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Superfinishing Motor Vehicle Ring and Pinion Gears

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American Gear Manufacturers Association

TECHNICAL PAPER

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Lane Winkelmann, Jerry Holland and Russell Nanning, REM Chemicals, Inc.

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Today, the motor vehicle market is focusing on "lubed for life" differentials requiring no service for the life of the vehicle. Still, differentials are prone to develop problems of one sort or another since they are used to transmit a heavy torque through a right angle. One weak point in the differential is the ring and pinion gearset. As such, a proper break-in period is essential to attain the required service life. Break-in is an attempt to smooth the contact surfaces of the gears and bearings through controlled or limited metal-to-metal contact. The roughness of the contact surfaces is reduced during this process until a lower and relatively stable surface roughness is reached. The lower surface roughness is advantageous, but irreversible metallurgical and lubricant damage occurs since break-in always results in stress raisers, metal debris and an extreme temperature spike. Break-in and its negative effects can be eliminated with chemically accelerated vibratory finishing. When this method is used to superfinish ground (AGMA Q10) or lapped (AGMA Q8) ring and pinion gearsets to less than 10 min.R_a, the life of the lubricant, bearings and gears is significantly increased. Just a few years ago, this technology was considered impractical for high production volume OEM ring and pinion gearsets due to lengthy processing times. This superfinishing technology also had difficulties preserving the geometry of rough lapped gears, which required more stock removal than finely ground aerospace gears (AGMA Q12+). As a result the transmission error of these gears was increased leading to unacceptable noise. The superfinishing technology discussed in this paper overcomes these obstacles and meets the needs of the motor vehicle industry. Gear metrology, contact patterns, transmission error and actual performance data for superfinished gearsets will be presented along with the superfinishing process.

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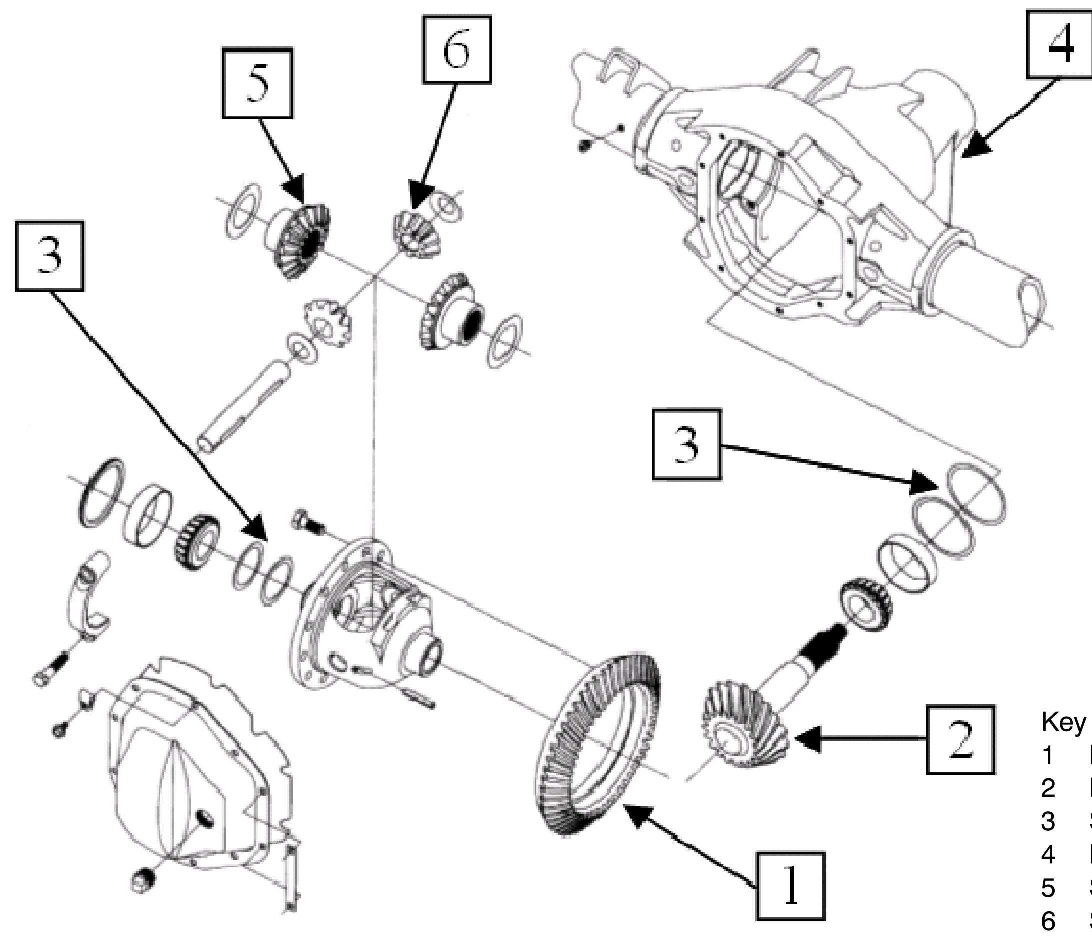
Introduction

Break-In Process

Vehicular differentials are apt to develop problems of one sort or another since they are used to transmit a heavy torque through a right angle. A differential consists of a ring gear, pinion gear, side gears, spider gears, and bearings. See Figure 1. The spiral bevel or hypoid gearsets can be a weak point in the differential since they need to withstand large sliding pressures and shock loading. Over the years, many improvements have been made to differentials such that now many require no maintenance (i.e., “lubed for life”). New ring and pinion gears are not normally ground after carburization, but rather are lapped at the factory and maintained as a matched gearset. Lapping partially corrects the distortion which occurs during carburization, and therefore somewhat reduces the operating temperature, wear and noise. It is impractical, however, to perform the lapping under the same loads as those which are experienced under actual driving conditions. Therefore, ring and pinion gearsets must always go through a “break-in” cycle, which is professed by car experts as the magic potion for preventing future failure. As one expert puts it, improper break-in results in a differential lasting 90,000 miles, and proper break-in results in a differential lasting, 180,000 miles.



Key
1 Ring
2 Pinion
3 Shims
4 Housing
5 Side gears
6 Spider gears

Figure 1. Exploded view of a differential pointing out the various parts discussed in this paper.

