The ultimate finish

John Stowe explores the science behind REM Isotropic Superfinishing

Readers of *Race Engine Technology* are now familiar with the isotropic superfinishing (ISF) process, and the increasingly broad acceptance of this REM Chemicals Inc-developed technology in virtually all forms of motorsport as well as in a variety of aerospace and military applications. As reported in RET issue 016 this chemical-mechanical methodology has largely replaced or enhanced conventional grinding, lapping, and abrasive honing techniques to produce an ultra-smooth, non-directional, and uniform surface that retains just enough rounded micro-texture to retain lubricating media and prevent pitting and/or material transfer.

The introductory article in issue 016 and the subsequent presentation regarding isotropic superfinishing by REM at the Race Engine Technology Summit in Cologne last November has sparked a great deal of interest in the process, testing procedures, and some of the more advanced applications possible using it.

ISF Up Close

There are four distinct levels of finish with the ISF process. REM conveniently identifies each as one of the following: 'worse', 'good', 'better', 'best'. The accompanying microphotographs on page 37 illustrate each condition.

Worse

This is the standard ground finish left completely untreated. The profilometer reveals the full extent of the peak and valley asperities present, as well as the distressed condition of the metal at the surface.

Good

This is the first level of the ISF process. The partially finished ISF surface has removed the peak asperities. This results in greater working surface area, and far less tendency for the irregularities to "puncture" the lubricant film.

Better

Further finishing results in the valleys beginning to disappear, with only a few left. Functionally this surface performs very well, although not all of the stress risers are removed.

Best

This is the final surface achieved by the isotropic superfinishing method. All valleys are completely removed, as well as any potential stress risers. What remains is a rounded micro-texture randomly uniform in all directions. (Hence the term isotropic.) Typically, there is less then .0001" (.0025 mm) material lost to attain this condition on a high quality component.

Lambda Ratio Improvements in Application

The key value being pursued here is, of course, the best possible Lambda ratio. In tribological terms, the Lambda ratio represents the ratio between the minimum lubricant film thickness, and the combined roughness of both working surfaces. Clearly, if the film thickness of the lubricant is exceeded by the peak and valley characteristics of these surfaces, direct metal-to-metal contact will result, with the resultant generation of heat and particulates.

One may well ask, "If that is the case, why not simply increase the viscosity and film strength of the lubricant, so that it is impossible for metal-to-metal contact to occur"? Indeed, this has been the traditional response to difficult lubrication problems, particularly in high-load gearing applications, such as final drive units. What is not generally recognized is that the thicker lubricant is not only consuming more energy because of its greater resistance to motion, but is also a significant contributor to high operational temperatures. This is because heavy lubricants, especially those with large, complex molecular structures, actually have significant amounts of friction created within them during use due to molecular "shear"; in some cases, the lubricant itself is producing more friction-generated heat than the load-bearing mechanical components.

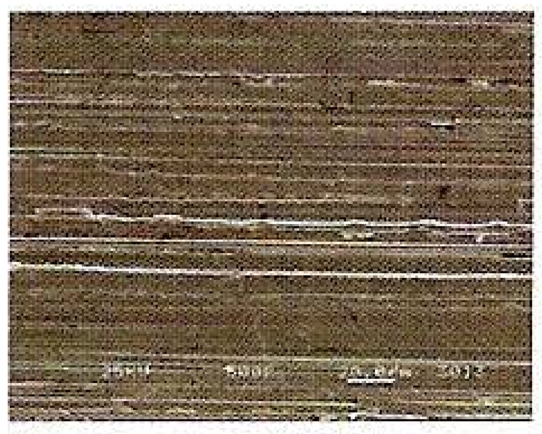
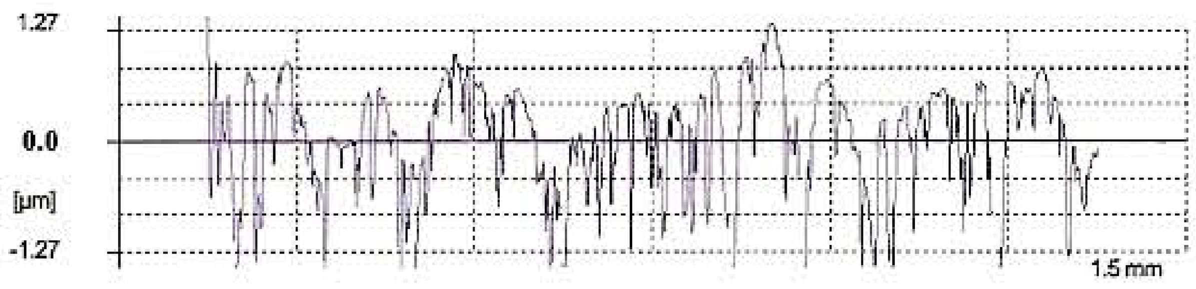
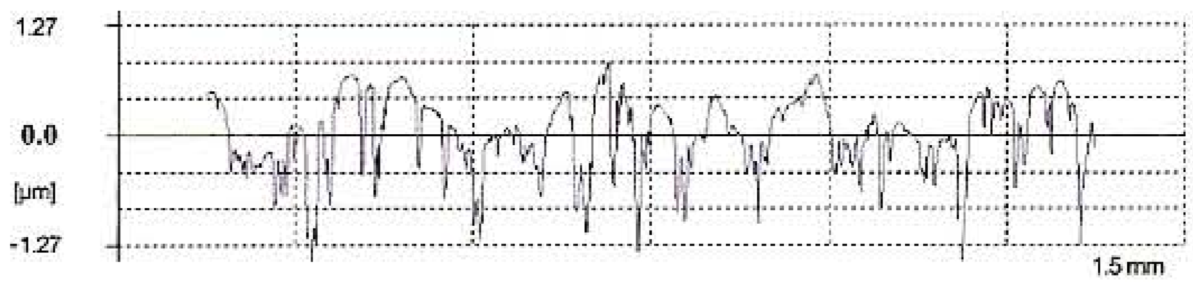
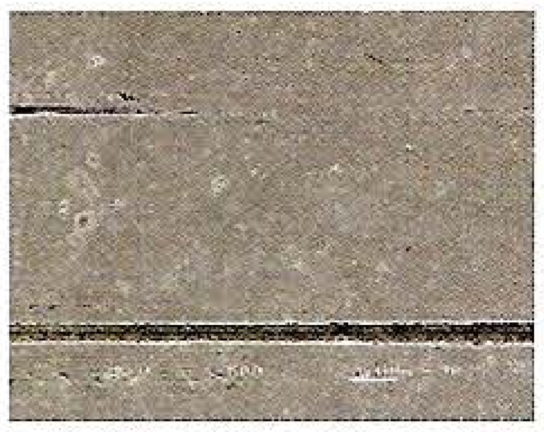
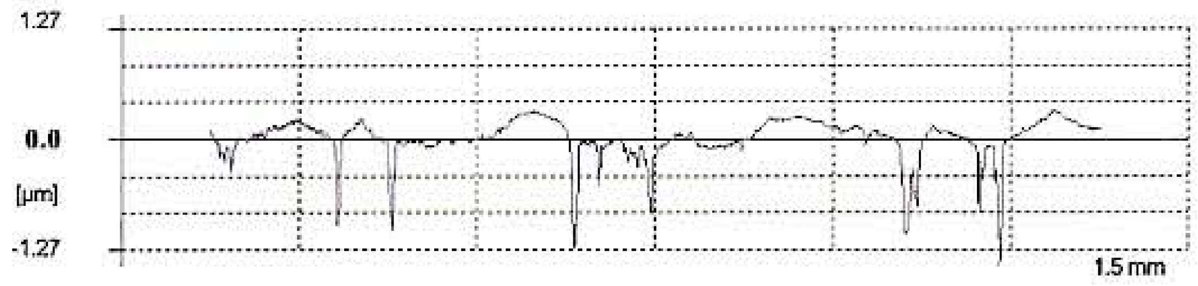
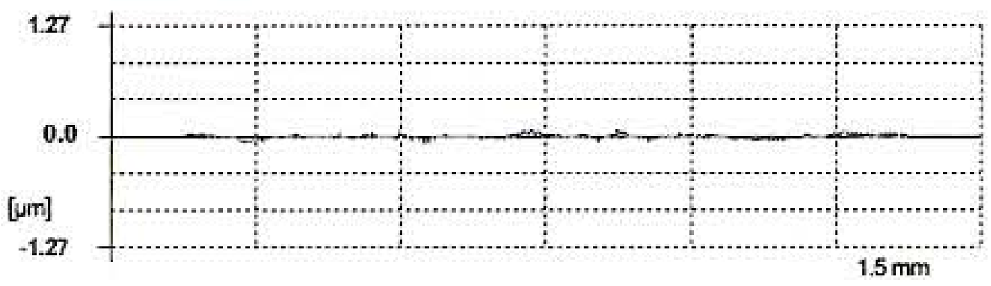
Of course, the Lambda ratio should always be better than one, and as this figure improves as result of better surface characteristics, one can then lower the viscosity from that of the original lubricants used. This capability creates other opportunities as well; one remembers the combined engine and gearbox lubrication system tried out in Formula One some years ago, and the resultant lack of reliability that occurred as well as the strain on filtration systems as a result of particulate fines circulating in the oil from the transmission. A new generation of unified systems using super-finished components may well be possible now, with both the engine and the gearbox enjoying the benefits of circulated, filtered, low drag lubricants.

At the same time, service cycles for oil and filter changes can be lengthened as well.

Conventionally finished cams and tappets are in working with a Lambda ratio of less than one at contact, which is referred to as "boundary" lubrication. Main and rod bearings usually maintain a Lambda ratio above three in use; this is the much more desirable hydrodynamic lubrication regime. Several of a mechanism's moving parts will fall somewhere in the middle, or, "mixed" category, with characteristics of both regimes present. Improving the Lambda ratio using ISF allows many of these components to "step up" a class in use. For example, units that now operate in a boundary-to-mixed lubricant regime can move to the mixed-to-hydrodynamic lubrication.

