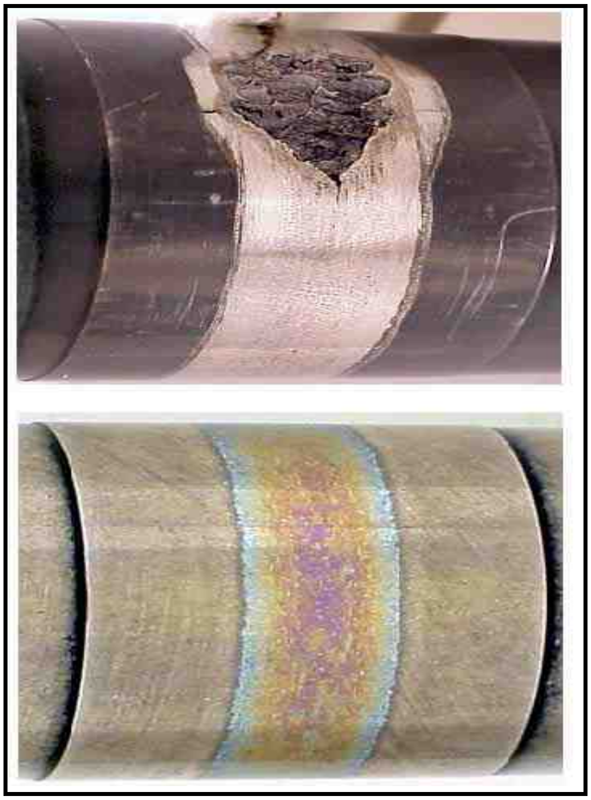


Image #14; R/SCF test, pin specimen results
Top – Ground/honed specimen #3 with pitting failure mode after 3.5 million cycles at 400 ksi load level.
Bottom – ISF Processed specimen #1 after 62.4 million cycles. No failure, no pitting.[8, 13]

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.[8, 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.

Conclusions
Grinding and honing are traditional surface finishing procedures applied to engineered metal-to-metal contact surfaces such as gears and bearings. Since these techniques are mechanical applied they leave a final unidirectional pattern on the surface of the part, visible as parallel rows of asperities.

The presence of asperities results in:

- reduced contact efficiency [7, 8, 12., 13]
- friction caused by peak-to-peak contact [8, 14]
- increased contact stress in the peak-to-peak contact areas [8, 14]
- Heat generation due to friction [11]
- Lost of energy horsepower transfer through these inefficiencies [12]
- Shortened component life due to contact fatigue wear and pitting [12, 13]
- Metal debris in the lube system [12, 13]

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

Since the asperity peaks have been wiped by the media during the ISF finishing process the ISF part has no contact fatigue initiation sites. Additionally, metallic asperity debris isn't present in the lubricant stream. [8, 14]

The ISF offers several advantages to the operation of the metal-to-metal contact surfaces:

- More efficient metal-to-metal contact [7, 8, 12, 13]
- Removing asperities diffuses surface contact stresses by spreading them across a larger surface area [8, 14]
- Reduction of parasitic, frictional, heat generation [11]
- Efficient energy transfer [8]
- Increase in component durability via a reduction of contact fatigue failure [12, 13]
- Elimination of metallic debris in the lubricant recirculation system [12, 13]

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