Break-in is an attempt to create a smooth surface on the contact surfaces of the gears and bearings through controlled or limited metal-to-metal contact. The roughness of the contact surfaces changes during this process until a lower and relatively stable surface roughness is reached. During the break-in cycle, it is hoped that the lubrication of the ring and pinion gearset is maintained. In fact, this is vital to the life of the differential. During the initial start-up of the break-in cycle, an oil film is formed on the surface between the gear teeth. This film is referred to as Hydrodynamic or Full Fluid Film Lubrication, which completely separates the ring from the pinion so that there is no metal-to-metal contact. As the speed of the ring and pinion increases, the hydrodynamic layer thickens as well. As a load, however, is placed on the gearset, the hydrodynamic layer decreases. At the same time, the temperature rises and the viscosity of the lubricant decreases, which further decreases the film thickness. As the load and/or temperature continue to increase, the lubricant film becomes too thin to provide total separation. Contact between the peak asperities occurs, which results in higher frictional forces and the concomitant temperature rise. This is referred to as the Boundary Lubrication or Thin Film Lubrication regime. The break-in process is an attempt to maintain the temperature low enough to provide boundary lubrication until the peak asperities are worn away leaving the lower and relatively stable surface roughness on the contact surfaces.

In order to understand the shortcomings and misconceptions concerning break-in, it is worthwhile to briefly examine what advice the experts are giving to the end user. Although every expert has his or her own recipe for break-in, the following is fairly typical:

> *All new ring & pinion sets run hot until they are "broken in" and in some situations they can run hot enough to break down the gear oil and damage the gear set. Some of those situations are:*
>
> - *Towing*
> - *Tall tires*
> - *Heavy loads*
> - *High numeric gear ratios (4.56 & up)*
> - *Motorhomes*
>
> *New gears are lapped at the factory but some are lapped more than others and even with lapping they are still not lapped under the same pressures that driving creates. The loads generated while driving force any microscopic high spots on the gear teeth back into the surface of the metal. This is called "work hardening". Work hardening is similar to forging in the way that it compresses the metal molecules into a very compact and hard formation. This can only be accomplished if the metal surfaces are lubricated and the temperature is not hot enough to change the molecular structure due to the heat alone. If the temperature of the metal gets hot enough to change the molecular structure it will soften the surface instead of hardening it. This may seem like a balancing act but it all happens easily & passively as long as the oil keeps the gear cool while it is breaking in. All new gear sets require a break-in period to prevent damage from overheating. Usually 500 miles will break-in the gears but until then, you want a cool rear end. The greatest damage results when a new ring & pinion has been run for several miles during the first 500 miles and the oil is very hot. Any heavy use or overloading at this time will cause irreparable damage to the gear set. So all this means keeping your rear end cool.*
>
> *During "break-in" cycle, it is desirable to run the gears under light loading so that the differential runs cool. During this period, it is hoped that the microscopic high spots on the mating gear teeth are flattened and worked back into the surface under actual driving conditions causing work hardening. [1]*

<u>Break-In Misconceptions and Problems</u>

Clearly then the differential break-in process only provides a partial solution to curing the problem, and has several serious and often ignored misunderstandings and disadvantages. First, these gears are typically case carburized to a high hardness, and therefore the peak asperities cannot be work hardened to a smooth surface during run-in. Instead the peak asperities are abraded away resulting in metal debris which is always found in used differentials upon inspection. This debris is not only damaging to the gears but also to the bearings. The wind turbine industry, for example, has recommended a 3.0 micron filtration system for its lubricants since it was discovered that even 10 micron particles cause premature gear/bearing failures. [2] If metal debris is a serious problem in filtered lubrication systems, it is not surprising then that it is even more problematic for systems such as differentials where the oil is recirculated by the ring gear and flung over all the parts without being filtered.

Furthermore, at the microscopic level the run-in abrading process consists of micro-cutting, micro-plowing, and micro-cracking, resulting in the creation of stress raisers setting the stage for future fatigue failure through contact fatigue.

Second, many vehicles which experience high loads at relative low gear speeds (e.g., buses, recreational vehicles, and off-highway equipment) are placed in immediate service such that their differentials never have the luxury of going through the recommended break-in process. Such vehicles often experience high loading and shock loading, whereby the operating temperature can increase to a point where the gear oil is non-functional as a result of its reduced viscosity or degradation. Premature gearset failure then occurs.

Third, break-in does little to remove the distressed metal at the surface of gears. Surface stress raisers are caused by heat treatment and residual machining lines, which serve as the initiation points for future wear and fatigue failure.

In spite then of all the advances in gear manufacturing and lubrication, there are still problems with ring and pinion failures. What is needed is a practical way to remove the peak asperities from the gearset without affecting the contact pattern such that both friction and damaging metal debris are reduced and/or eliminated. These gearsets would require no break-in and could be used immediately for high load service.

The Superfinishing Challenge

Chemically accelerated vibratory finishing, henceforward referred to as superfinishing is routinely used on aerospace spiral bevel gears (AGMA Q12+). Since the flanks are typically ground after heat treatment to a 12 μin. R_a, little stock needs to be removed to superfinish such gears to a desirable 3.0 μin R_a final surface finish. As was previously reported, these superfinished gears maintain their critical geometrical tolerances. [2] Superfinished aerospace spiral bevel gears experience hydrodynamic or full fluid film lubrication immediately after being placed in service. It is well documented that these gears have significantly lower wear, noise/vibration, and operating temperature as well as an increased service life. [4] [5] [6]

Likewise, for over ten years, the motorsports industry has utilized superfinishing on high performance ring and pinion gearsets (AGMA Q10) typically ground to a starting 25 μin. R_a. These high performance gears are superfinished to approximately 10.0 μin. R_a and in certain venues to as low as 1.5 μin. These motorsport gears have been widely recognized for their enhanced durability and efficiency throughout the industry.

On the other hand, ring and pinion gears used for motor vehicles (AGMA Q8) are seldom ground in the U.S. after carburization for economic reasons, but instead are lapped and maintained as a matched gear set. Their starting surface roughness typically has a 60 μin. R_a in the contact area. In Europe, however, ring and pinion gears are precision ground to a 30 μin. R_a after carburization. By grinding to the final net shape, the need to keep the ring and pinion together as a matched set is eliminated. This precision grinding has recently been introduced to the North American market.

Until recently, superfinishing motor vehicle ring and pinion gearsets had two major problems. First, since the starting surface is much rougher than that for ground aerospace gears, much more stock has to be removed to achieve a smooth surface. Since the stock removal was not uniform across the flank, however, there was an increased transmission error resulting in increased noise. Interestingly, the contact pattern did not drift after superfinishing, and so could not be used to flag changes in transmission error. Second, the processing time to superfinish a ring and pinion gearset using chemically accelerated vibratory finishing was too long for it to be commercially viable for high production manufacturing.