The high fiber greases that normally are used with sealed bearings, as well as in applications where circulation is not possible, should no ▶

> "If the film thickness of the lubricant is exceeded by the peak and valley characteristics, direct contact will result"

Performance	Surface at 500X Magnification	Roughness Average
Worst **Starting Condition:** Ground surface having peak and valley asperities along with a distressed layer of metal at the surface.	 	R_a: 0.58 µm R_z: 3.5 µm
Good **Stage 1:** Partially superfinished surface where the peak asperities have been planarized.	 	R_a: 0.30 µm R_z: 2.0 µm
Better **Stage 2:** Superfinished where only a few valley asperities remain on the surface.	 	R_a: 0.13 µm R_z: 1.1 µm
Best **Final Condition:** Superfinished surface with all asperities removed while displaying the beneficial and inherent micro-texture.	 	R_a: 0.025 µm R_z: 0.17 µm

longer require nearly as much fiber content to ensure an acceptable Lambda ratio, again resulting in less heat being generated at the source. This is especially important in spindle applications where heat-generated expansion effectively changes optimum bearing preloads.

Finally, it should be mentioned that these thinner oils, combined with ball and roller bearings that have smoother surfaces, result in less "cushioning effect" due to the lower plasticity of the bearing faces. This means that shafts stay centered better in their rotation, both axially and radially, and "micro- flutter" i.e. small, high frequency, uncontrolled motion is reduced. In application, systems such as linear positioning devices that use ball-screws will translate rotary motion from their servomotors into linear motion more accurately as a result.

Correct Lambda values are not just important to bearings, shafts, and gears; high-pressure fuel systems, such as the pump and plunger systems used for diesel fuel injection are now coping with increased loads, as pressures for these systems have grown ever higher to achieve the best possible atomization. At the same time, especially in the USA, the lubricity of compression ignition fuel is diminishing because of reduced sulfur content brought on by increasingly stringent diesel fuel cleanliness requirements.

Methodology and Equipment

There is probably no area that receives more attention to friction reduction than gears, transmissions, and bearings. In the not-so-distant past, test results meant to measure the efficiency of both components and lubricants were often inconclusive. For example, high-quality gears with accurate and correctly crowned tooth profiles were efficient enough to make getting a reliable determination of the relative losses in the consumed energy remainder quite difficult; indeed some studies actually produced results that pointed to operational efficiencies of greater than 100 percent because of the minor errors in the measured input and output values as recorded during tests exceeded the nominal friction loses. As a majority of the engineering community did not (and does not) accept perpetual motion as a viable theory, it was clear that better equipment would be required to obtain accurate performance assessments!

The digital age has been with us now for some time now, however, and high accuracy digital torque meters and strain gauges that use advanced electronic systems are now combined with well engineered, dedicated equipment that can measure variations to a much finer degree than the strictly analog machines of a generation ago. This makes it possible to examine accurately the effects of minor changes in lubricant grades and types, as well as surface conditions, preload and/or backlash, etc. The significant volume of testing that has been done in this area therefore provides highly reliable information; these tests are performed over long periods with varying loads and speeds applied, and under all temperature conditions. The tests are then repeated several times to ensure the quality of the data obtained.

The procedure most frequently specified for gear and gear lubricant evaluation is commonly known as the FZG gear test, which is performed on the machine bearing the same name. The FZG gear test rig has become widely accepted for a variety of tests for specific conditions. In addition to power loss and wear measurements, this piece of equipment can be used to determine the scuffing load capacity of gear lubricants, as well as perform pitting and micro pitting tests to determine how different gear oils and additives affect this condition in relation to the load capacity of gears and lubricants. Shear stability tests can be conducted to examine the sheer loss of multi-grade lubricants, and there is a low-speed wear test for EP and other gearbox lubricants.

The FZG device is essentially a back-to-back test rig with mechanical power circulation, driven by an electric motor. Two sets of gears are arranged in a "four-square" configuration on two parallel shafts. One shaft has an adjustable clutch between its gears that allows for changes in loading. The electric motor makes up for the power losses in the system, which can be operated under very high loads, typically up to 1000 Nm. Normally, the test gear set is run in lubricant with a load progressively increased until failure, which is represented by a 10 mg weight loss on the pair of these test gears. In addition to recorded weight loss and dimensional changes, photographs of the gears' faces are taken at each stage of the testing so that the correct correlation between loading, lubricant, and surface condition is recorded. This procedure is also called the "Niemann four-square gear oil test", and sometimes the equipment is generically referred to as a "four-square test rig", especially in United States.

Another common test is for the measurement of sliding friction losses. This is the "Block-on-Ring" test, and is normally conducted on a Falex block-on-ring test machine. While Falex and FZG are manufacturers of specific pieces of equipment, both of them have become virtually synonymous with their respective applications because of their wide acceptance in the field. The Falex block-on-ring machine is a refinement of the original Timken wear tester developed by that company for its own internal use, and comes with a broad array of attachments and software applications for specific purposes.

Essentially, a ring of a given material is rotated against a stationary block. Oscillating motion may also be applied as well as various regimes of standard rotation throughout the test cycle. On machines equipped with the available software, rotational speed, load, friction, lubricant temperature, and block temperature are recorded every six seconds and automatically written into the test file. It is therefore possible to accurately correlate this information with the distance travelled (literally, slid). Blocks and rings are weighed and measured before and after each test, so that wear coefficients can be computed for the particular combination of materials and lubricants being examined.

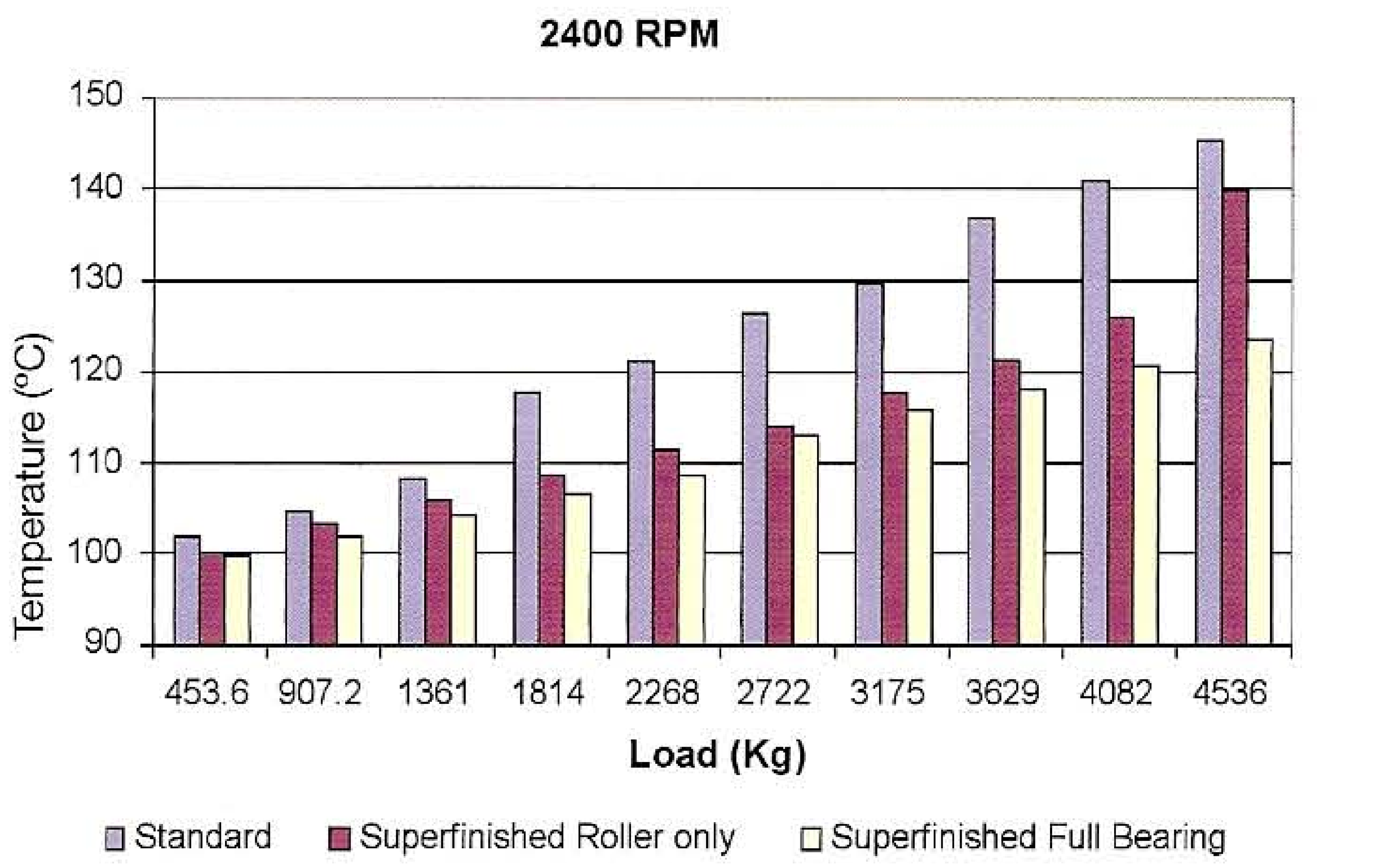
In addition to these two test rigs, there are several other weapons in the tribologist's arsenal; some of the more common of these include various multi-specimen test machines, a "pin & vee block test" device, the four-ball wear test machine, various abrasion test machines, fretting test machine, ball-on-three disk (BOTD), and the four-ball extreme pressure test machine. These and other machines are used in tribology laboratories worldwide, and frequently are the products of the Falex Corporation.

