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Superfinishing Rear Axle Gears – A Significant Step Toward Reducing Automotive Greenhouse Gas Emissions

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ABSTRACT

New regulations make it imperative that the European and US automotive industries meet strict, lower greenhouse gas emission standards. It is well documented that isotropic superfinishing automotive rear axle gears can play a significant role in reducing these emissions. Rear axle gears have been commercially isotropic superfinished using conventional vibratory finishing for many years, but this process has often been viewed as being too expensive and cumbersome for large-scale automotive production. After five years of development and testing, the drag finishing process has been perfected to a point that rear axle gears can be isotropic superfinished economically in a matter of minutes. The gears are rapidly mounted and dismounted to the machine via magnetic fixturing making this equipment amenable to full robotic operation.

This paper will give details on the reduction of greenhouse gas emissions by isotropic superfinishing, the drag finishing machine, the magnetic fixture of the rear axle gears, the achievable surface finish, and the superfinishing cycle time.

INTRODUCTION

Government regulators have established lower Greenhouse Gas (GHG) emissions for automotive emissions. For example, the European Union is imposing strict financial penalties of about at €95/(g-CO_2/km) for emissions above the standards in Europe.[i] Since the automotive market is global, US car manufacturers must also meet equivalent standards.[ii] Currently, CAFE non-compliance is only fineable by the EPA. On the other hand, emission levels are mandatory. NHTSA can refuse to certify a car for sale if emission regulations are missed. Mandatory recalls can also be implemented if it is discovered that vehicles are not meeting emission requirements due to discovery of original certification, false positives, or observed field degradation of emission compliance equipment. Now that the EPA has included CO_2 as a GHG over which it has statutory authority; CO_2 per mile goes right along with MPG. Therefore, the financial consequence of missing CAFE MPG can possibly result in loss of ability to sell, exposure to recalls and worse.

The rear axle is a major contributor to energy loss in today's passenger vehicles. See Figure 1.

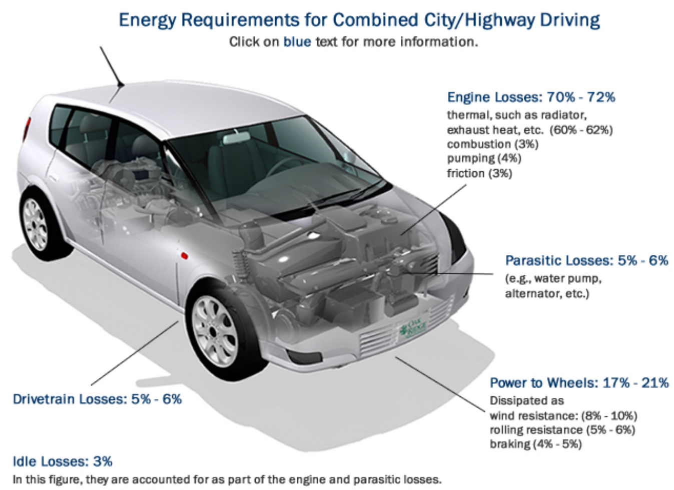


Figure 1iii. Shows that 5.6% of a passenger car's fuel is wasted on friction and slippage in the drive train.

Hypoid gears are used in passenger cars since they are stronger, quieter and can be used for higher reduction ratios. Since they experience sliding action along the teeth, energy is expended to overcome friction which is shed in the form of heat. It has been well over a decade since the motorsport industry took advantage of isotropic superfinishing to increase fuel efficiency and durability. For this reason it should also be noted that a number of aerospace companies use or plan to use isotropic superfinishing to increase performance, especially on gears that are highly loaded such as those in rotary aircraft.

In the OEM automotive industry, Ford[iv] found that isotropic superfinished hypoid gears "resulted in about a 0.5% improvement in fuel economy in chassis roll dynamometer tests under metro/highway cycles". Others have seen similar fuel efficiency increases for isotropic superfinished rear axle gears.[v]

A recent study[vi] on the energy consumption by passenger cars due to friction states: *The topography of a surface in sliding contact has a remarkable influence on friction in both dry and lubricated sliding. This friction has long been considered only as a surface roughness property of the component. Recent research has shown that the influence of the micro-and nanoscale topography is more complex but, at the same time, offers interesting possibilities for friction reduction. Changing the surface topography of gears to be smoother by superfinishing has been shown to reduce friction by typically 30%.*

Another recent study on hypoid efficiency makes an interesting point[vii]*: On the other hand, the efficiency of the drive-train is highly dependent on temperature. A further complication is that most legislation is based upon a small number of, typically low-power, drive cycles. Testing for compliance with the rules on fuel economy and emissions involves rig testing of the vehicle under conditions that do not necessarily reflect their real-world usage. For example the European fuel economy test (which follows the "New European Drive Cycle, NEDC") requires a starting temperature of 20–25 ºC and lasts for only 20 minutes. During this period, the engine warms up to its thermostatically controlled temperature, but the axle, which is dip-lubricated and physically separate, remains relatively cool, as will be shown.*

In contrast, the same vehicle may be subject to severe usage involving hot weather, high towing loads, steep gradients and high speeds leading to very much higher temperatures and appreciably different tribology. Therefore, isotropic superfinished hypoid gears will impart even more significant fuel savings than that determined by legislative testing.

