02MSEC-20

The Reduction of Parasitic Friction in Automotive Gearbox and Drive Train Components by the Isotropic Superfinish

William P. Nebiolo
REM Chemicals, Inc.
Southington, CT 06489

Microscopic examination of the traditionally ground tooth surfaces of automotive transmission gears reveals a micro-roughness, and unidirectional pattern corresponding to the direction of the gear tooth grinding operation. This unidirectional grind pattern degrades the performance of the gear by acting as a parasitic, friction-inducing surface. Engine horsepower is lost in the inefficient transfer of power through the drive train caused by this friction. This loss of power can most easily be monitored as heat generation; however, other gearbox characteristics are indicators of reduced performance. These include, but are not limited to, high Hertzian contact stresses on the complementary gear tooth flanks; gear tooth flank metal loss through wearing, pitting, spalling or breakage as well as increased torque requirements for complementary gear meshing.

By refining the surfaces of the teeth of a transmission's gears to achieve the Isotropic Superfinish (ISF), the gears require no break-in period, produce a cooler gearbox operational temperature, almost completely eliminate gear tooth wear, pitting, spalling or breakage, diffuses Hertzian contact stresses during gear meshing, and reduces rotational torque requirements. These improvements synergistically combine to reduce parasitic loss of engine horsepower through the gearbox, resulting in a more efficient transfer of power from the engine to the wheels.

This paper will review the chemically accelerated vibratory technique used to generate the ISF on automotive gearbox, and drive train components. Additionally, before and after testing results of traditionally ground and ISF components will be presented describing the aforementioned benefits.

Traditional Gear Tooth Finishing and the Ground Surface

By far, the most common technique utilized to impart the final surface finish to the teeth of automotive transmission and rear end gears is conformational grinding.[6] Gear teeth are cut into forged gear blanks during a hob and shave operation. Following a heat treatment step the gear's teeth are then ground to generate the final tooth geometry, to correct any heat treatment distortion and to produce the final surface finish. See Photo 1.

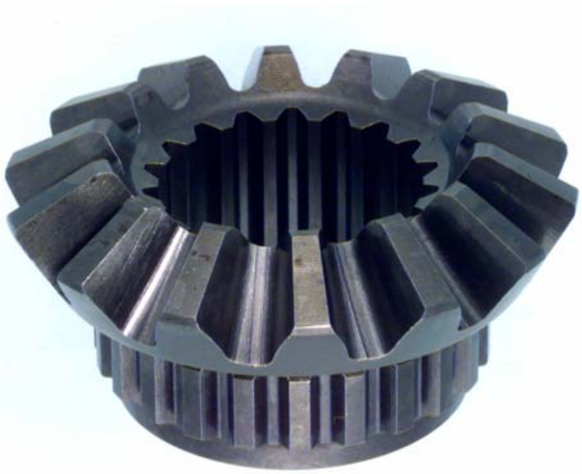


Photo 1; Grinding lines are clearly visible on the flanks of the gear teeth in this traditionally finished bevel gear.

A microscopic examination of the surface of a ground gear tooth reveals a directional surface pattern consisting of parallel rows of grinding line asperities.[6,10] See Photo 2

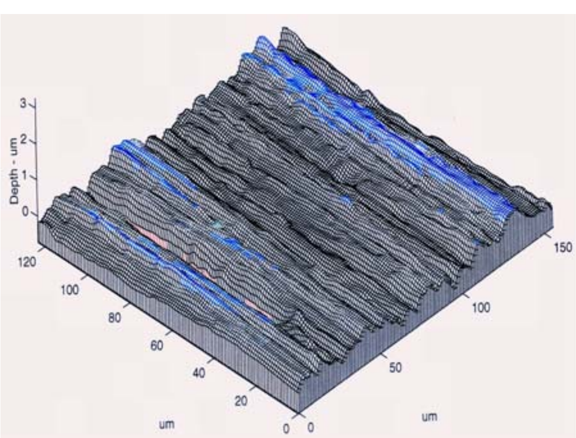


Photo 2; shows a 3-dimensional, 20X magnified view of the surface of a gear tooth that has been ground to a final surface finish of R_a = 35 µinches. Note the parallel rows of surface asperities corresponding to the directional pattern of the grinding operation.