Test Sources and Venues

It should be remarked here that close-mouthed Formula One teams do not generally reveal the results of their testing work in specialized areas like this one, but, in many cases, the US military does, and even supplies this information in trade journals, such as Amptiac Quarterly. A number of the test results summarized in the previous article are from these publications – apparently, Formula One is now more security-conscious than even our Armed Forces! Nevertheless, in the absence of Formula One test results, there are still plenty of other valuable places to draw information from, such as NASCAR and other racing series, various car manufacturers, as well as the afore-mentioned military sources. Several representative tests and experiments will be discussed in greater detail below, each illustrating a particular facet or application of ISF performance. Full reports of each of the cited tests, along with several others, are available from REM Chemicals, Inc. A complete list of referenced sources is included.

Temperature Reduction on Spherical Roller Bearings

The Torrington Company, now a division of Timken, performed a series of tests on its own proprietary SRB test equipment. Equipped with variable speed, this rig ran at 1200, 1800, and 2400 RPM. Applied loads ranged from 1000 to 11,000 pounds.



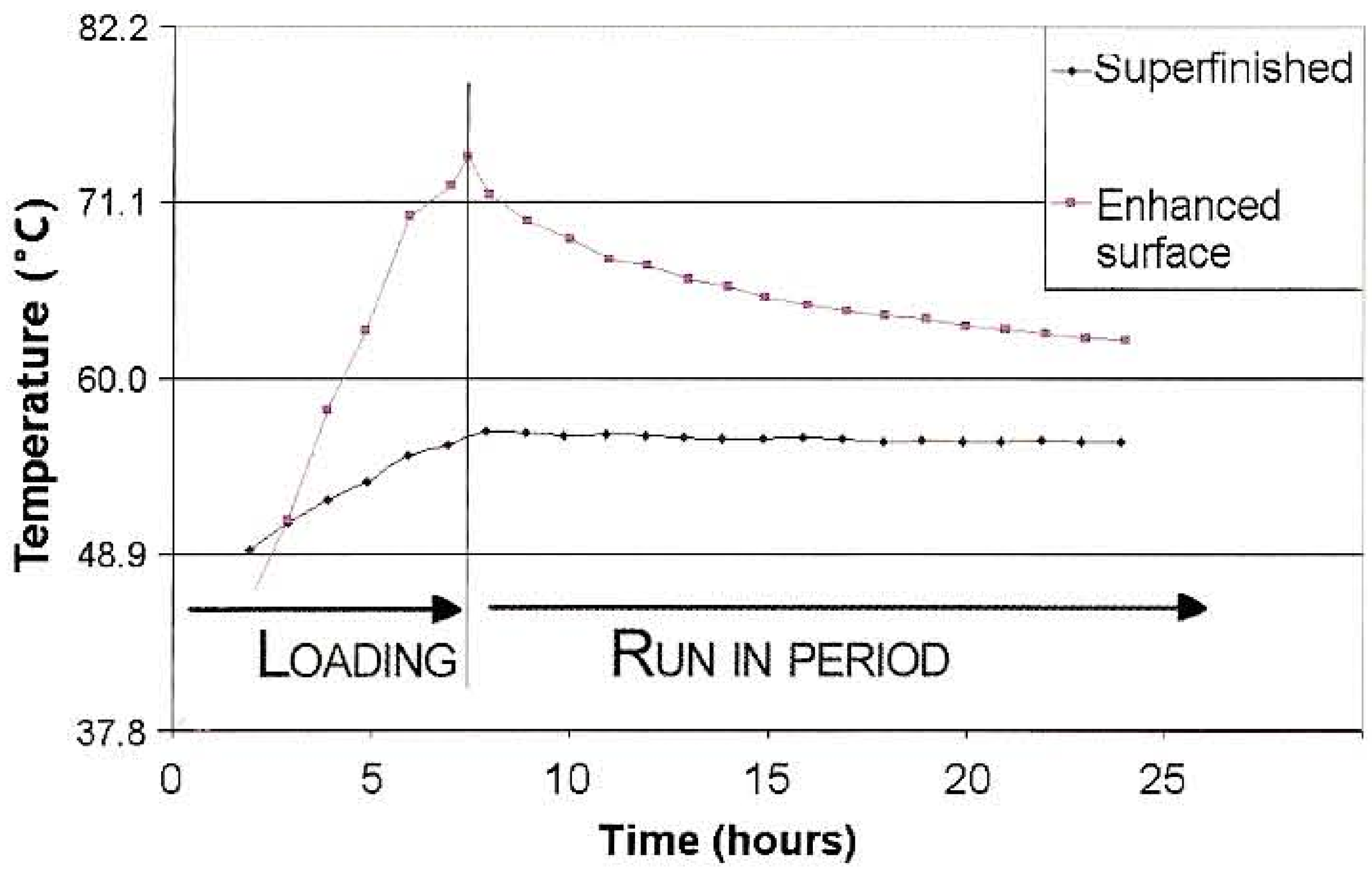
The test results are perfectly consistent with ISF theory; at light loads, where the surface film on an untreated bearing would remain essentially intact, the ISF process bearings only ran slightly cooler than standard product. As the load increases to between 4-5,000 pounds, the ISF bearings start to exhibit markedly lower temperatures. By the time the full load of 10,000 pounds was applied at the maximum speed of 2,400 RPM, the ISF treated bearings were running fully 37 degrees F cooler than their untreated counterparts.

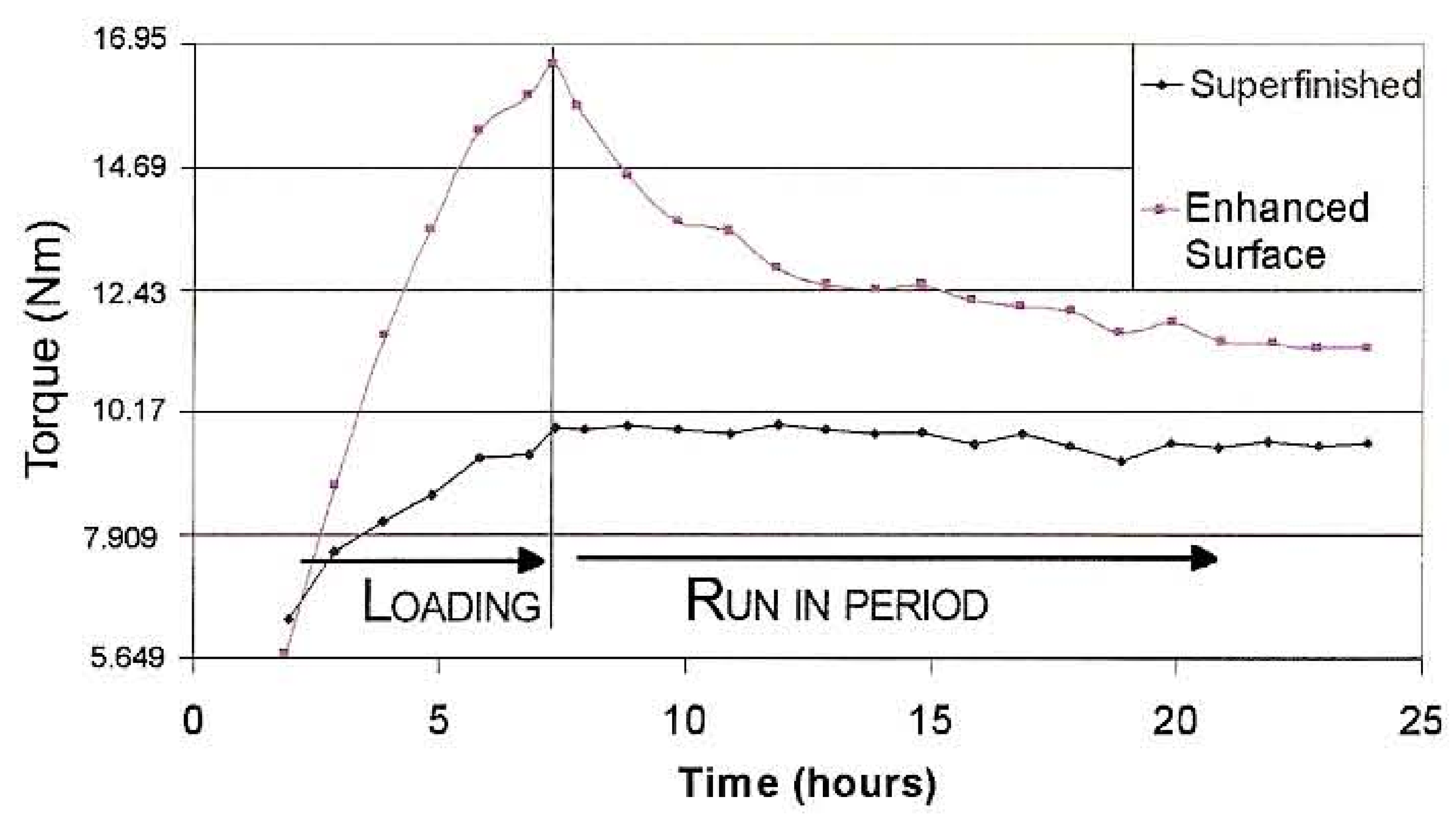
The greatest effect occurs when a complete bearing is processed, not just the rollers. At very high loadings, the bearings that only had the rollers treated are beginning to return to the performance of the untreated units; clearly at this point asperities on the races are breaching the lubricant film at these very high pressures. By contrast, the temperature improvement increases progressively with the fully treated bearing units. The next test will illustrate more clearly why this is so.

Temperature and Friction Reduction of Roller Bearings

The Timken Company shares US patent number 5503481 ("Antifriction bearings") with REM Chemicals, Inc. This development was an outgrowth of an intensive research program conducted by Timken on ISF processed roller bearings. In particular, Timken was interested in the effects of ISF on run-in time, especially when compared to their "enhanced surface" roller bearings that already had additional fine honing to reduce the break-in period. This honing actually brought the best of these bearing surfaces near to the ISF range of approximately three microinches for this application. Unlike ISF, however, the honing and grinding was still producing the directional surface texture, replete with the same sharp peak and valley asperities, that is characteristic of all abrasive techniques.