Experimental

Description of Ring and Pinion Gearset

For the majority of work in this study, Yukon DANA 44 ring and pinion gearsets were used. This is a very popular and readily available gearset used in various vehicles since its introduction in 1955. It was also selected since it matched an existing housing of the single flank test rig used in this study. The DANA 44 ring and pinion used in this study consists of a 46-tooth, 10-bolt hole, ring gear and a 26 spline, 13-tooth pinion gear, resulting in a 3.54 gear ratio. The ring gear has a diameter of 8.5 inches, and the pinion has a diameter of 1.376 inches. The pinion offset is 1.50 in. The ring and pinions are a matched set which have been case carburized and lapped for correct contact patterns.

Superfinishing Using Chemically Accelerated Vibratory Finishing

Details of using chemically accelerated vibratory finishing have been published elsewhere. [7] The following is a brief summary of the technique. The superfinishing is produced in vibratory finishing bowls or tubs. An active chemistry is used in the vibratory machine in conjunction with high density, non-abrasive ceramic media. When introduced into the machine, this active chemistry produces a stable, soft conversion coating on the surface of the metal gears being processed. The rubbing motion across the gears developed by the machine and media effectively wipes the conversion coating off the "peaks" of the gears' surfaces, but leaves the "valleys" untouched. No finishing occurs where media is unable to contact or rub. The conversion coating is continually re-formed and rubbed off during this stage producing a surface smoothing mechanism. This process is continued in the vibratory machine until the surfaces of the gears are free of asperities or until the surface attains the desired level of finish. At this point, the active chemistry is rinsed from the part and the gears are dipped in rust preventive.

Details of Processing Procedure

The Yukon DANA 44 ring and pinion gearsets were fixtured as shown in Figure 2 in an early attempt to maintain the lapped ring and pinion together as a pair. This fixture is rugged and protects the threads on the pinion from damage, and also prevents media from lodging in the tapped holes on the ring gear. Since that time, other proprietary devices have been designed, which have the same features, but are more applicable for handling high production volumes.

The gearsets used in this study were processed in a 3-ft^3 vibratory bowl using a newly developed high speed gear finishing process, which has a much higher stock removal rate than that previously available. Two different medias were used to superfinish the gearsets to determine the effect of media size and shape on the uniformity of stock removal, contact pattern and ultimately noise. Descriptions of Media A and Media B are detailed in Figure 3.

In a previous project, Media A had been used to superfinish similar OEM gearsets to a 4.0 μin. R_a. Although the operating temperature of this gearset was significantly reduced, the customer reported that superfinishing increased the noise level. Therefore, this test was designed to verify whether or not Media A was the root cause of the problem.

Based on in-house process knowledge, it was anticipated that Media B would be less likely to alter the gear profile. From the outset of this study though, it was uncertain if it was possible to superfinish gears having a high starting roughness to a 4.0 μin. R_a without increasing the noise level. Therefore, Media B was used to process one gearset to a 10 μin. R_a, and another gearset to a 4.0 μin. R_a.

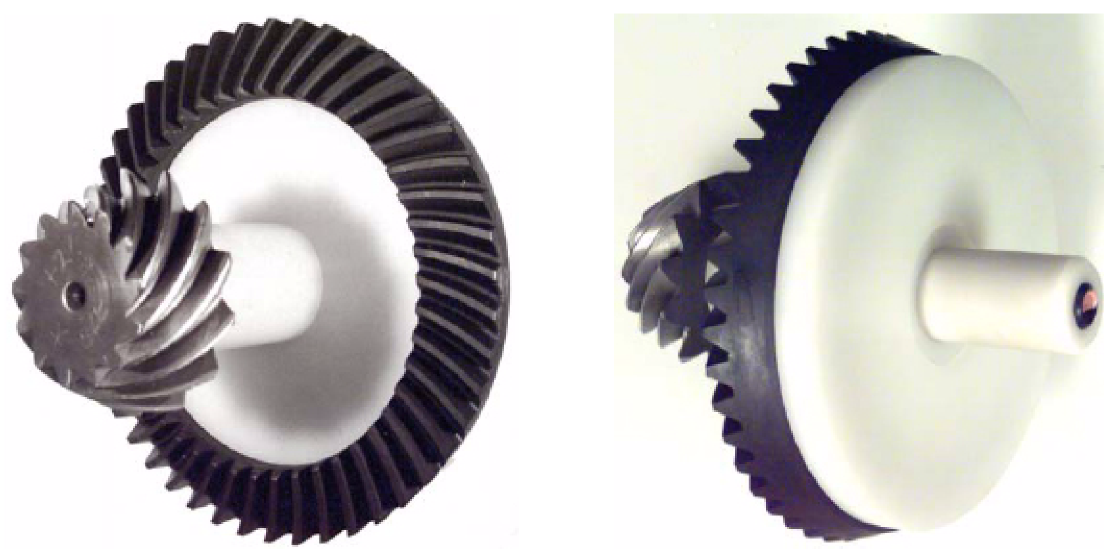


Figure 2. Fixture used to superfinish and keep the lapped gearsets as a matched pair.

Media A

Non abrasive Ceramic Media

Mixture of:

- 6 mm x 10 mm tristar
- 20 mm x 15 mm x 5 mm ellipse

Figure 3a. Media A

Media B

Non abrasive Ceramic Media

Mixture of:

- 3 mm x 6 mm angle cut cylinders

Figure 3b. Media B

Two separate groups of gearsets were processed and analyzed. See Table 1 for details. Group I was tested at the Gear Dynamics and Gear Noise Research Laboratory at Ohio State University. Group II was tested at The Gleason Works. Neither laboratory was aware of the processing conditions or the expected outcomes.

Table 1.

Group I	Group II
Gear Dynamics and Gear Noise Research Laboratory	*The Gleason Works*
• Lapped baseline.	• Superfinished using Media A to a 4.0 μin. R_a.
• Superfinished using Media A to a 4.0 μin. R_a.	• Superfinished using Media B to a 10.0 μin. R_a.
• Superfinished using Media B to a 10.0 μin. R_a.	• Superfinished using Media B to a 4.0 μin. R_a.
• Superfinished using Media B to a 4.0 μin. R_a.	

Uniformity of Stock Removal

Three different experimental methods were used to determine the effect of superfinishing on gear geometry: (1) Direct measurement of stock removal across the flanks of the ring and pinion gearsets; (2) measurements of the contact patterns; and (3) single flank testing.

