An Evaluation of the New Rapid ISF® Process for Rear-Axle Gears

INTERNATIONAL CONFERENCE ON GEARS
October 7-9, 2013
Technical University of Munich (TUM), Garching, Germany

Dr. Tom Beyersdorff, Lane Winkelmann and Dr. Gary Sroka,
REM Surface Engineering, Inc., Brenham, Texas, USA

Abstract

The benefits gained by Superfinishing rear-axle gearsets using traditional chemically accelerated vibratory finishing is well documented. Contact fatigue life is dramatically increased while friction, wear and operating temperature are significantly decreased. This is facilitated by reducing the surface roughness of the mated gear teeth, thereby allowing full hydrodynamic lubrication to occur during operation. One large impediment to full commercial implementation of this process has been the fact that it is a lengthy batch process and not readily automatable to meet the demands of the automotive industry's JIT production environment.

The newly developed Rapid ISF® process addresses these drawbacks while still providing all the benefits. This process couples drag finishing equipment, traditional non-abrasive tumbling media and chemical accelerants into an automatable, high speed gear finishing system. This system has the ability to take either lap matted or ground automotive axle gearsets and convert them into low friction superfinished gearsets of R_a less than 0.2 µm within a 5- 8 minute cycle.

A detailed description of the new system and its operational parameters are presented as well as performance data of the Superfinished gearsets. The before and after processing data includes gear geometry checks, contact pattern comparisons and surface roughness measurements.

1. Background

A rear axle is the final stage in the drivetrain of a vehicle, and is responsible for transforming the engine power into useful propulsive force. A major component of the rear axle is the ring and pinion gearset. Typically ring and pinion gears are made by machining, hardening and sometimes shot peening. Since the hardening step introduces distortion, the gears are either lapped and maintained as a matched set, or ground to the final geometry to obtain acceptable noise levels. Since both the lapping and grinding process leaves a rather rough surface, a break-in or run-in process is recommended. Break-in is an attempt to smooth the contact surfaces of the gears 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. Even when the break-in procedures are followed and a lower surface roughness is achieved, irreversible metallurgical and lubricant damage often occurs since break-in always results in stress raisers, metal debris and an extreme temperature spike, which ultimately can lead to the premature failure of the rear axle.

Winkelmann et al. reported a number of studies that document the improvement in rear axle efficiency by using chemically accelerated vibratory finishing, henceforward referred to as Superfinishing [1]. In another paper, Winkelmann et al. showed that chemically accelerated vibratory finishing can successfully superfinish ring and pinion gearsets to a low 0.1 µm R_a without affecting the gear geometry such that the contact pattern and NVH were acceptable [2]. This technology was used commercially to solve premature wear and noise problems of problematic bus and recreational vehicle ring and pinion gearsets, and is currently used on production pick-up truck gears. Superfinishing using vibratory machines, however, is not easily automated, and requires a finishing time between 30 – 60 minutes depending on the initial roughness and the desired surface finish. Therefore, a much faster process is desired for high-volume manufacturing operations.

This paper discusses a recent development in the Superfinishing of hypoid ring and pinion gearsets in considerably shorter cycles using Rapid ISF®. A novel fixturing method is also introduced to help make this new method fully automatable.

2. Introduction

Only a very brief description of conventional chemically accelerated vibratory finishing will be presented here since it is discussed in detail elsewhere [3], [4], [5]. The process is carried out in vibratory bowls or tubs. A proprietary 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 asperity 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.

The rate at which a gear is superfinished is a function of both the rate of formation of the conversion coating and the rate of mechanical removal of the conversion coating by the media rubbing. The rubbing energy must be sufficient to remove the conversion coating. In conventional chemically accelerated vibratory finishing, the rate of superfinishing is limited by the rate of rubbing and in some cases by the rubbing energy. If rubbing energy is insufficient, the superfinishing process will stop resulting in a very heavy tenacious conversion coating.