In the process of conducting these tests, Timken discovered that the surface plasticity of the ISF treated surface was much lower than even the most finely "enhanced surface" bearings they had produced by normal methods. While their best "enhanced surface" bearings would follow a typical break-in cycle, the ISF processed bearings neither required nor produced any break-in whatsoever. The lower surface plasticity of the ISF treated bearings also allowed them to accept higher loadings even as they ran cooler. Essentially, the more uniform, non directional surface of the ISF bearing was displacing itself less under load, so there was much less heat being generated from the internal friction of the bearing material working against itself. The time and temperature chart below illustrates this relationship nicely.



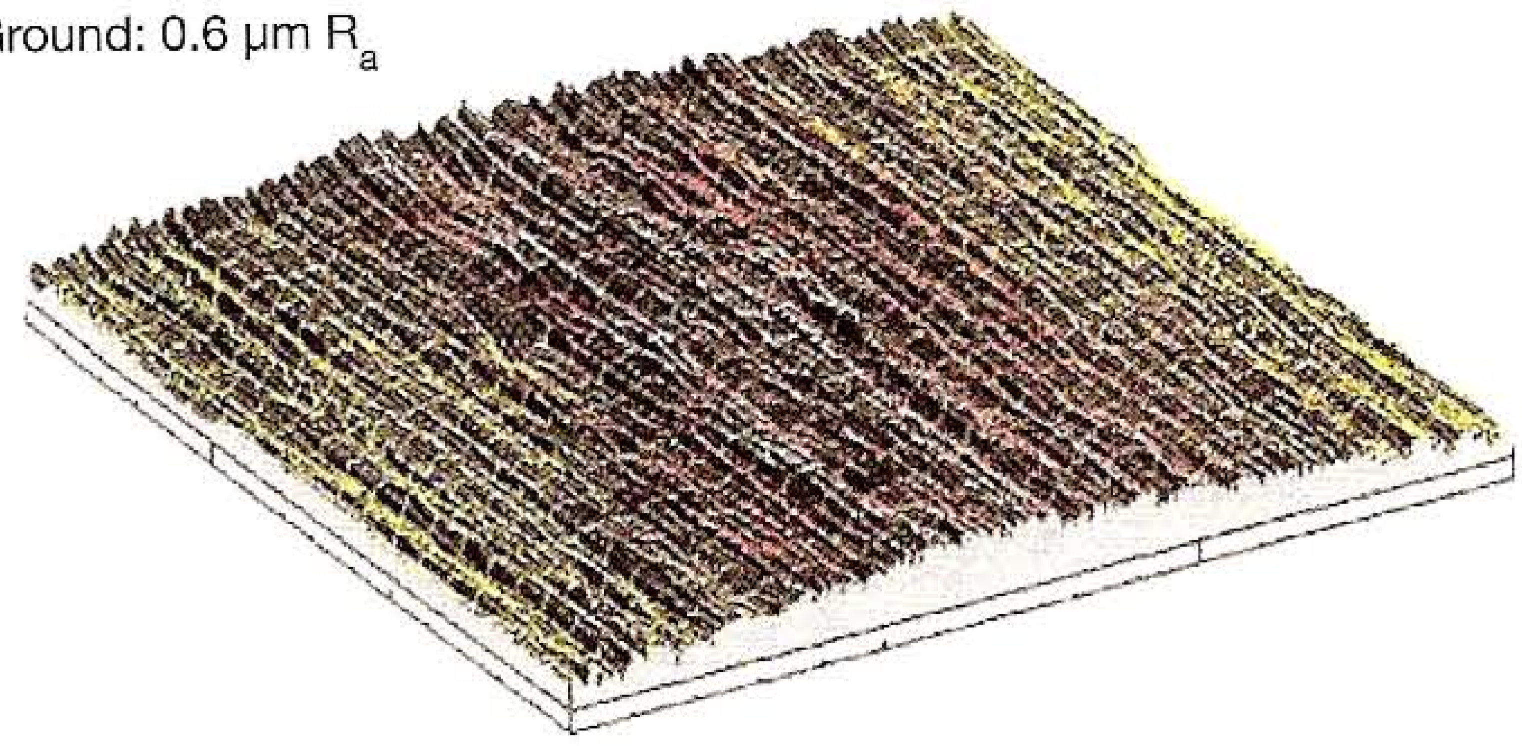


"In this test the ISF treated block shows almost no weight loss or wear whatsoever"

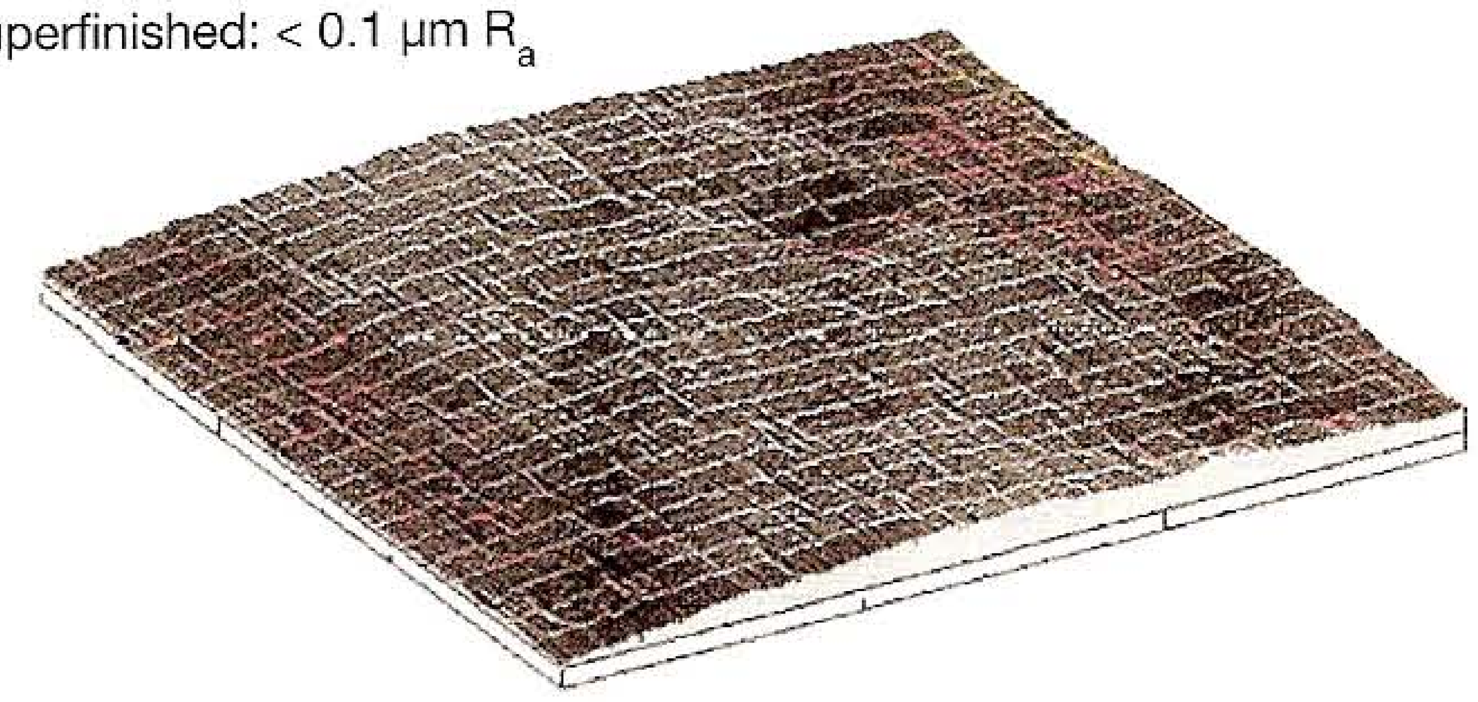
Friction and Wear Reduction Test

This set of experiments were set up as classic "block-on-ring" tests to compare tribological contact performance between an ISF treated surface and a conventional ground surface, replicating normal sliding friction. In this case, the 50 mm ground rings and blocks had a roughness of .06 micron; the superfinished components were brought to less than 0.1 micron.