Direct Measurement of Stock Removal

Figure 4 shows the relative stock removal normalized to unity across the flank of the gearsets superfinished using Media A and Media B. From these charts, it is apparent that Media A distorts the profile by removing more stock from the flank of the gear nearer the tip than the root, but does not negatively affect the spiral. Therefore, it is expected that gears superfinished with this media mixture will have a higher transmission error leading to an increase in noise. On the other hand, Media B does not distort the spiral or the profile, but removes stock uniformly from the tip to the root and across the spiral. The small variations seen in the Media B charts are due to slight measurement inaccuracies. Therefore, it is expected that the transmission error will not be increased. This will be shown and discussed in more detail later.

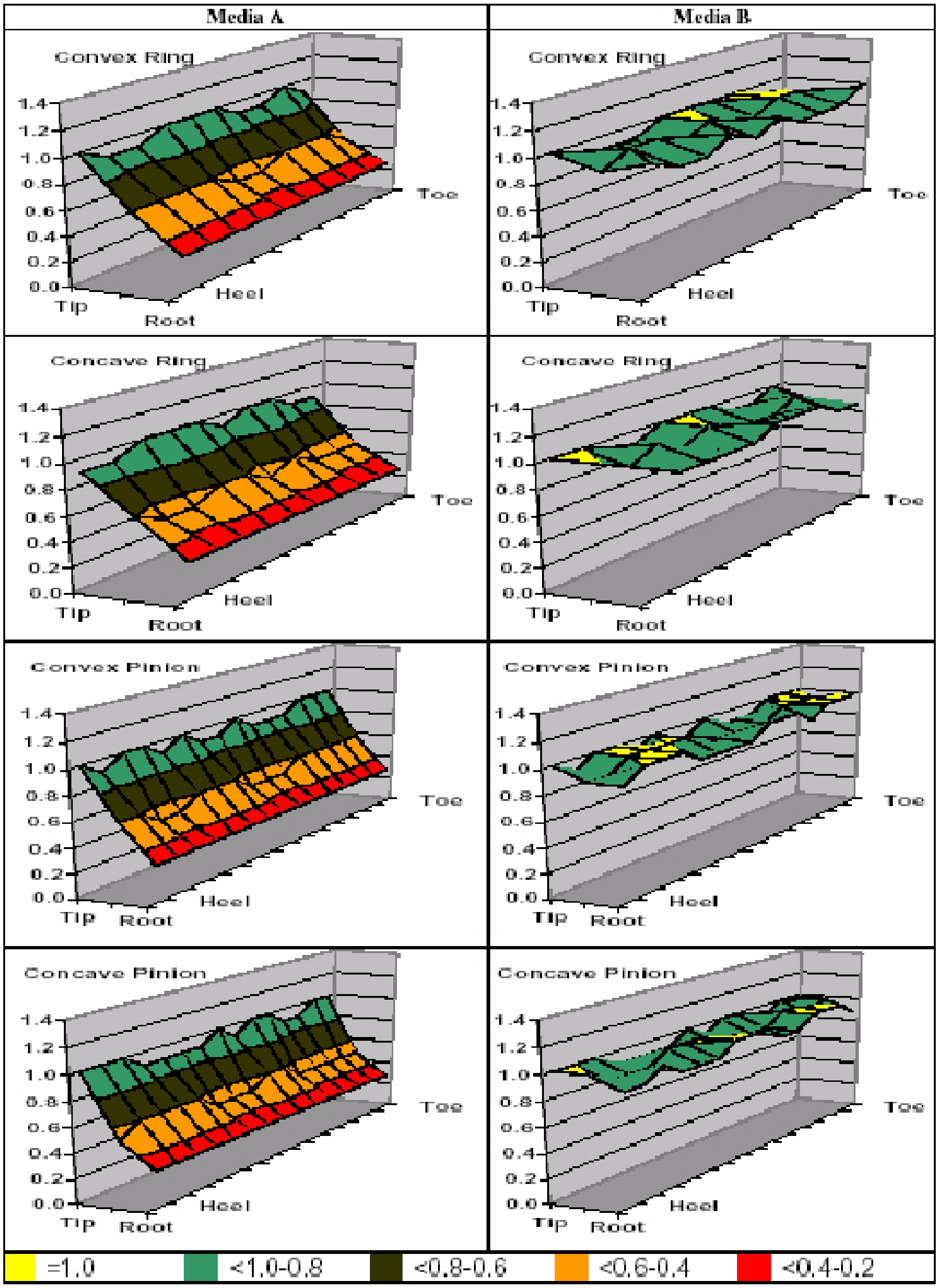


Figure 4: Relative stock removal normalized to unity using Media A and Media B.

<u>Contact Patterns</u>

Group I contact patterns were measured for the four gearsets to ensure proper alignment and positioning. The gearsets were then installed in a DANA 44 housing which had been modified for use in the Loaded Bevel Gear Test Rig at the Gear Dynamics and Gear Noise Research Laboratory at Ohio State University. General Motors marking grease was used to coat the gearsets. They were then rotated by hand in both the forward and reverse directions until a clear contact pattern was developed on the ring gear. The contact pattern for each gearset was then checked to determine if the superfinishing had altered or caused a contact pattern to become unacceptable. Though there were some very slight deviations from the baseline contact pattern, all contact patterns before and after superfinishing were found to be acceptable.

Group II gearsets were superfinished identically to those tested at the Gear Dynamics and Gear Noise Research Laboratory. The contact patterns of before and after superfinished gearsets were measured at The Gleason Works. Again, the laboratory reported no change in the contact patterns after superfinishing. The contact patterns are displayed in Figure 5.