The parallel rows of asperities are of course, the residual pattern left by the conformational grinding step.

The Isotropic Superfinish

It has been reported[1,2,6,7,8,11] that metal-to-metal contact areas such as bearing surfaces and gear tooth flanks, if refined by chemically accelerated vibratory finishing[4,5,6] have a resultant Isotropic Superfinish (ISF). The ISF is characterized by a random, non-directional surface topography, a surface roughness of $R_a \approx 1.5$ µinches (0.04 µm) and a mirror-like appearance. See Photo 3.

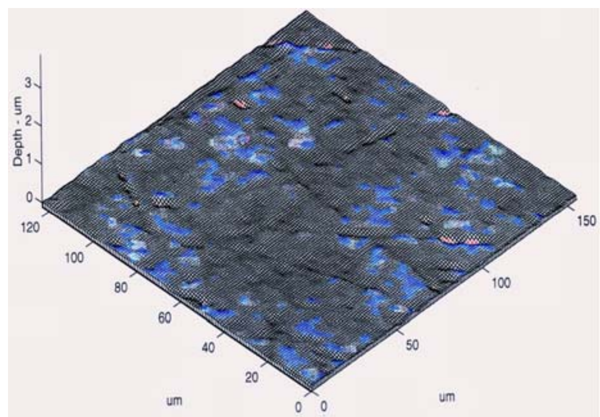


Photo 3; Shows a 3-dimensional, 20X magnified view of an ISF gear tooth. The R_a = is 1.5 µinches. The surface has been produced by chemically accelerated vibratory finishing. Note the elimination of the directional surface asperities (grind lines) when compared to Photo #2.

Generating the Isotropic Superfinish

According to the techniques described by[4,5,6,10] the generation of the Isotropic Superfinish (ISF) occurs in a chemically accelerated vibratory finishing process. The gears to be refined are placed into a vibratory bowl or tub containing a high-density, non-abrasive media[5].

See Photos 4 and 5. The process consists of two steps that are conducted sequentially within the same vibratory unit.

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

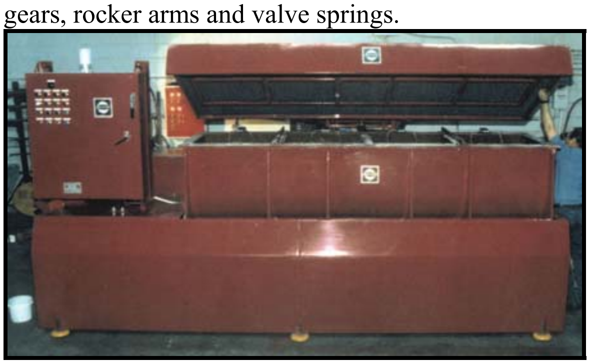


Photo 5; Shows a traditional vibratory tub. Ideal for processing long parts such as splines, camshafts, crankshafts and pinion shafts.

During the initial or refinement step, active chemistry is added to the vibratory unit.[4] Testing has shown that the active chemistry does not hydrogen embrittle the processed steel.[3] The active chemistry reacts with the gear to produce a thin; approximately 1-micron, conversion coating on its surface.[6,10] The conversion coating is physically softer than the basis metal upon which it is formed. As the gear interacts with the media in the vibratory unit, the conversion coating is physically rubbed from the surface to expose clean metal beneath.

Since the asperity peaks are elevated, they are rubbed preferentially.[6,10] The recessed valleys between the rows of grind line asperities are untouched by the media, therefore, the conversion coating remains intact and the valleys remain unaffected.[6,10] The conversion coating then reforms at the freshly exposed areas and the process repeats.[6,10] As a function of continuous vibratory time, the asperities are gently leveled, leaving only the deepest valleys, thereby, generating the improved micro-finish.[6,10]

Once the required micro-finish is achieved, the second step, referred to as the burnishing process, is conducted sequentially in the same vibratory unit using the same media.[6,10] A soap-like mixture is introduced[6,10] to the vibratory unit. After a relatively short period of time, a mirror-like polished finish is achieved.[6,10] Cost savings are realized through the ability to process parts in mass, thereby, producing the superior ISF at per piece costs lower than conventional machining and grinding operations. See Photo 6.