Consequently, there are two approaches for increasing the rate of finishing. (1) Select a machine that provides a higher rate of rubbing than a conventional vibratory machine. (2) Select a machine that has a higher rubbing energy. Fortunately, the drag finishing machine has both of these features. Rapid ISF® (referred to as Superfinishing from here on) combines traditional high energy drag finishing equipment and a significantly more aggressive active chemistry than used with conventional vibratory finishing. A description of the drag finishing machine is given below by Chmielewski [6].

“The concept of drag finishing goes back centuries to when farmers first pulled plows through their fields. Although the farmers' intention was not to deburr or polish their plows, dragging the plow through the abrasive soil did just that.

The initial thesis work of drag finishing's developer focused on the need for a machine that would increase performance levels over conventional mass-finishing equipment. The "think-tank" design people knew that pressure and velocity were responsible for the work of mass finishing; therefore, drag finishing was the natural result.

It is the magnitude of these two elements that provides drag finishing an advantage. Subsequent experience taught the developer that these two elements, in concert with properly prescribed media and compounds, allow drag finishing to achieve performance levels as high as 40 times faster than conventional levels.

Drag finishing uses a circular bowl containing stationary, loose finishing media and a circular rotating turret above the bowl with multiple rotating part-fixture stations. (Ten stations are average.) Fixture stations rotate about their own axes, similar to a planetary system.
Parts are attached singularly or in groups to part-fixture stations around the perimeter and under the main turret. The rotating turret is then lowered so the parts are submerged and "dragged" through the stationary loose media.
Programmed sequences such as rpm, depth and rotational direction provide mechanical repeatability that assures uniformity cycle to cycle. By combining the right media and compound with the physical action of the drag finisher, you can mechanize processes that previously only could be done manually. Refined surfaces as low as one to two Ra (Roughness average) are consistently achievable."

3. Process Description

Equipment

The machine used in the testing is a Rosler Mini-Drag Finisher. See Figure 1 for a 3D image of the machine. The spindles are fastened to the machine and can be rotated around the axis of the spindle. As the spindles are rotated around their axis, they are also dragged in a larger circle around the circumference of the bowl containing the media. It is this motion that imparts the force of the media rubbing the part and makes it possible to use a faster accelerating chemistry than can be used in conventional vibratory finishing (i.e., circular vibrator).

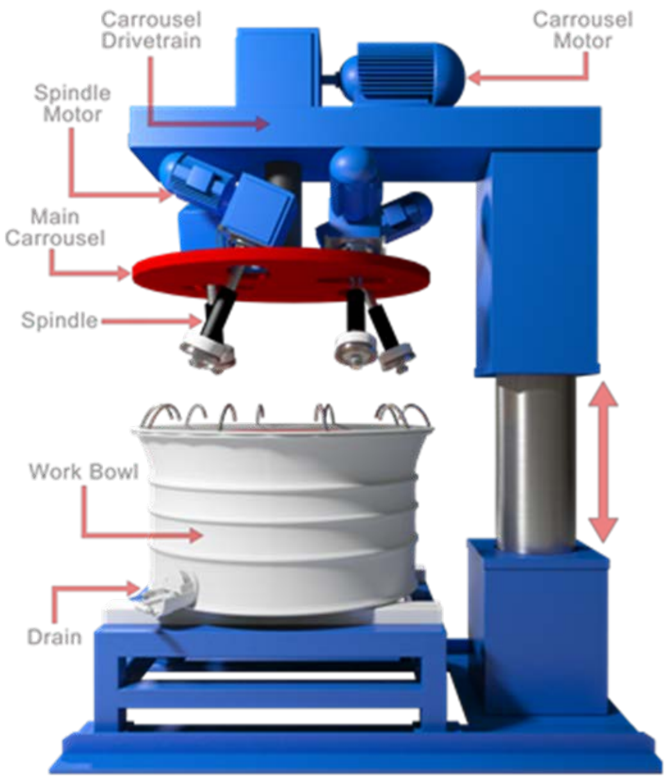


Figure 1: 3D image of a drag finisher showing the key components.

The specifications of the ROSLER SSA-L Series Mini Drag Finisher are given in Table 1.