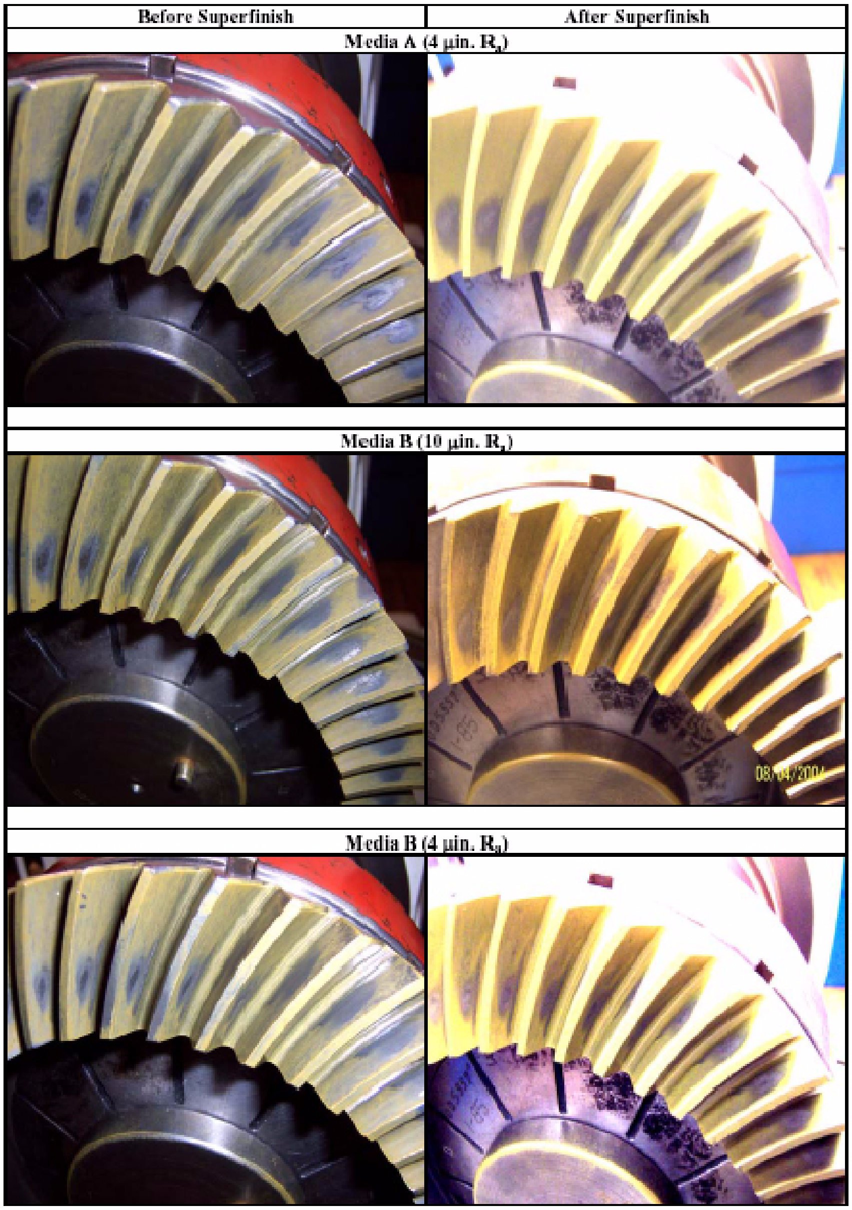


Figure 5. Contact patterns of Group II gearsets as determined at The Gleason Works.

Single Flank Testing

Single flank transmission error testing was conducted on Group I gearsets at the Gear Dynamics and Gear Noise Research Laboratory at Ohio State University. Their Loaded Bevel Gear Test Rig was used to measure the transmission error (TE) with the gearsets mounted in an actual differential housing. This was done in order to measure the TE under light load as well as under loading so that the effect of friction on noise/vibration could also be determined. Unfortunately, technical difficulties were encountered such that the TE could only be measured under light loading. Only a ranking of the TE could be derived from their data. A blind test was conducted such that the testing laboratory did not know the history of the gearsets. See Table 2.

Although variation in the test results were reported from the assembly/disassembly and alignment processes, the rankings are noteworthy and expected. The gearset with non-uniform stock removal by superfinishing with Media A had the highest TE. Interestingly, gearsets No. 3 and 4 with uniform stock removal by superfinishing with Media B had the lowest TE, and were even better than the raw lapped gear. At this time, there is no explanation for this latter result.

In an effort to verify the previously measured noise/vibration results, The Gleason Works measured the TE on the Group II gearsets before and after superfinishing using the 552 Gleason Single Flank Tester. The changes in transmission error (TE Before Superfinishing – TE After Superfinishing) is shown in the last chart of Figure 6.

It is apparent that Media A significantly increases the TE. On the other hand, Media B has proven that even a 4.0 μin. R_a can be achieved without any perceptible noise level. It is also clear that an acceptable contact pattern is no guarantee that the TE has not increased.

Table 2: Results of Single Flank Testing on Group I gearsets at the Gear Dynamics and Gear Noise Research Laboratory

Description of Surfaces Tested	Transmission Error Ranking Lowest Highest 1 2 3 4
Raw Lapped Baseline	3
Superfinished using Media A to a 4.0 μin. R_a.	4
Superfinished using Media B to a 10.0 μin. R_a.	2
Superfinished using Media B to a 4.0 μin. R_a.	1

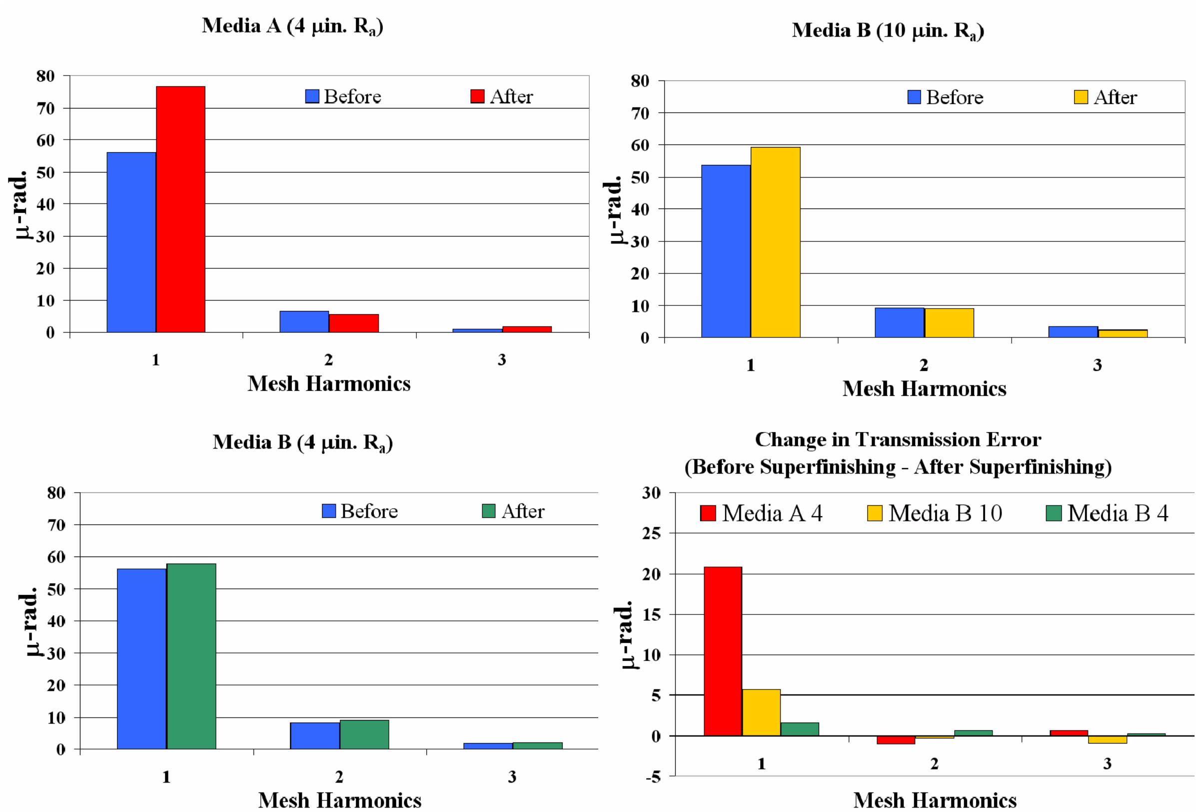


Figure 6. TE measurements of Group II gearsets by The Gleason Works.