Ground: 0.6 μm R_a



Superfinished: < 0.1 μm R_a



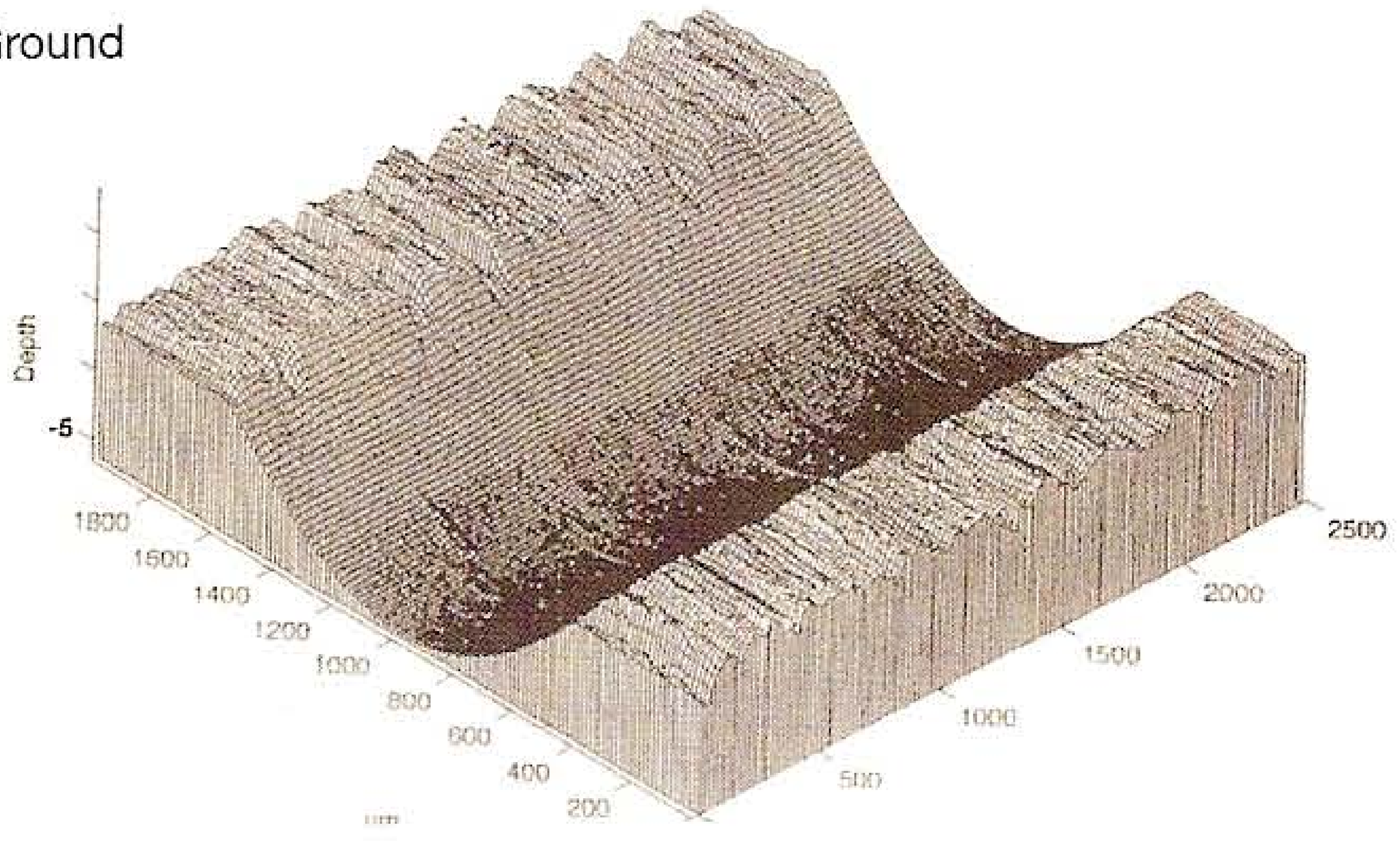
SAE 20 reference life test oil was used as the lubricant for these experiments. The test was run for six hours starting at ambient temperature at a rotational speed of 800 RPM. Both the frictional force and sump temperature were monitored throughout the tests.

	Superfinished 0.058 μm mm R_a	Ground 0.58 μm mm R_a
Friction Force of Sliding Contacts (Newtons)	6.1	57.6
Temperature (°C)	46.8	65.1

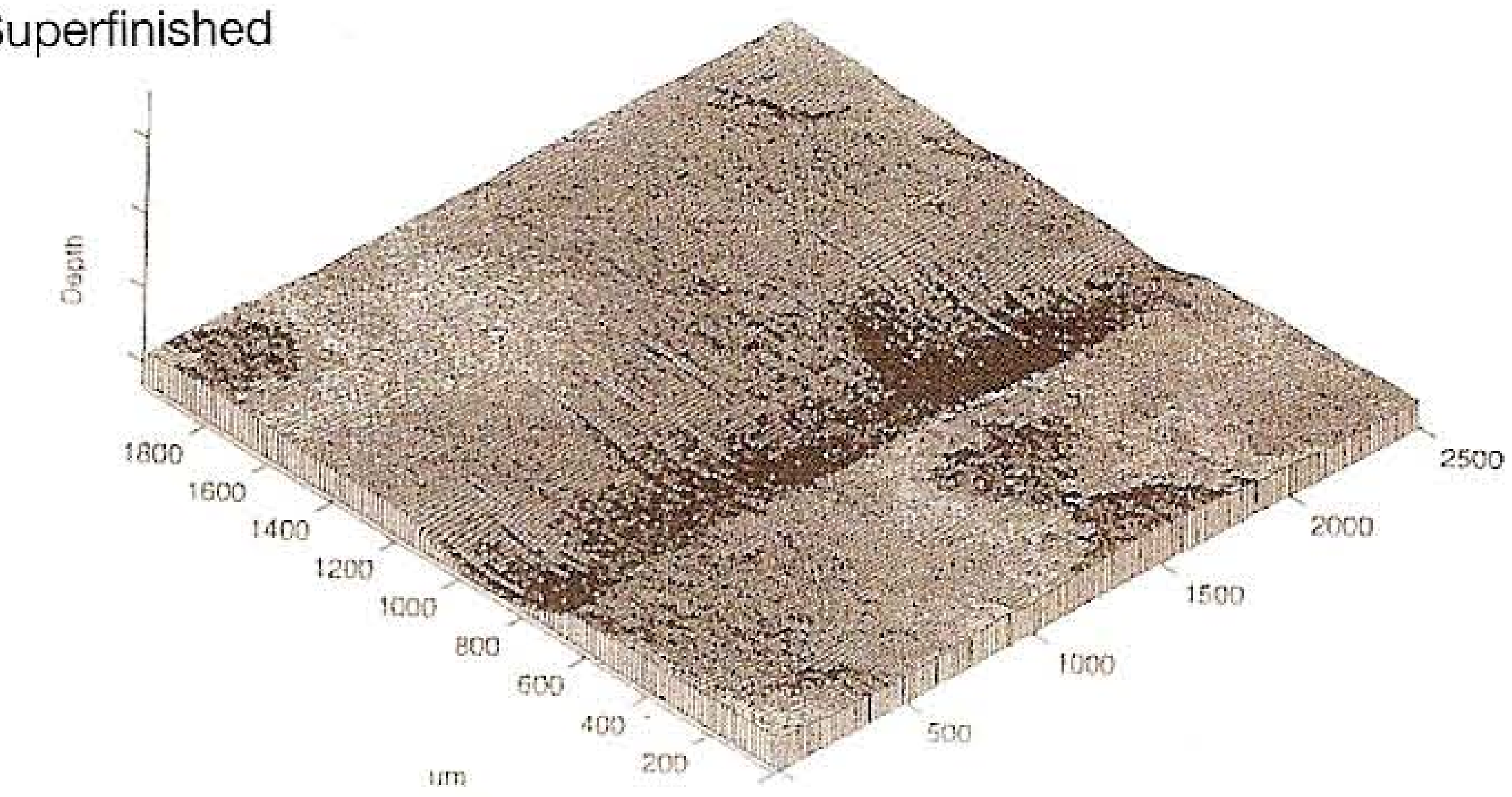
Friction and temperature results for Falex Ring on B

As seen from the charts of the two different block and ring combinations, the friction force is ten times lower with the superfinished set, which also produced a sump temperature 20 degrees C less than the unfinished set.

Ground



Superfinished



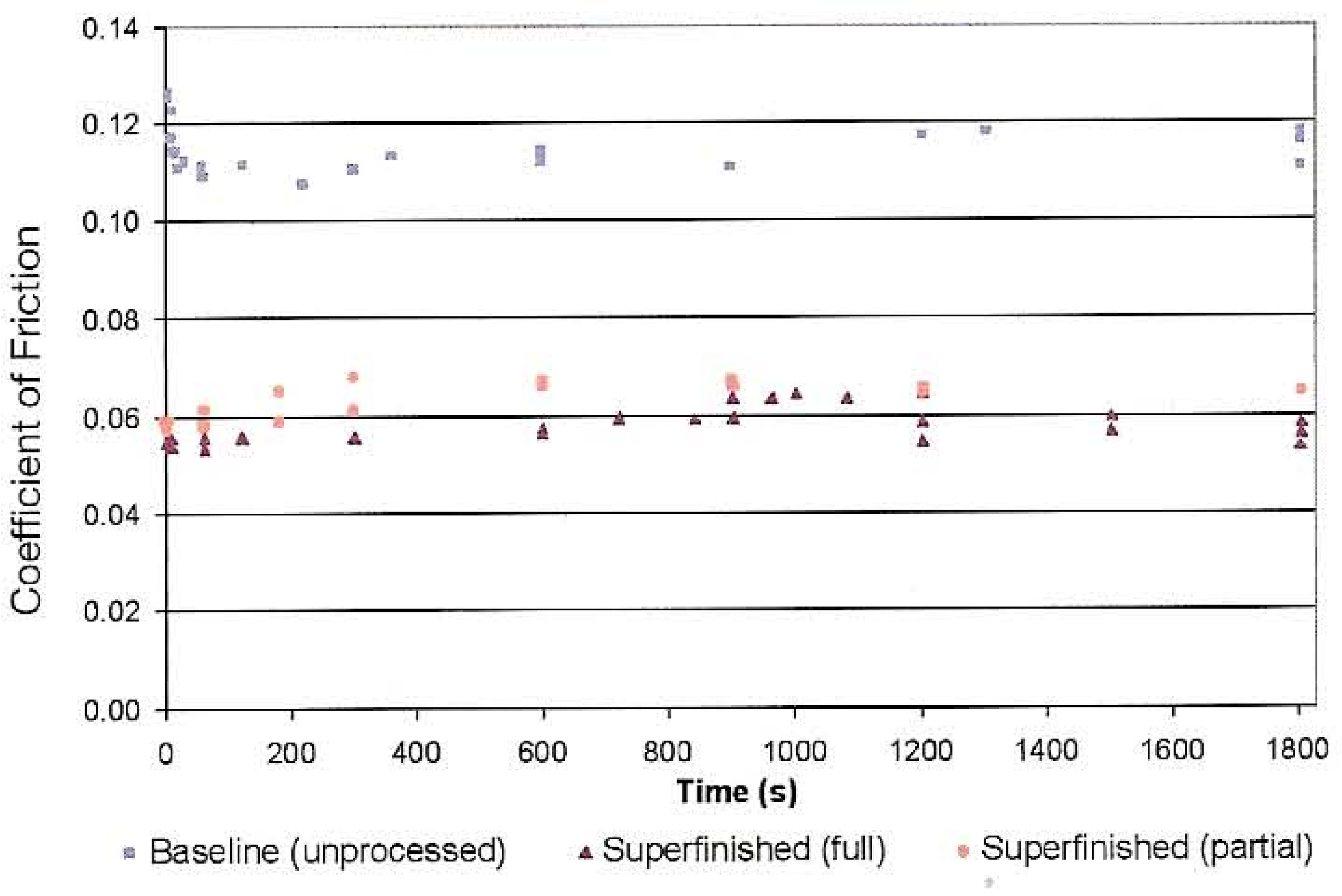
The illustration above demonstrates the vastly improved wear pattern on the blocks after the test was completed. The wear pattern on the ground block is extreme, and accompanied by significant weight loss, whereas the ISF treated block shows almost no weight loss or wear whatsoever.