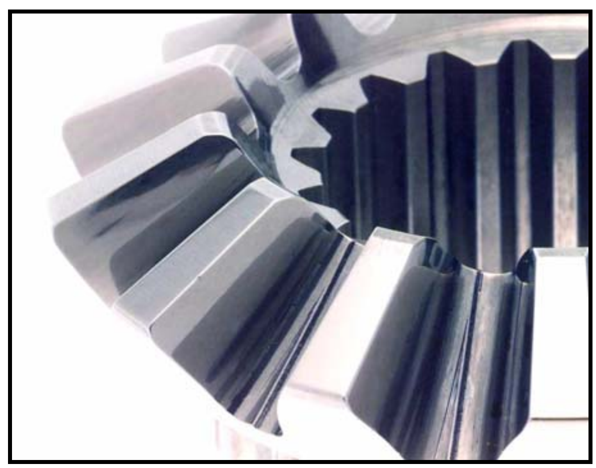


Photo 6; Shows a close-up of the teeth of the bevel gear as shown in Photo 1. The gear was processed using the described chemically accelerated vibratory finishing technique to generate the Isotropic Superfinish. The resultant surface has an is R_a of 1.5 μinches. Note when compared to Photo 1, that all grind line asperities have been removed.

Engineered metal-to-metal contact surfaces such as bearings, bearing races, gear teeth, push rods and cams are mechanisms for transferring energy in the automobile. These items have mechanical contact surfaces that function by rolling, sliding, pushing or meshing with complementary contact surfaces. Asperities on these surfaces introduce a degree of friction (i.e. inefficiency) into the mechanical transfer of energy that produces an energy loss most noticeable as heat.[2,6,9,10,11] However other energy transfer losses can be noted as increased rotational torque requirements[2,7,11], and loss of horse power[10].

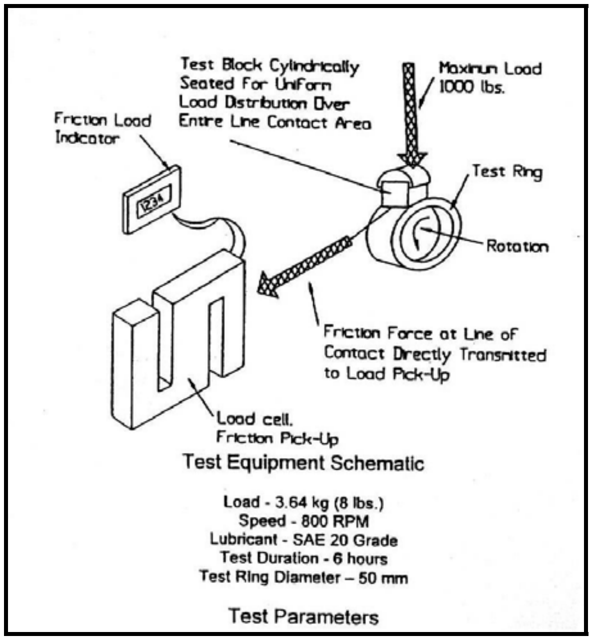
Component durability is also affected by asperities. This is noted typically as scoring pitting and wear.[6,7,10] Since grind line surface asperities are the major source of mechanical friction their efficient removal results in a number of engineering advantages to the operation of the metal-to-metal contact surfaces and helps to maintain, not minimize, the efficient transfer of energy through the automobile.

Monitored Frictional Heat Reduction and Monitored Frictional Torque Reduction Resulting from the Isotropic Superfinish.