Operation	Programmable with full automation capabilities
Dimensions (L x W x H)	2.6 m x 3.0 m x 3.6 m
Work Bowl Diameter Media load Vibratory Motor Wear-resistant Liner	 1.35 m 0.85 m^3 1.2 hp polyurethane
Main Carousel Drive Power Speed Range Carrousel Movement	 10 hp 30 – 100 RPM CW/CCW
4 Work Stations with Independent Drive Drive Power Speed Range Spindle Movement Spindle Angle	 4 x 2.0 hp 4 – 40 RPM CW/CCW Adjustable 0° – 30°
Maximum Workpiece Dimensions Diameter Height	 43 cm 38 cm

Table 1: The technical specifications of the ROSLER SSA-L Series Mini Drag Finisher.

Description of the Magnetic Fixture

The ring gear may, or may not have bolt holes, and this makes it difficult to mount to the spindle of the machine. The pinion gear is similarly problematic to mount to the spindle. The problem was overcome by using magnetic fixturing [7]. A plastic fixture sized to fit the dimension of the particular rear axle gears is fastened to a steel shaft as shown in Figures 2 and 3.

Figure 2: The small circles are the location of supermagnets placed around the larger plastic cylinder to hold the ring gear in place. Similarly, the small circles on the smaller cylindrical section are the location of supermagnets to hold the pinion to the fixture.

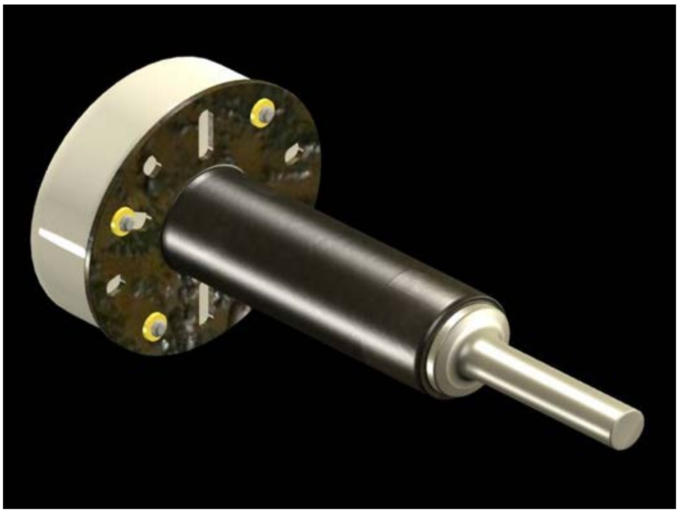


Figure 3: The plastic magnetic fixture shown above and attached to the spindle.

A number of cylindrical supermagnets are embedded around the larger and smaller cylindrical sections of the fixture. The number of magnets and their strength are adjusted to firmly secure the ring gear and pinion gear to the plastic fixture during the drag finishing process, but also not too strong such that the ring and pinion can be easily removed at the end of the process.

The ring gear and pinion gear are held to the fixture by the magnetic force as shown in Figure 6, thereby allowing one gear and one pinion to be processed simultaneously on each spindle.

Figure 4: The ring gear and pinion gear are held to the magnetic fixture.

The shaft is then secured to spindle of the drag finishing machine as shown in Figure 5.

Figure 5: The spindle is attached to the drag finisher with the ring gear and pinion gear held by the magnetic force to the plastic fixture.

Once fastened to the machine, the spindles do not have to be removed to load fresh gears, since the gears are easily removed from their magnetic fixture. Refer to Figure 4. The spindles are fastened to the machine and are rotated during operation around the axis of the spindle. Refer to Figure 5. As the spindles are rotated around their axis, they are also dragged in a larger circle around the circumference of the bowl containing the media. It is this motion that imparts the force of the media rubbing the part and makes it possible to use a faster accelerating chemistry than can be used in conventional vibratory finishing (i.e., circular vibrator).

In the machine described in this paper, there are four separate spindles such that four rear axle gears sets can be superfinished simultaneously.