Wear and Friction Reduction Test – Falex 3 Ball on Flat

This test was conducted by a transmission manufacturing company to validate the ISF process. The balls were 0.5" 52100 steel with a surface hardness of 64 Rockwell C; the 1.6 inch diameter disks were 8620 steel, with a hardness of 60.7 Rockwell C. The surface finishes were one microinch for the balls, and 27 microinch for the disk. The experiment was run at a total load of 300 pounds at 300 RPM (equivalent to 64 meters per second). The initial Hertz stress was set at 438 ksi, with a maximum sheer stress of 136 ksi. The lubrication used was an SAE extreme pressure synthetic with a kinematic viscosity of 119.7 at 40 deg.C, and 16.68 at 100 deg.C. Testing temperature was 20 deg.C at the start, with the tests sustained for 30 minutes.

The ISF components were finished into different conditions, some being fully finished with cut and burnish cycles, and others partially finished without a burnishing cycle. Surface conditions of the two finishes were 1.6 and 2.9 microinches respectively.

▶

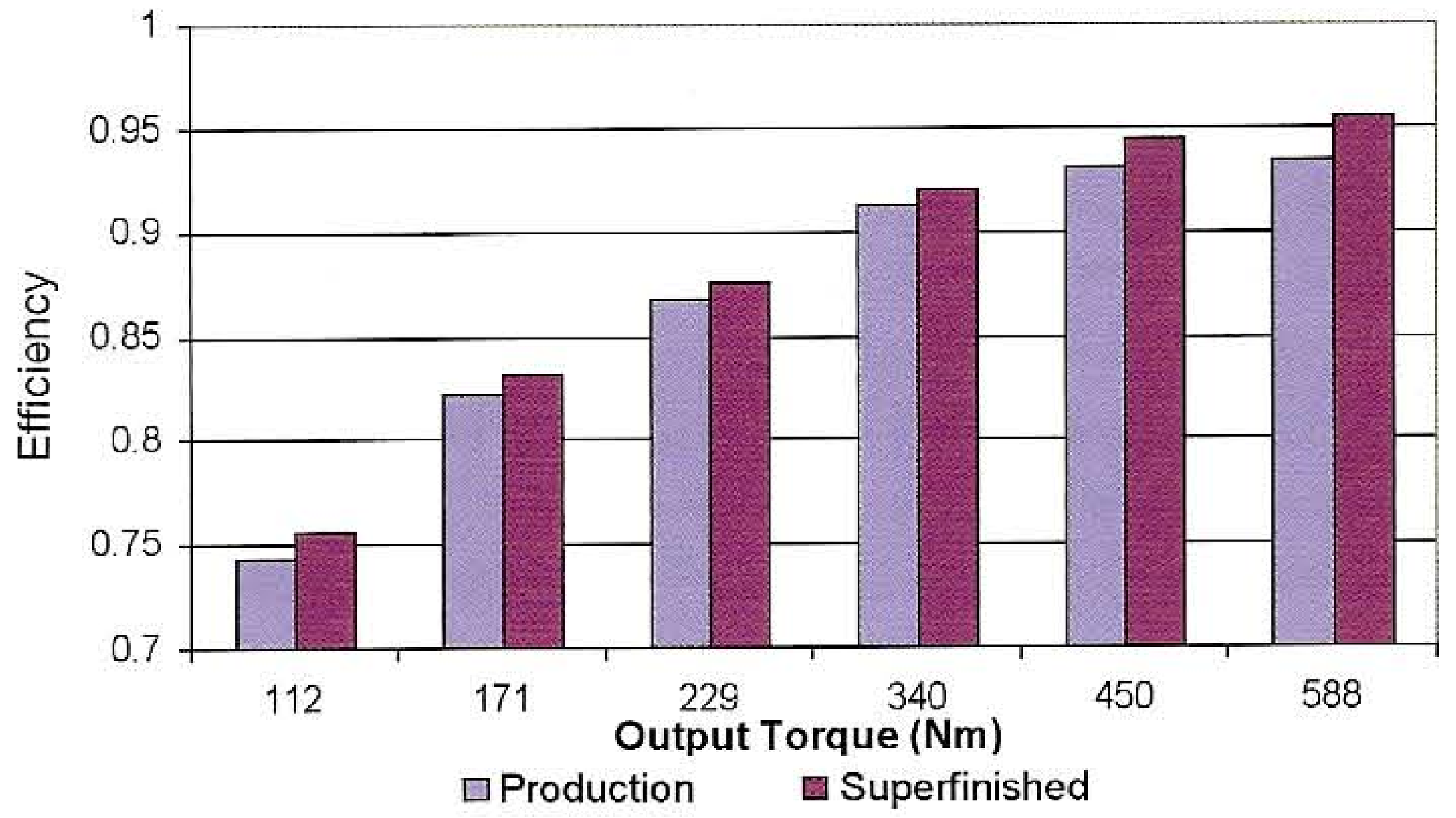


The test chart reveals that ISF processed balls and rings had a 30 to 40 percent reduction in their coefficient of fiction, and these parts had a reduction of wear volume of up to five times less than the baseline components. While they were not quite as efficient as the fully-finished pieces, the partially-finished components still out-performed non-ISF pieces by a wide margin.

Rear Axle Ring and Pinion Test

This next test, which was conducted by Ford Motor Company, had its results included in 'The Handbook of Lubrication and Tribology Volume 1'. This test is of an isolated component set, making it possible to assign a specific, precise, improvement value for the ring and pinion alone; it should be borne in mind that complete drivetrain systems benefit similarly at all points of operation, and that the gains are cumulative. For this test, rear axle ring and pinion units were superfinished to an Ra of .07 um. Typical highway cycles were replicated on a chassis roll dynamometer.

The following illustrates the relative efficiencies of the REM ISF processed gears vs. the standard production items at 1000 RPM.



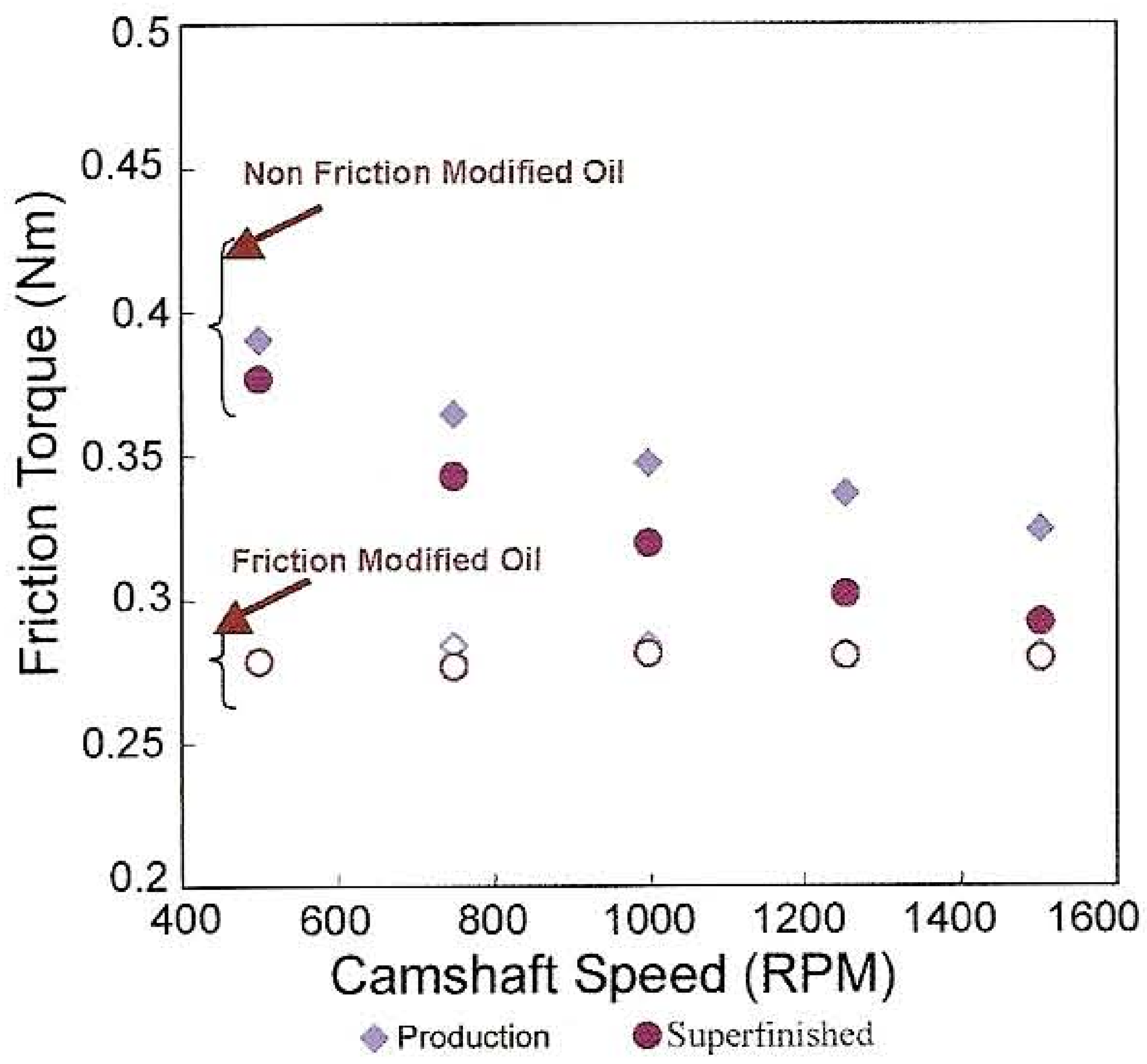
Operating temperatures were recorded as well; engineers noted the nearly exponential change in temperature differentials as progressively higher loads are applied. A one-half percent improvement in overall fuel economy is attributable to superfinishing this one component set alone. The reduction of the operating temperature underscores the greater efficiency of the ISF processed units. See US patent application 2005/0202921 for more details.