It is widely accepted that when placed into operation for the first time, metal-to-metal contact surfaces; such as gear teeth, undergo a break-in cycle.[2,6,7,10,11] During the break-in cycle the gears are worn-in; or more specifically, the surface grind line asperity peaks are abraded away by complementary gear tooth peak-to-peak contact.[2,6,7,10,11]

In a recent evaluation, a major bearing manufacturer[7] monitored the performance features of two functional metal-to-metal surfaces by means of an ASTM D2714 and D2792 block-on ring test. See Schematic 1. This test is also used for determining the load carrying capacity of lubricants and additive systems[7].

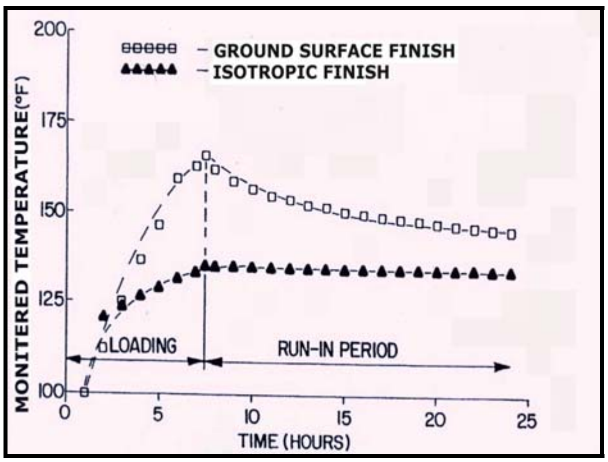
In the experiment, the test specimens were Isotropic Superfinish (ISF) by use of the chemically accelerated vibratory finishing technique described earlier.[6] A second set of specimens; the control standard, were tested using the company's traditional, as-ground, final finish surface condition. During the evaluation, the sump temperature of the lubricant system and the frictional force as a function of bearing torque were monitored.[7]



Schematic 1; Shows a simplified schematic of the block-on-ring apparatus.

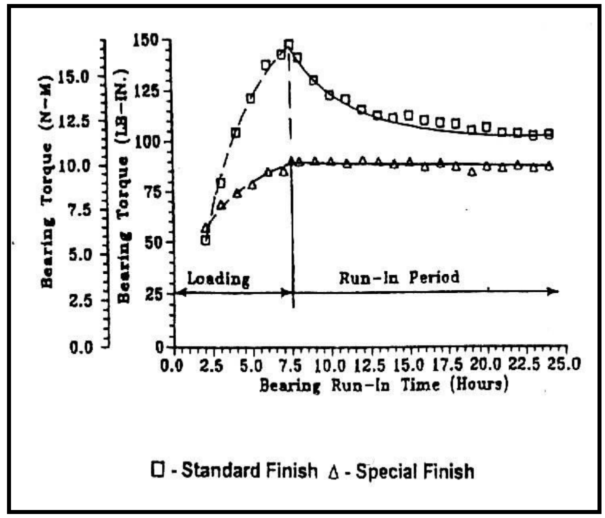
Concomitant to the mechanical abrading of the asperities on the ground specimens, was a higher bearing temperature.[2,6,7,9,10,11] There was a definitive temperature spike associated with the completion of the loading phase of the break-in cycle of the as-ground test specimens.[2,6,7,9,10,11] Once the metal-to-metal contact surfaces were broken-in; (i.e. asperity peaks removed,) the monitored temperature dropped to a lower, steady state operating temperature.[2,6,7,9,10,11]

When the temperature of the ISF specimens was monitored, it was noted that there was just a gradual rise to a steady-state operational temperature during the loading phase of the cycle.[2,67,9,10,11] There was no temperature spike because there was no break-in. Lastly, the final operating temperature was significantly lower, 130°F versus 150°F when compared to the traditionally ground specimens. This clearly indicates the capability of the ISF Process to reduce friction as monitored by heat generation.
See graph 1.