Superfinishing Process Description

In order to Superfinish both the drive and coast side of the ring gear to the same R_a, it has been found necessary to rotate the spindles in opposite directions during the process. This process results in a total cycle time of approximately 5 – 8 minutes. The cycle time is directly related to the starting surface roughness and the desired final surface roughness. The cycle times can be adjusted to fit takt time requirements shorter than 5 – 8 minutes, but the final surface roughness may be R_a > 0.1 micron. Surfaces with R_a 0.1 – 0.2 will still result in efficiency gains as compared to standard OEM lapped or ground gearsets, however, if one desires to take advantage of a lower viscosity lubricant, it is recommended that the superfinished surface be approximately 0.1 micron R_a.

In table 2 and 3, depicted below, a current production set of ground OEM hypoid gears was Superfinished using the drag finishing process described in this paper to achieve a final surface roughness on the gear teeth of 0.1 micron R_a or less. Note the significant change in surface topography as the working area of the gear tooth has been planarized to remove the asperities. The total cycle time for this improvement was 8 minutes. See the image in Figure 6 for a visual representation of the Superfinished final condition of the pinion.

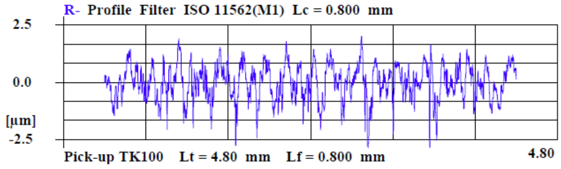
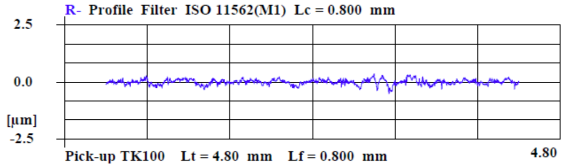
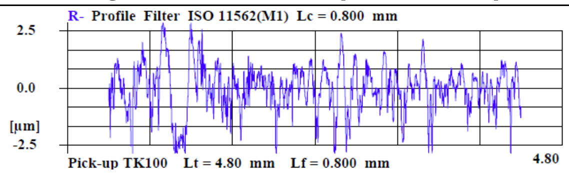
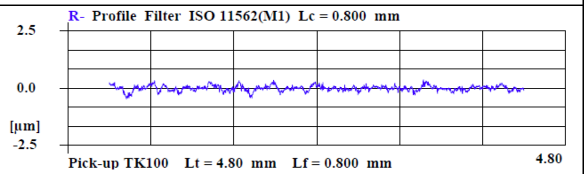
	Ring Gear Convex (Drive Side)
Before	 Ra = **0.63 µm,** Rz = **4.48 µm**
After	 Ra = **0.10 µm,** Rz = **0.62 µm**
	Ring Gear Concave (Coast side)
Before	 Ra = **0.81 µm,** Rz = **5.7 µm**
After	 Ra = **0.10 µm,** Rz = **0.68 µm**

Table 2: Typical before and after surface roughness measurements of ground OEM ring gear after Superfinishing for only 8.0 minutes using drag finishing technology.

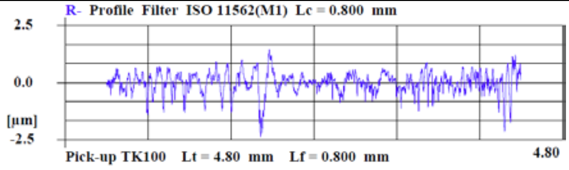
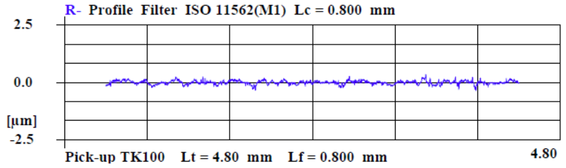
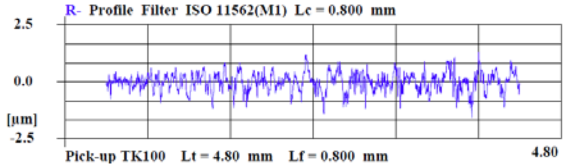
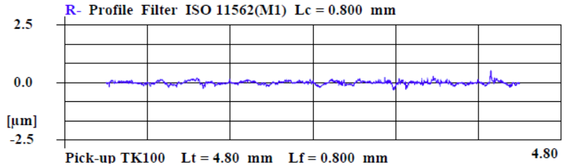
	Pinion Convex (Coast Side)
Before	 Ra = **0.36 µm,** Rz = **2.61 µm**
After	 Ra = **0.07 µm,** Rz = **0.56 µm**
	Pinion Concave (Drive Side)
Before	 Ra = **0.32 µm,** Rz = **2.24 µm**
After	 Ra = **0.07 µm,** Rz = **0.53 µm**