Performance Testing

Laboratory Testing:

Automotive OEM Ring and Pinion: Several years ago, ring and pinion gearsets were superfinished using Media A for an OEM automotive application to evaluate the effect of superfinishing on operating temperature. This superfinished gearset was compared to a standard carburized and lapped gearset using the L-37 (ASTM D6121) Performance of Gear Lubricants at High Speed, Low Torque, Followed by Low Speed, High Torque. The L-37 test is used by individual OEMs, the Military, and Federal Government, to measure five parameters that are the result of distress on gears. The results are shown in Figure 7. The superfinished gearset had a peak temperature of 124 °C while the standard gear had a peak temperature of 165 °C. It is assumed that the slight temperature increase in the initial phase of the testing of the superfinished gearset is attributable to bearing break-in. The absence of a large temperature spike during break-in eliminates the possibility of any thermal degradation of the lubrication. It is also indicative that the superfinished gearset does not generate damaging metal debris and will have significantly lower wear throughout its service life. This same phenomenon was observed a number of years ago for superfinished bearings by The Timken Company. [8] [9]

In a separate study [6], Sikorsky Aircraft Corporation tested superfinished second stage spiral bevel gears (Q12+), third stage pinion gears and the bull gear of their S-76C+, Low Noise Transmission to an R_a of less than 4.0 μin. The standard ground surfaces of these gears have a nominal R_a of approximately 15 μin. The results of the standard two-hour Acceptance Test Procedure (ATP) are shown in Figure 8. This test is mandatory for all gearboxes prior to flight approval. As such, the baseline results shown are from three standard production gearboxes. The superfinished gearbox was run through the ATP three separate times. This is indicated by the multiple data points at the same torque loading. It should be noted that this test is conducted using an oil recirculation system and an external cooler. The temperature is measured on the outflow side. Again, it is seen that the superfinished gears had a very significant temperature drop in comparison with gears having the standard ground surface. The superfinished gears showed no damage or wear upon final inspection. As a result of their testing, Sikorsky has licensed this flight certified superfinishing technology. This data is presented here to exemplify that even ground spiral bevel or hypoid gearsets can realize huge performance benefits from superfinishing.

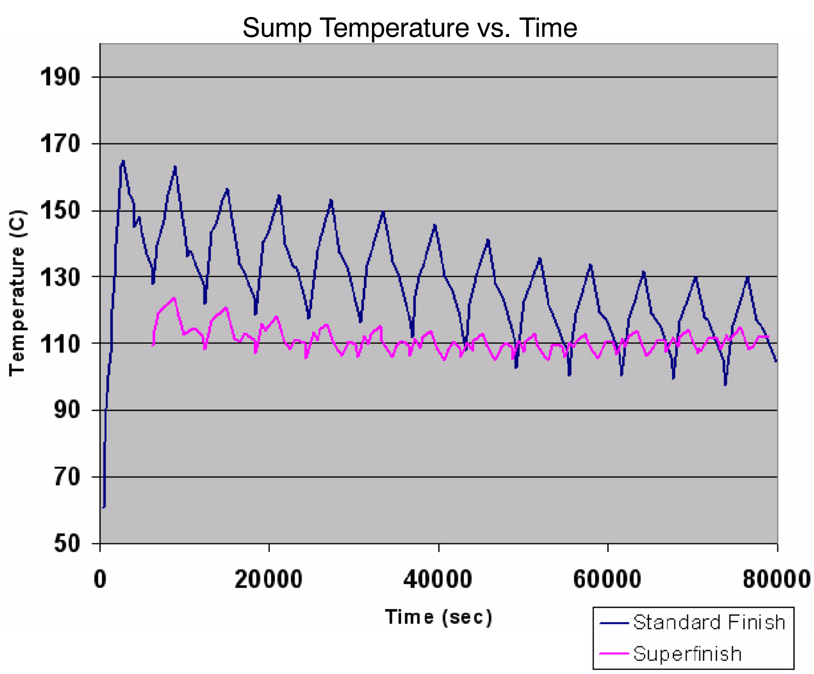


Figure 7. Sump Temperature (°C) versus Time (seconds) for gearset with a standard lapped finish versus a superfinished gearset.