Graph 1; Shows the temperature curves for both the traditional ground specimen and the Isotropic Superfinish (ISF) specimen. Note the temperature spike for the ground surface corresponding to the end of asperity break-in and the complete absence of a spike for the ISF specimen.[2,6,7,9,10,11]

The results of the monitored frictional force showed a nearly identical graph set.[2,7,11] It was noted that the level of applied torque to the traditionally ground specimens had to be increased during the loading phase as a function of asperity peak abrasion and to counteract the increase in frictional resistance.[2,7,11] Torque spiked at a value of 17.5 Nm at which point the asperities were broken-in.[7] The break-in cycle was continued until a final steady state operational value of 12 Nm was achieved at the 25-hour mark.[7] See Graph 2.



Graph 2; Shows the break-in period torque curve for a traditional ground surface and the Isotropic Superfinish (ISF).. Note the torque spike for the traditionally ground surface and the absence of a spike for the ISF.[2,7,11]

Conversely, the applied torque value during the loading phase for the ISF specimens showed a gradual rise to a steady-state operating condition of 10 Nm.[2,7,11] While the traditionally ground specimens had to run an additional 17.5 hours until a steady state value of 12 Nm was achieved, the ISF specimens had no asperities and, therefore, demonstrated no torque spike.[2,7,11] Additionally, they were at their steady state operational value of 10 Nm at the end of the 7.5-hour loading phase. When compared to the steady state operational value of the traditionally ground specimens this value represents a 2 Nm or approximately 20% reduction in the applied torque value needed to rotate the bearings.

Since the monitored torque value is a measure of the amount of energy lost to friction, we can inversely look at these results as follows:

- At the 7.5-hour mark, the torque load on the traditionally ground sample was 17.5 Nm and on the ISF sample the value was 10 Nm, this represents a difference of 7.5 Nm or 75% more applied torque to rotate the traditionally ground bearings.

- At the 25-hour mark, the torque load on the traditionally ground sample was 12 Nm and on the ISF sample the value was 10 Nm. This represents a difference of 2 Nm or 20% more applied torque to rotate the traditionally ground bearings.

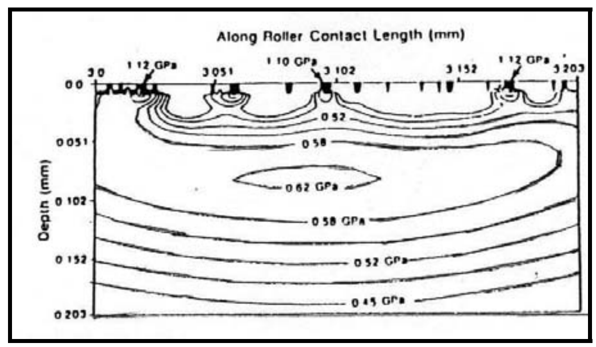
It can be inferred from this experiment that the reduction in friction resulting from the ISF Process generates components requiring less operational force due to their smoother surface condition.

Diffusion of Shear Stresses Resulting from an Isotropic Superfinish.

It is known that metal-to-metal contact surfaces are separated (elastohydrodynamic lubrication (EHL)) or partially separated (boundary lubrication) by a lubricant film.[11] The thinner the film thickness, or the taller the asperity peaks, the more asperity peaks will contact and the higher the localized contact pressures will be.[11] A major bearing manufacturer performed an experiment to evaluate both the surface and near surface, micro-Hertzian stress concentrations on tapered roller bearings with the Isotropic Superfinish (ISF) generated by chemically accelerated vibratory finishing.[11] Tapered roller bearings with an enhanced (i.e. super-ground) finish, the company's traditional finish served as a control standard.