Table 3: Typical before and after surface roughness measurements of ground OEM pinion after Superfinishing for only 8.0 minutes using drag finishing technology.

Drag finishing technology has been used to Superfinish a number of rear axle gears for a wide variety of potential customers. The geometry of the gears was always found to be within tolerance, and the noise, vibration and harshness never negatively altered.

Figure 6: Image of a typical ground OEM pinion after Superfinishing for only 8.0 minutes using drag finishing technology.

4. Test Parameters

The parameters of the drag finisher used to process the OEM lapped and mated hypoid gearsets are given in Table 4.

Main Carousel Speed	40 RPM
Main Carousel Rotation	CW
Spindle Speed	80 RPM
Spindle Rotation	CW for ½ time; CCW for ½ time
Spindle Depth	600 mm
Spindle Angle	20 degrees
Media description	3 mm x 5 mm Straight Cut Triangles, non-abrasive ceramic
Chemistry	FERROMIL® FML-7800
Liquid Level	200 mm
Process Time	5.0 min. & 7.0 min.
Temperature	48 °C

Table 4: Superfinishing parameters used to process two gearsets with the drag finisher.

One gearset was processed for a total of 5.0 minutes, and the other gearset was processed for a total of 7.0 minutes. During the first half of the processing cycle the spindle is rotated in the CW direction. During the second half of the processing cycle, the spindle is rotated in the CCW direction.

5. Results and Discussion

Contact Pattern

The surface roughness of each ring and pinion was measured on the lapped region after processing using the same instrument and parameters as used for the initial measurements. The results are presented in Table 5. All surfaces had a ≤ 0.25 µm R_a. Numerous automotive racing teams have discovered that Superfinished ring and pinion gearsets finished to only a 0.25 µm R_a have superior performance compared to non-superfinished lapped gearsets.

	Surface Roughness, R_a (µm)	
	5-minute process	7-minute process
Ring	0.20 – 0.25	0.10 - 0.15
Pinion	0.19 – 0.25	0.08 – 0.15

Table 5: Final surface roughness of a gearset Superfinished for 5.0 minutes and a gearset processed for 7.0 minutes.

The contact pattern of the gearsets processed for 5.0 min. and 7.0 min. were determined, and the results are presented in Figure 7. Both contact patterns were deemed acceptable by the customer.

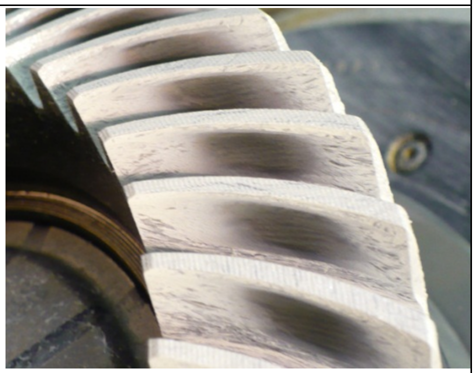
	5 Minute Cycle		**7 Minute Cycle**
Drive			
Coast			

Figure 7: Pictures of the drive side and coast side of the gearsets processed for 5.0 minutes and 7.0 minutes.

Efficiency Gain & Temperature Reduction

The Ford Motor Company tested the effect of Superfinishing rear axle ring and pinion gears on the overall fuel efficiency [8]. A rear axle ring and pinion gearset was Superfinished to a 0.07 µm R_a. Chassis roll dynamometer tests under metro/highway cycles were then conducted. Figure 8 compares the axle efficiency between the superfinished gears and production gears at 1000 RPM.