> "The friction modifier in combination with ISF processed surfaces would make for efficiency gains"

Valvetrain Efficiency Improvements

A Ford research laboratory conducted this study to investigate the effect of ISF processing on valvetrain components. Standard nitrided steel production cams and tappets were given a break-in cycle before the test, and then compared to ISF-treated parts. Two oils were used; one was a standard SAE 5W-30 lubricant, and the second was a special version of the same oil with an added friction modifier. The tests were run at a speed of 400 to 1600 rpm.

The friction torque was measured for both the ISF and the production gears with both types of oil. See the figure below.



Once again, with a standard lubricant, a familiar pattern arises: the difference in efficiency improves progressively with rotational speed, with the ISF cams and tappets outperforming conventionally-processed components, even after a break-in is applied to these pieces. Their lubricant film is starting to be progressively breached as revolutions climb, and cam-to-tappet shock increases. The special friction modifier added to the oil was clearly effective in preventing this – the production components are performing nearly as well as their ISF finished counterparts with this lubricant. Given the efficacy of the modifier, it would have been an interesting exercise to repeat the test with a yet lower viscosity, similarly modified, oil to take advantage of the improved Lambda ratio that the modifier clearly allows. The obvious implication is that if the fiction modifier is viable for general use, it, in combination with ISF processed surfaces, would make possible a general lower-level of viscosity and the attendant efficiency gains.

It is important to note that optimum performance benefits are expected when both mating surfaces (cam and insert) are superfinished to a <0.025 µm Ra. Whereas racing teams are superfinishing their valvetrain components to <0.035 µm composite Ra, the composite Ra in this study was approximately 0.55 µm. It would be interesting to repeat this testing with both the cam and the inserts superfinished to a <0.025 µm Ra.

Effect of Surface Characteristics and Lubricants on Spur Gear Efficiency

This was an extensive study conducted by General Motors Powertrain Division in conjunction with Ohio State University that required a full month to complete. The scope of this investigation was not confined to ISF surfaces alone, or even a single lubricant. Instead this was a broad-based study to examine several different surface finishing and coating techniques and their interaction with various lubricants.

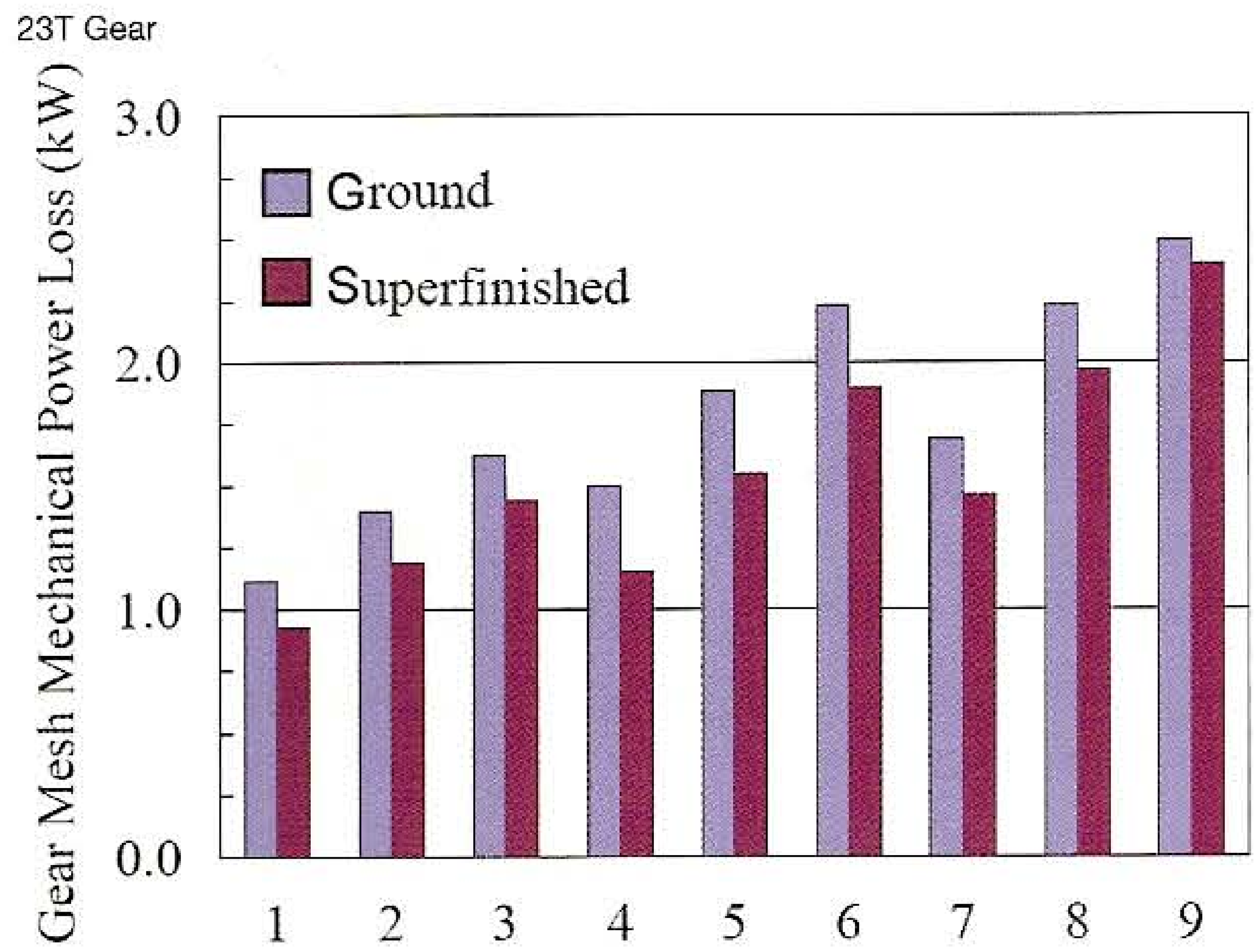
The testing was performed on a four-square gear test rig. Extreme care was taken with this apparatus to ensure repeatable, accurate results. Use of a digital torquemeter kept the repeatability of torque readings well within +/- .15 Nm. Both gearsets were identical with a one-to-one ratio; since this doubles the measurable friction torque, it provides increased accuracy in the same measure. A jet lubrication system was employed along with a dry sump to minimize turning losses and ensure consistent characteristics of a lubricant being sprayed on the gears. The temperature and pressure of the synthetic 75W90 oil used as the lubricant was kept consistent through the use of an external heating and cooling system.

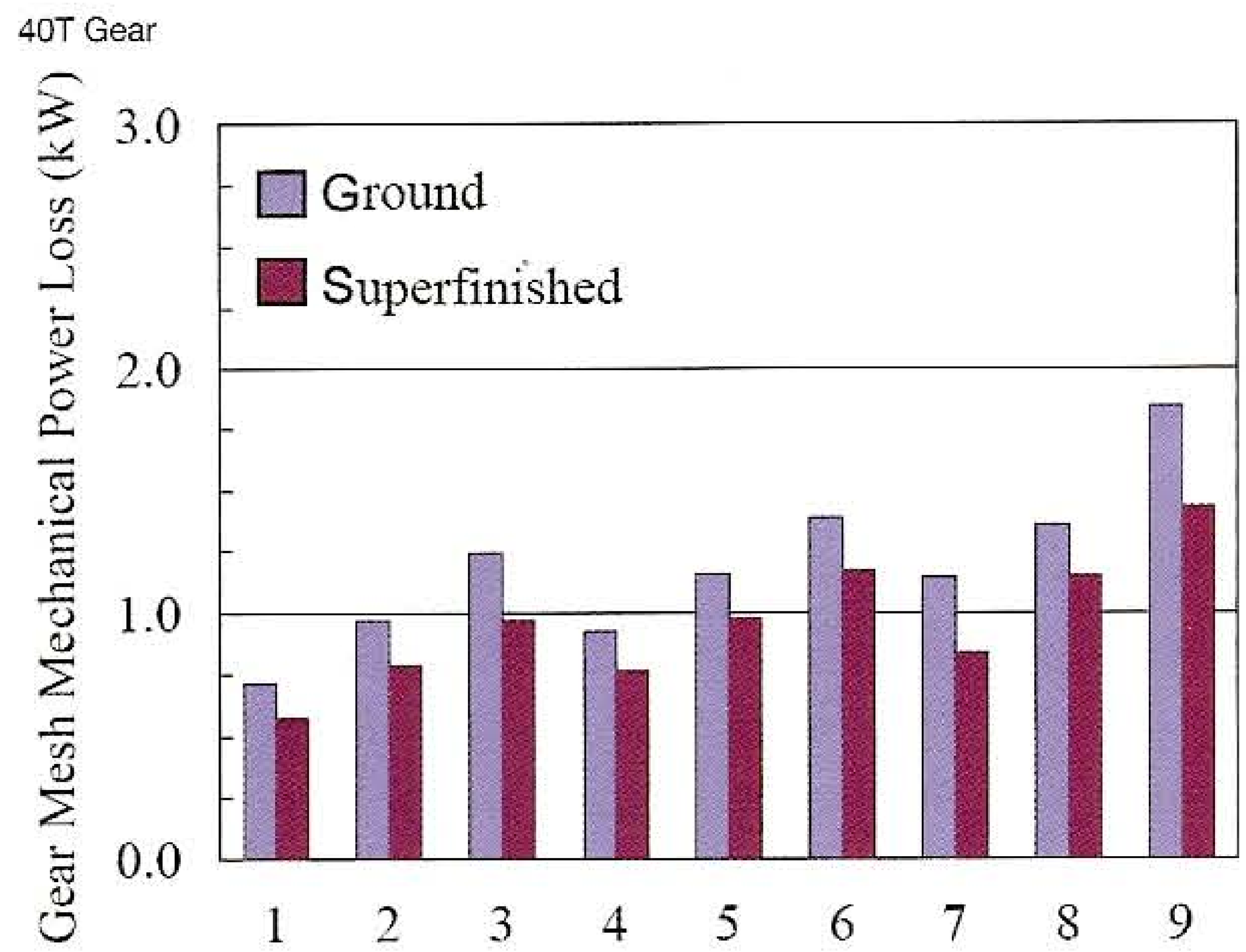
The gears themselves received the same kind of attention to ensure the validity of the tests; both fine pitch and course pitch gears were used, with the fine pitch gears adjusted dimensionally to achieve the same bending strength as the course pitch gears. Because of the lower sliding velocity associated with fine pitched gears, power losses are generally lower.