The stress values were calculated during the bearing break-in cycle for a randomly chosen 0.20 mm length of each tapered roller bearing. The bearings were manufactured from carburized steel and the experiment was conducted with an average lubricant film thickness of 0.15 μm. The bearing manufacturer calculated the shear strength of the carburized steel to be 0.93 GPa.[11]

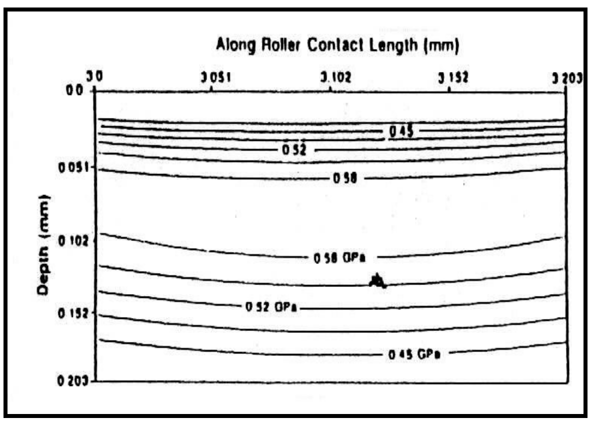
The experiment showed that the control standard, super-ground, tapered roller bearings had localized high stress concentrations at the surface.[11] Stress values of up to 1.12 GPa were found at the surface.[11] The bearing manufacturer also noted that each of the high surface stress locations corresponded directly to the presence of a grind line asperity peak on the surface of the tapered roller bearing.[11] Since the shear strength of the roller bearings was 0.93 GPa the authors[11] concluded that the high localized stress levels would result in a reduction in the expected life of the bearing by eventually leading to a surface peeling failure mode.[11] See Graph 3.



Graph 3; Shows a plot of the measured shear stress values of the enhanced or super-ground tapered roller bearing across a 0.2 mm length of the tapered roller bearing's contact area.[11] Note the high Hertzian stress peaks at the surface. The authors noted that each of these stress points occur immediately beneath an asperity peak.

When the testing was repeated utilizing ISF tapered roller bearings a maximum stress value of 0.59 GPa was calculated.[11] Interestingly this area of maximum stress was not on the surface of the roller bearing but at a sub-surface depth of 0.076 mm.[11] The calculated contact stress values at the surface of the ISF roller bearings was less than 0.45 GPa.[11] This represents a surface stress value of less than 50% the shear stress value of the carburized steel used to prepare the roller bearings. See Graph 4.

Interpreting this data we can infer that the durability of ISF processed metal-to-metal contact areas will be enhanced. The data plotted in Graph 3 demonstrates a concentration of Hertzian stresses corresponding to the points of actual metal-to-metal contact, (i.e. asperity peaks). Whereas, ISF surfaces have had their asperities removed by chemically accelerated vibratory finishing and therefore have a more efficient metal-to-metal contact pattern. On the ISF tapered roller bearing, all Hertzian stresses associated with the metal-to-metal contact area have been dispersed across a wider contact area thereby significantly reducing the stress in any one location[6]; Graph 4.



Graph 4; Shows a plot of the measured shear stress values of the Isotropic Superfinish tapered roller bearings along a 0.2 mm length of the tapered roller bearing's contact area.[11] Note that the high stress location is at a subsurface depth of 0.076 mm and that the surface stress values are < 0.45 GPa.

As illustrated in Graph 3, it is possible to exceed the shear stress level of the base metal used to prepare the tapered roller bearings. As such, during a break-in cycle asperity peak removal by physical snapping of the peak from the surface of the as ground bearings is a common occurrence.[6] This phenomenon is a precursor to surface pit formation.[6]

Metal Loss from Propagational Pit Formation and Wear

As suggested in Graph 3, asperity peak break-in due to shear stress snapping, results in the formation of a surface micro pit in the former location of the asperity peak.[6] Much like a pothole in a city street that expands as it is continuously struck by passing traffic, the micro-pit formed during the break-in run is continuously exposed to the action of gear meshing. As such, it too will continue to loose metal and its diameter will expand. This gradual expansion eventually results in numerous pits coalescing into spalling damage across the gear tooth flank.[6] See Photo 5.

Photo 5; Shows gear tooth spalling caused by surface pit propagation. The gear shown was finished using traditional gear grinding techniques. Asperity peak contact during the gear break-in phase produced micro-pits, that with continued gear operation expanded and eventually coalesced into irregular craters over a significant area of the gear tooth.[6]

Concomitant to the evaluation described earlier by a major bearing manufacturer in which temperature and frictional torque levels of the Isotropic Superfinish specimens were evaluated versus control specimens finished with the manufacturer's traditional as-ground finish, the manufacturer also examined the surfaces of its test specimens for wear due to metal loss. The test apparatus was as previously described, a block-on-ring test rig.[7] Again, see schematic 1.