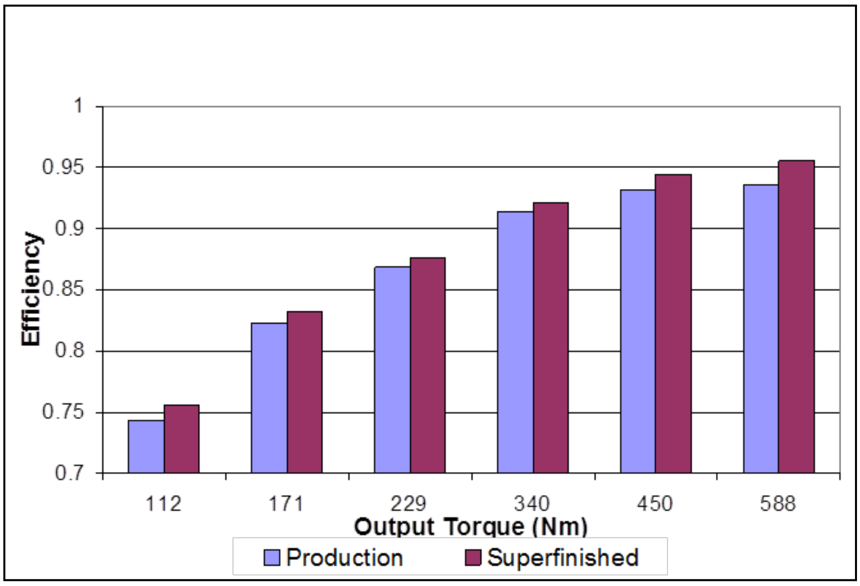


Figure 8: Axle efficiency of the Superfinished ring and pinion gearset.

The Superfinished ring and pinion showed an improvement in efficiency that resulted in approximately 0.5% increase in fuel economy. The operating temperature of the rear axle was also significantly reduced with the Superfinished gears.

6. Conclusions

1. The Rapid ISF® process can Superfinish ground or lapped OEM hypoid gearsets to a <0.25 µm R_a in less than 5.0 minutes, and <0.10 µm R_a in less than 8 minutes.
2. The geometry of superfinished gears has always been found to be within tolerance, and the noise, vibration and harshness never negatively altered.
3. The contact pattern checks of lapped gears finished for 5.0 minute and 7.0 minute cycles were deemed acceptable by the OEM.
4. Efficiency gains due to reduced parasitic friction resulted in approximately 0.5% increase in fuel economy after Superfinishing OEM hypoid gearsets.
5. The drag finisher machine lends itself to full automation by robotics if desired and satisfies the need of modern manufacturing facilities where JIT cells are desired.

7. References

[1] Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2007 September 4-7, 2007, Las Vegas, Nevada, USA DETC2007-34860

[2] Lane Winkelmann, Jerry Holland & Russell Nanning, REM Chemicals Inc. "Superfinishing Motor Vehicle Ring and Pinion Gears", AGMA 2004 FTM

[3] Hashimoto F.F.H., Zhou R.S., Howlett K., U.S. Patent 5,503,481 (1996) "Bearing Surfaces with Isotropic Finish," (Assigned to REM Chemicals, Inc., Southington, CT.)

[4] Mark Michaud, Lane Winkelmann, Ray Snidle, Mark Alanou, "EFFECT OF SUPERFINISHING ON SCUFFING RESISTANCE" ASME 2003 Design Engineering Technical Conference.

[5] Sroka, Lane Winkelmann. "Superfinishing Gears- The State of the Art", Gear Technology magazine, Nov-Dec 2003

[6] David Chmielewski, Walther Corp. "Is This the Mass-Finishing Answer You Have Been Looking For?". PF online, May 1997

[7] US Patent Application 20110117820 Magnetic Fixture Sroka and El-Saeed

[8] US 2005/0202921 A1 FORD GLOBAL TECHNOLOGIES, LLC, Dearborn, MI (US) Application of Novel Surface Finishing Technique for Improving Rear Axle Efficiency