Parameter	Fine Pitch 40T	Coarse Pitch 23T
Number of Teeth	40	23
Operating Diametral Pitch	11.104	6.39
Diametral Pitch	10.955	6.43
Module	2.319	3.950
Operating Pressure Angle	26.5	25.9
Pressure Angle	28	25
Face width, mm	26.67	19.4818
Contact Ratio	1.40/1.45	1.53/1.56
Tip Thickness, mm	1.1176	1.2446
Tip Clearance, mm	0.5334	0.6096
Backlash, mm	0.114/0.191	0.119/0.196
Operating Center Distance, mm	91.501	91.501

Test	Speed (rpm)	Torque (N-m)
1	6,000	406
2	6,000	542
3	6,000	677
4	8,000	406
5	8,000	542
6	8,000	677
7	10,000	406
8	10,000	542
9	10,000	677
10	10,000	0
11	8,000	0
12	6,000	0
13	4,000	0
14	2,000	0

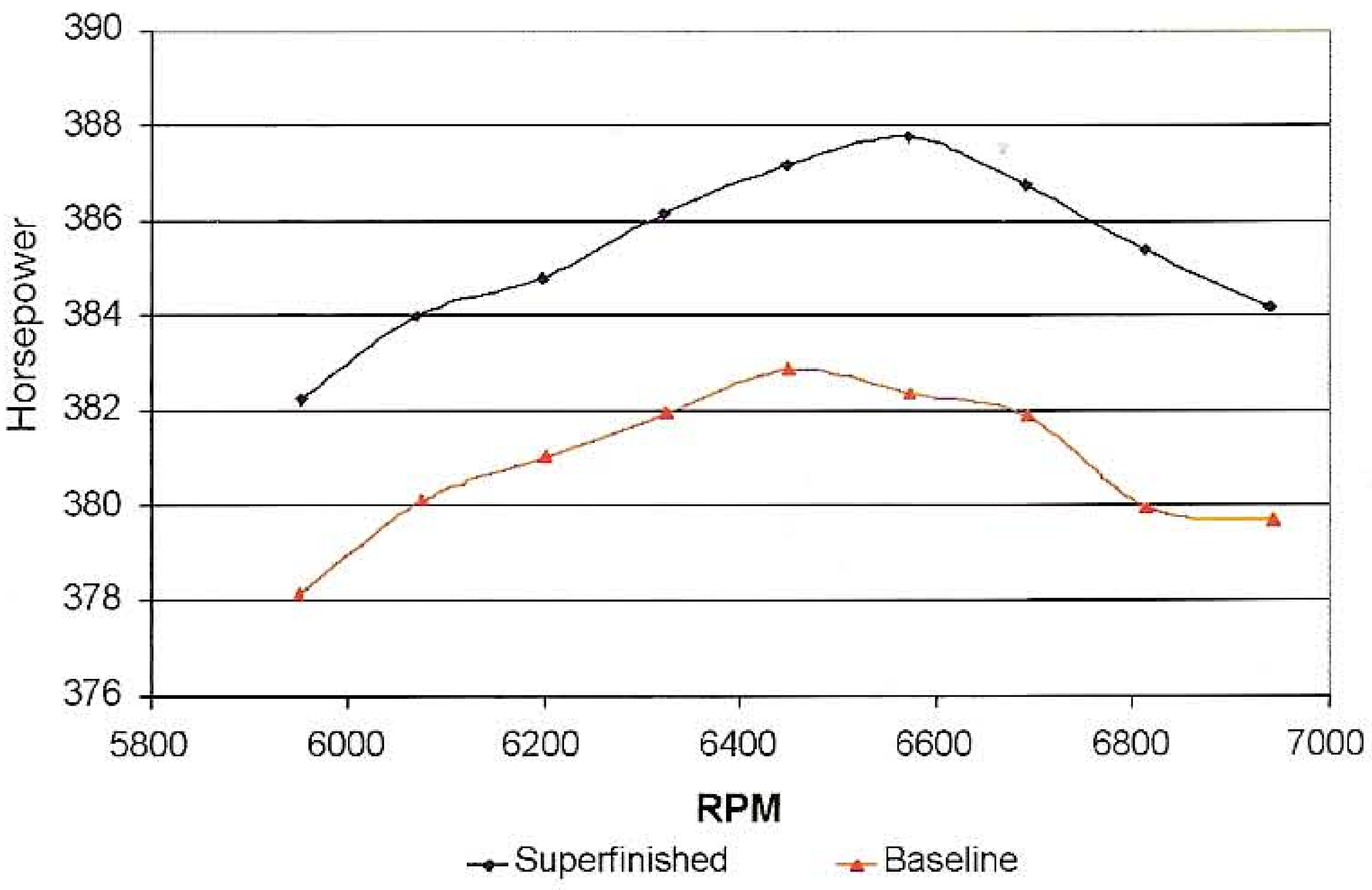
Relevant findings of this investigation establish three main principles. One, the lower sliding velocity of fine pitch gears increases efficiency by roughly 34 percent over course pitch gears. Two, an improvement of approximately 17 percent for both classes of the gears was achieved through ISF treatment, which was consistently the best performer of the groups tested. Three, "spin loss" at low loads can be reduced with lower viscosity lubricants, but fully loaded losses are not significantly affected.





NASCAR Transmission Study

Two T101 transmissions as used in Nextel Cup competition were run under load sequentially for this test. One transmission had standard ground gears; the other was equipped with ISF-treated gears. All possible steps were taken to ensure uniformity in the testing process. With each test, the engine and transmissions were preheated to the same operating temperature; the engine was brought to the same normal operating temperature when running with the applied load; drive shaft tangles were monitored rigorously. Third gear was used during this procedure, which was conducted by an independent testing facility.



It can be seen from the graph that approximately one percent more power was recovered from the transmission with ISF-treated components. Ford engineers also recorded a significant reduction in tempurature.

Temperature Reduction in S-76 Helicopter Transmission

Sikorsky Aircraft carried out this trial to quantify temperature and vibrational noise reduction on its new S-76 C++ main transmission. Surface roughness measurements indicated that the ISF gears had tooth surfaces with three to five times finer finish when compared to the "fine aerospace grind" that is normally found on these components. After ISF, the second stage bevel gears and the third stage bull and pinion gears, the transmission was run through the Standard Acceptance Test Procedure (ATP) which simulates torque loadings experienced during flight. During this test, oil operating temperature and vibration levels are measured on the transmission. The ISF transmission completed the ATP and then went on to complete a 200-hour endurance test with the same torque loadings used in the ATP. See tables below.

Ground	Bevel Pinions & Gears	Spur Pinions	Bull Gears
	µm	µm	µm
R_a	0.330 to 0.457	0.0406 to 0.432	0.033 to 0.432
R_z	2.032 to 2.921	2.463 to 2.565	2.108 to 2.870
R_{max}	2.769 to 4.242	3.023 to 3.277	3.378 to 3.581

"Motorsport is leading the way to the widespread adoption of mechanisms with ISF processing"

ISF	Bevel Pinions & Gears	Spur Pinions	Bull Gears
	µm	µm	µm
R_a	= 0.089	= 0.076	= 0.076
R_z	= 0.533	= 0.584	= 0.559
R_{max}	= 0.759	= 0.739	= 0.658

Sikorsky engineers recorded a 2.8 deg.C reduction in the "oil out" temperature, a 3.7 dB reduction at the second stage bevel gears, and a 7 dB reduction of the bull gear's first harmonic during the successful 200 hour test.

Conclusion

The experiments described above demonstrate that ISF-treated wear surfaces and bearings create significant improvement in rolling, sliding, and line-to-line contact conditions. The removal of asperities allows for lower viscosity lubricants that absorb less energy, and create less destructive heat for the mechanisms they are used with. The tests described here were chosen to illustrate a number of different conditions of interest to the motorsports community, but they only represent a small portion of the total volume of testing that has been done with isotropic superfinishing. The improvement in the critical Lambda ratio is of great significance: in addition to the benefits of lower friction, heat, and wear, the ISF surface simplifies lubrication problems, and greatly reduces the need for special additives. Accordingly, low viscosity and environmentally friendly lubricants become much more viable.

Current regulations for endurance racing sports cars encourage the ongoing development of highly efficient, low friction engines because of their restricted-output nature. Ultra-high rpm Formula One and MotoGP units also require superior operating surfaces in their prime movers as well – there is an exponential increase in parasitic drag losses at their engine speeds when compared to standard powerplant operating rpm.

In general, advanced working surfaces are now de-rigueur in the upper levels of all forms of racing. As a result, motorsport is leading the way to the widespread adoption of mechanisms with advanced ISF-processing. ■

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