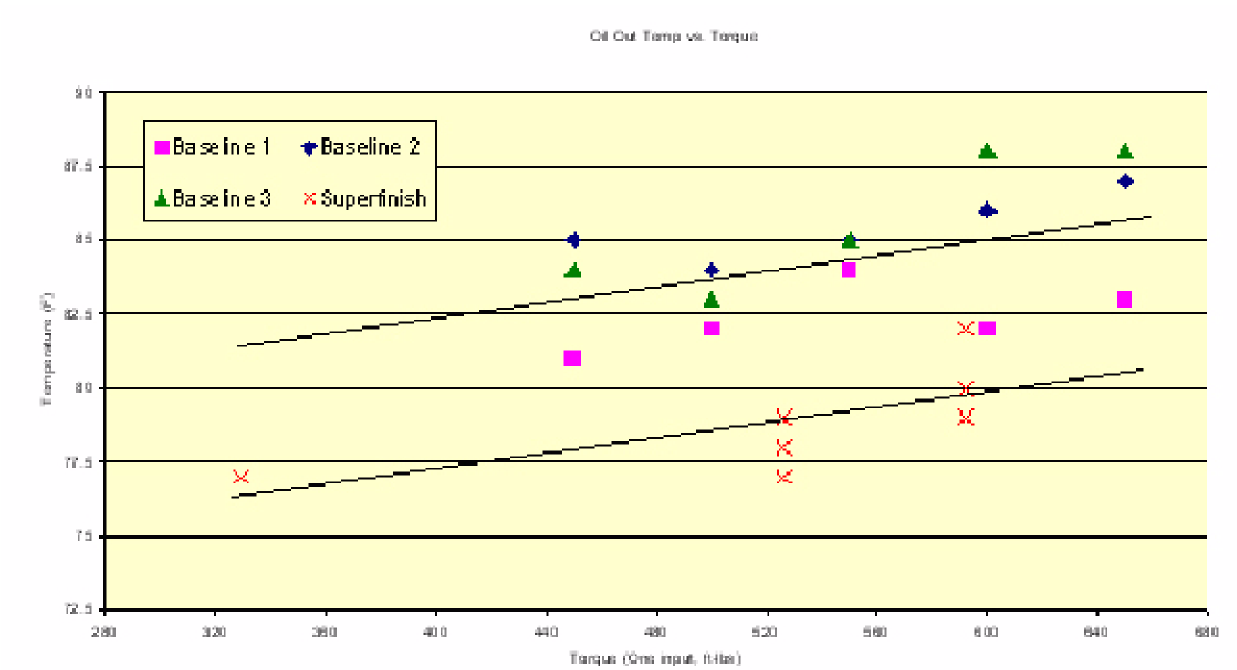


Figure 8. Main gearbox oil out temperature of a Sikorsky S-76C+ Low Noise Transmission during their standard ATP test.

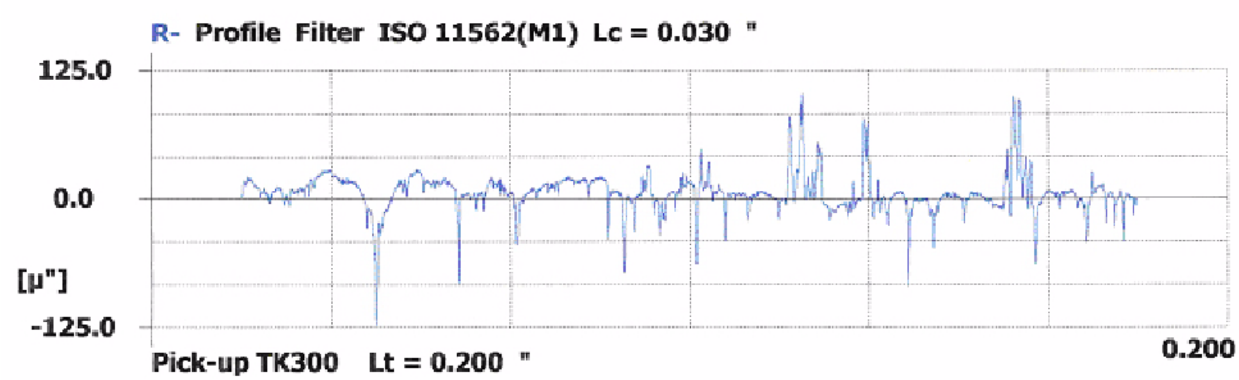
Field Testing

Heavy Duty Ring & Pinions: Ring and pinions used in heavy axle vehicles can often experience premature failures. As mentioned earlier, gears like these, which operate under high loads at relatively low gear speeds, typically experience boundary lubrication during their initial operation, and do not have the luxury of going through a proper break-in period. Since mid-2003, more than 200 heavy axle ring and pinion gearsets were superfinished to solve a severe micropitting problem. Superfinishing has now been incorporated as the final production step for this application. Prior to installation, the gearsets pass their contact pattern and transmission error acceptance tests.

NASCAR Racing Ring & Pinions: NASCAR ring and pinions (AGMA Q10) are subjected to extreme loads and shock loading during racing. These ring and pinions are lapped after carburization typically resulting in a 25 μin. R_a. Today virtually all NASCAR gearsets are superfinished to a 10 μin. R_a to reduce wear and to gain efficiency. Two gearsets were obtained courtesy of TEX Racing. One was only lapped, and the other was lapped and superfinished. Both went through a break-in cycle on a dynamometer prior to being placed in service. The break-in process is still done on the superfinished ring and pinion gearsets only because the other differential components are not superfinished. As previously discussed the large break-in temperature spike is absent for the superfinished gearset. Each has accumulated 2,000 miles in NASCAR sanctioned races in differentials containing oil recirculation pumps, cooling, filtration and magnetic particle separator systems.

Figure 9 is the profilometer traces and surface roughness parameters measured on the drive side pinion of each gearset. It is evident that the superfinished pinion has a superior surface in comparison to the lapped pinion. Whereas the lapped pinion has large peak asperities remaining (R_p = 104 μin.), the superfinished gearset is much smoother (R_p = 27.6 μin.). Similarly, the material ratio is vastly superior for the superfinished pinion. As discussed previously, the superfinished gearset will therefore continue to run longer, cooler and more efficiently because of the reduced friction.

As an indication of the acceptance of superfinishing in the racing industry, it is reported by TEX Racing of Ether, North Carolina that approximately 85% of Cup level NASCAR ring and pinions are currently superfinished. [10] As such, it is common to find used superfinished ring and pinion gearsets for sale by race teams. For example, the authors purchased four used superfinished gearsets from a top Winston Cup racing team's website (www.Roushracing.com). Each set comes complete with the racing history and miles completed prior to removal and sale. By contacting www.Roushracing.com, the authors found that the gearsets are typically removed after completing one race and practice racing before the next. These are then sold to the general racing public for two reasons: First, they are an inexpensive replacement item for the Racing Team and second, because they are still perfectly fine for further use in other racing venues. The examples purchased by the authors do not show any indications of wear or micropitting and in fact, the ring and pinions that have been run for 800+ miles appeared no different than the ones that have only been run for 100 -120 miles. Table 3 gives a summary of the history of the four gearsets purchased by the authors.



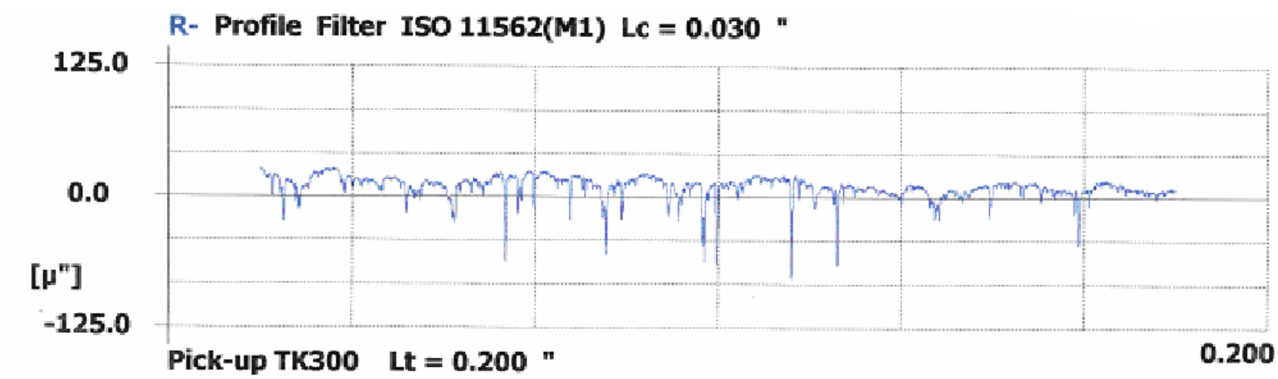


Figure 9: Profilometer traces of the post race condition of two similar pinion gears used in NASCAR sanctioned events. The top profile shows a standard lapped gear that has gone through an optimal break-in cycle and completed a nominal distance of 2,000 miles of racing. The bottom profile is of a ring gear superfinished to an R_a of approximately 10 μin. after completing a nominal 2,000 miles of racing. Gears courtesy of TEX Racing.