After weighing, the ISF block and the traditional as-ground control block were each fixtured against a ring that was rotated at 800 rpm for 6 hours.[7] Following the 6 hours of run time the blocks were removed from the test rig, reweighed and examined for possible wear.[7]

The traditionally ground control block showed 22 times the weight loss when compared to the ISF block.[6,7] The significant difference in metal loss is clearly visible when examining the wear pattern.[6,7] See Photo 6 and Photo 7.

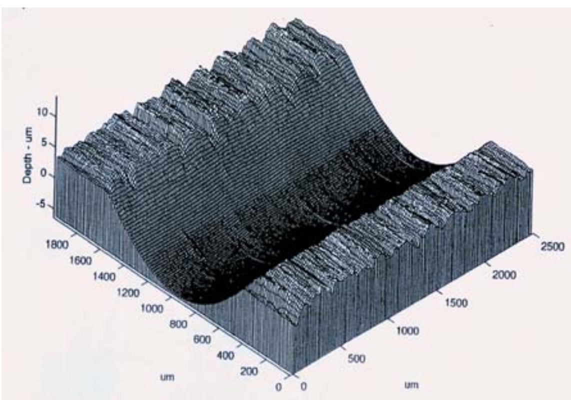


Photo 6; Shows the wear pattern produced in a block-on-ring evaluation[6,7] of a traditionally ground steel block.

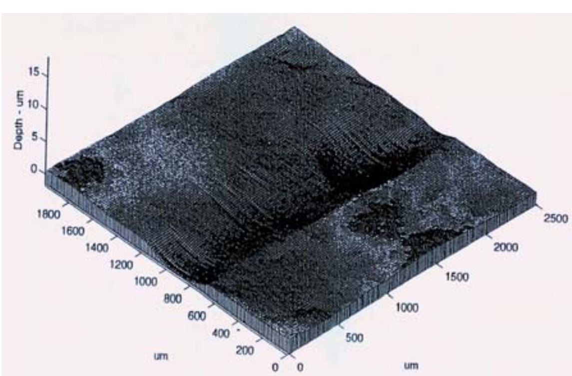


Photo 7; Shows the wear pattern produced in a block-on-ring evaluation[6,7] of the Isotropic Superfinish (ISF) steel block. The result of this evaluation produced 22 times less metal loss when compared to the block pictured in Photo 6.[6,7]

It has been previously presented[6] that during a metal-to-metal contact break-in cycle, asperity peaks are removed from the contact surfaces by snapping and breaking away. The initiation of this snapping and breaking action occurs during boundary lubrication conditions when surface Hertzian contact stresses exceed the shear strength of the steel from which the components are manufactured.[6]

After snapping off the surface of the part, the metal debris does further damage to the surface of the component as it is carried throughout the gear train by the lubricant system where it continues to be interdispersed between other gear teeth causing scoring damage as it is pulverized.[6]

A micro-pit is left on the surface at the former location of the asperity peak.[6] This pit continues to expand as the gear continues to cycle with its mating gear.[6] See photo 6. The key to reducing pitting and wear, therefore, appears to be eliminating the initiation sites for surface degradation.[6] As evidenced in photo 7, the ISF block was void of asperities and final surface wear was minimal.[7]