Table 3: Summary of the racing history of four used superfinished gearsets purchased by the authors from Roushracing.com.

Set	Race Location	Miles Completed	Ratio	Series	Car #	Date Archived
1	Dover	510	4.44	Winston Cup	99	10-23-03 TB
2	Nazarath Richmond	65[1] 53[1]	4.71	Busch Grand National	60	Not Available
3	Indy	565	3.75	Winston Cup	6	2-28-02 TB
4	Talladega Daytona	632[2] 247[2]	3.10	Winston Cup	99	2-2-04

[1] Used for practice, testing and/or qualifying.
[2] Used for the last race at Talladega and the first of the year practicing at Daytona

A recent paper presented at the 2003 SAE Performance Racing Industry (PRI) Conference and later published by Circle Track Magazine [11] documented the increased efficiency of a high performance differential containing a superfinished ring and pinion gearset. The test specimens used were a standard quick change differential with standard bearings and seals, and a quick change differential with low friction bearings, seals and superfinished ring and pinion gears known as a "Tiger" in the racing industry. This study used a Dynojet Model 248 chassis dynamometer (as used to monitor NASCAR Winston Cup cars) and a NASCAR Late Model with a 350 cubic inch engine running a two barrel carburetor. For this test, the dynamometer was used to measure the horsepower as the RPM climbed and also the horsepower during the coast-down. The goal was to measure the maximum horsepower output of the engine on run-up in fourth gear and then the amount of resistance at two speed intervals, 85 and 100 mph while the car was coasting. The run was stopped after coasting down to 80 mph. The results showed an average gain of 14.25 horsepower and a reduction in parasitic friction losses through the rear end by 50 percent at 85 mph and 52 percent at 100 mph. These testing results are shown in Table 4.

Production Ready

Processing Times

Gearsets with two different starting surface roughnesses were superfinished using Media B in a 3-ft^3 vibratory bowl using a newly developed high speed gear finishing process, which has a much higher stock removal rate than that used for the aerospace industry where only small amounts of stock removal is necessary. The first gearset tested had a starting 54 μin. R_a and is representative of a typical carburized and lapped gearset, while the second gearset had a starting 35 μin. R_a and would be similar to the surface roughness recently advertised by a large OEM which supplies ground ring and pinions to the motor vehicle industry. See Table 5 for the superfinishing process time and the final R_a achieved at the contact area of the teeth. It was found that both gearsets can be superfinished in less than 30 minutes to a point where considerable performance benefits will be realized.

Table 4: Results of chassis dynamometer testing of standard and low friction (superfinished) quick change differentials in a NASCAR Late Model car. [11]

	Standard Quick Change Bearings and Seals					**Low Friction Bearings and Seals with Polished Surfaces**				
	Run #1	Run #2	Run #3	Run #4	Run #5	Run #1	Run #2	Run #3	Run #4	Run #5
Max. HP	286.5	284.4	282.3	285.3	280.9	296.8	297.16	296.80	299.80	300.10
Coast @ 85 MPH	N/A	N/A	17.5	16.5	16.1	9.60	8.56	8.13	8.00	7.70
Coast @ 100 MPH	N/A	N/A	24.0	25.5	22.3	13.40	11.66	10.97	10.67	10.40

Averages: Standard	Averages: Low Friction
Max. HP = 283.88	Max. HP = 298.13
85 MPH Coast = 16.70 HP	85 MPH Coast = 8.40 HP
100 MPH Coast = 23.93 HP	100 MPH Coast = 11.42 HP

Gains:

Maximum Horsepower = +14.25 (represents a 5% gain in HP)

85 MPH Coastdown = (-) 8.30 HP (represents a 50% Reduction)

100 MPH Coastdown = (-) 12.51 HP (represents a 52% Reduction)

Table 5: Times required to superfinish gearsets with different starting surface roughness using Media B and the newly developed high speed gear finishing process.

Starting R_a (μin)	Final R_a (μin.)	Processing Time (minutes)
54	<10	< 30
35	<4	<30

Since processing times have now been reduced to less than 30 minutes, vibratory equipment manufacturers have more flexibility in the design of high volume superfinishing systems. Gearsets can be either superfinished in large numbers in a batch process or even in a continuous through-put operation to provide a constant flow of parts. Mounting or fixturing has been developed to a point that the superfinishing system can easily be partly or completely automated. Proposed designs are capable of superfinishing numerous gearsets per hour in conventional vibratory equipment. See Table 6 for various production output scenarios based on the newly developed high speed gear finishing process using vibratory equipment of different volumes.

Table 6: Production output scenarios using conventional vibratory equipment and the newly developed high speed gear finishing process.

Processing Times (minutes)	Machine Volume (ft^3)	Estimated Equipment Cost (dollars)	Part Through-Put (sets/hour)	Production Output* (sets/year)
30	20	75,000	30	187,200
30	30	100,000	80	499,200
30	50	150,000	120	748,800
*based on 3 x 8 hour shift, five day week production schedule.				

Conclusions:

1. Superfinishing eliminates the need for break-in, and reduces or eliminates friction, metal debris, wear, operating temperature and micropitting with little or no increase in transmission error.

2. An acceptable contact pattern is no guarantee that the transmission error has not increased.

3. Lapped motor vehicle gearsets can be superfinished to a 10 μin. R_a in under 30 minutes.

4. Ground motor vehicle gearsets can be superfinished to a 4.0 μin R_a in under30 minutes.

5. Superfinishing has already proven its value in NASCAR, heavy axle vehicles, helicopter gearboxes, and other demanding applications.

6. Since ring and pinion gearsets are a considerable source of parasitic friction in OEM vehicles, fuel efficiency can be increased by the application of this technology.

7. The superfinishing process is production ready.

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