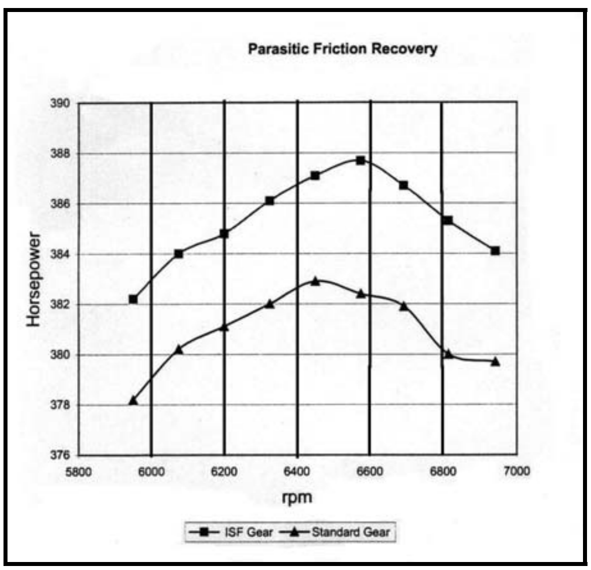
Parasitic Friction Recovery

This paper has presented laboratory test data that hypothesize and offer test results that demonstrate and describe the engineering advantages of Isotropic Superfinish (ISF) when applied to metal-to-metal contact surfaces. However, the ultimate proof of the benefits must be shown with actual test data under true automotive running conditions.

As stated earlier, parasitic friction is a horsepower thief. If friction can be reduced can engine horsepower be more efficiently transferred to the rear wheels and thereby reduce horsepower loss during the transfer?

A recent paper[10] discussed this very possibility. In recent dynamometer testing a pair of Winston Cup Auto Racing T 101 transmissions were evaluated. One T 101 transmission was completely ISF processed as described by[5,6,7,10]. The second transmission was left in the standard as-ground condition.[10]

Third gear was selected for the comparison tests.[10] Testing occurred sequentially on the same dynamometer stand using the same engine.[10] During each test the engine and transmission were preheated by idling until the transmission oil (Unocal 90W) reached 180°F.[10] The engine was then cooled back down to normal operating temperature before running with the applied load to measure horsepower losses through the transmission.[10] Drive shaft angles were monitored to ensure a consistent angle was maintained for all runs.[10] See graph 5.



Graph 5; Shows the resultant horsepower graphs at various rpm levels for the tested T 101 transmissions.[10] Note an approximate 1% horsepower recovery with the Isotropic Superfinish transmission.

Examination of the resultant horsepower graph shows that between 6,400 – 6,600 rpm the standard as-ground T 101 transmission averaged approximately 383 hp compared to the ISF transmission that averaged 387 hp in the same rpm range.[10] This difference of 4 hp represents slightly more than a 1% horsepower recovery.[10]

The only difference between the two transmissions tested in this evaluation was that the surface finish was improved by the ISF Process. As hypothesized earlier in this paper, the presence of asperities increase friction and contribute to the inefficient transfer of engine power. By eliminating this source of friction, there is a demonstrated benefit in regaining some lost horsepower.

Conclusions

Conformational gear tooth grinding is the traditional method of finishing automotive gearing.[6] Conformational grinding leaves parallel rows of asperities on the gear tooth flanks.[6]

The presence of asperities adds friction to the enmeshment action of the gear train and increases the chances of boundary lubrication conditions. Friction and boundary lubrication conditions have several deleterious effects on the efficiency of engine horsepower transfer and the durability of the components:

- Excessive heat generation
- Increased torque requirements
- Increased surface contact stresses
- Increased pitting
- Increased wear
- Increased scoring
- Reduction in component durability

The Isotropic Superfinish (ISF) offers an efficient way to improve the surface of the gear teeth.[6,10] ISF has a non-directional surface pattern and is asperity free.[6] The ISF Process removes initiation sites gently with a combination of chemical and mechanical action, not through abrasion.[6,10]

ISF offers several advantages to the operation of the engineered metal-to-metal contact surface:

- Elimination of excessive heat generation
- Reduction in torque requirements
- Decreased surface contact stresses
- Virtual elimination of pitting and metal wear[10]
- Decrease scoring
- Increase in component durability

References

1. 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"

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

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

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

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

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

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

8. 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)

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

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

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

Contact

William P. Nebiolo
Sales Engineer
REM Chemicals, Inc.
325 West Queen Street
Southington, CT 06489
Phone (860) 621-6755
Website: www.remchem.com
e-mail: sales@remchem.com