When production gears are evaluated in head-to-head comparison testing to isotropic superfinished gears, the production gears usually go through a "proper run-in" whereas superfinished gears require no run-in. Since the majority of passenger vehicles do not experience a "proper run-in", the performance of vehicles with superfinished gears will have even greater performance benefits. The data shows this under carefully controlled testing.

In addition, isotropic superfinished gears do not demand the higher viscosity and/or additive packages like production gears. Therefore, the fuel efficiency can be further increased by lowering the rear axle lubricant viscosity to minimize losses while still maintaining their durability.

A number of major automotive manufacturers have evaluated the isotropic superfinishing of rear axle gears, and have obtained promising fuel efficiency savings. Why then has this technology been so slow to gain acceptance in the automotive industry?

The main reason is that the process is not user friendly for high volume production of rear axle gears. In the past, conventional isotropic superfinishing was carried out in vibratory machines with finishing times ranging from approximately half an hour to an hour, and required manual labor. Up until this time, there has been no pressure put on the industry to lower GHG emissions or suffer severe financial penalties.

The following sections of the paper discuss the nature of hypoid gears, Rapid ISF technology and data on the benefits that it provides.

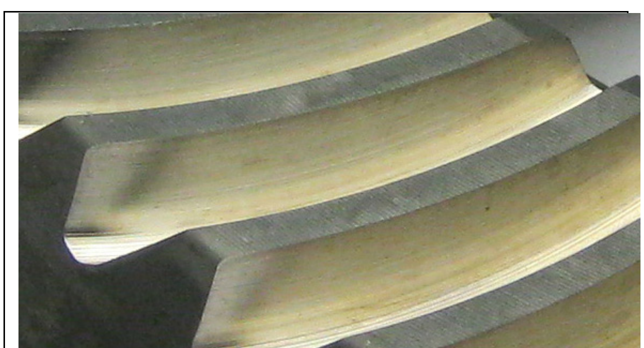
NOMENCLATURE

- Roughness Average
- Supermagnets
- Accelerated Chemistry
- Media
- Drag Finisher
- TOE (narrow part of the gear tooth)
- HEEL (wide part of the gear tooth)
- DRIVE SIDE (convex side of the gear tooth)
- COAST SIDE (concave side of the gear tooth)

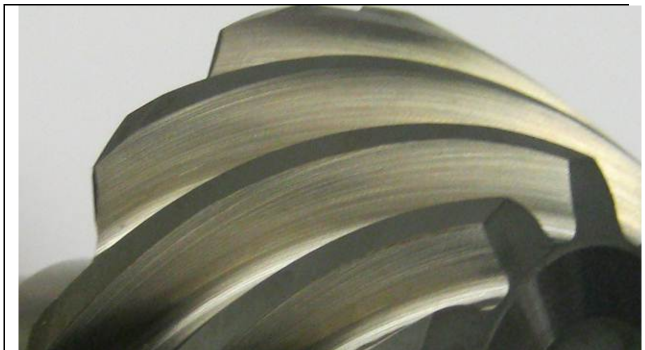
DESCRIPTION OF THE TEST

Description of the Hypoid Gears

Hypoid gears are used in heavy trucks, four-wheel-drive and rear wheel drive passenger cars, sport utility vehicles, and light trucks. They and are the type of gears used in this study. The convex side of the ring gear and the concave side of the pinion gear are the drive sides of this hypoid set. Since the vast majority of operating time is spent on the drive side, these are the most important surfaces to finish to obtain increased fuel economy (i.e., or lower greenhouse gas emissions). The ten hypoid gears isotropic superfinished in this paper have a gear ratio of approximately 2.8 with the diameter of the ring gear being approximately 140mm. The gears were carburized and then ground. The average surface roughness of the convex side of the ring gear was 0.56 micron R_a; the average surface roughness of the concave side of the pinion gears was 0.57 R_a. The ring gear may or may not contain bolt holes depending on whether the ring gear is bolted or welded to the differential case assembly. See Figure 2 showing a close-up of the ground ring gear and pinion gear.



Initial ground surface of drive side (convex) of ring gear.



Initial ground surface of drive side (concave) of pinion.

Figure 2. Close up photos of ground surface of ring gear and pinion gear before isotropic superfinishing.

Vibratory Finishing Description

A description of vibratory finishing rear axle gears using chemically accelerated vibratory finishing was presented in an earlier paper.[viii] The following is a brief summary of the technique. The isotropic superfinish 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.

The speed of isotropic superfinishing can be significantly increased by using a more aggressive active chemistry and/or raising the temperature of the vibratory machine. The media rubbing provided by a conventional vibratory machine, however, is not aggressive enough to keep up with the formation of the conversion coating. Thus, a hard conversion coating will be formed, and the isotropic superfinishing mechanism will come to a standstill. Therefore, by using a machine that moves the media faster and with more energy it is possible to reduce the isotropic superfinishing time by a factor of seven. The machine to accomplish this is called a drag finisher.

Drag Finisher Description

A description of the drag finishing machine is given by Chmielewski.*[ix]

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.

As you visualize a plow cutting through a field, you can appreciate the significance of these physical elements. 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.

The machine used in the test is a four-spindle industrial drag finisher. See Figure 3 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).

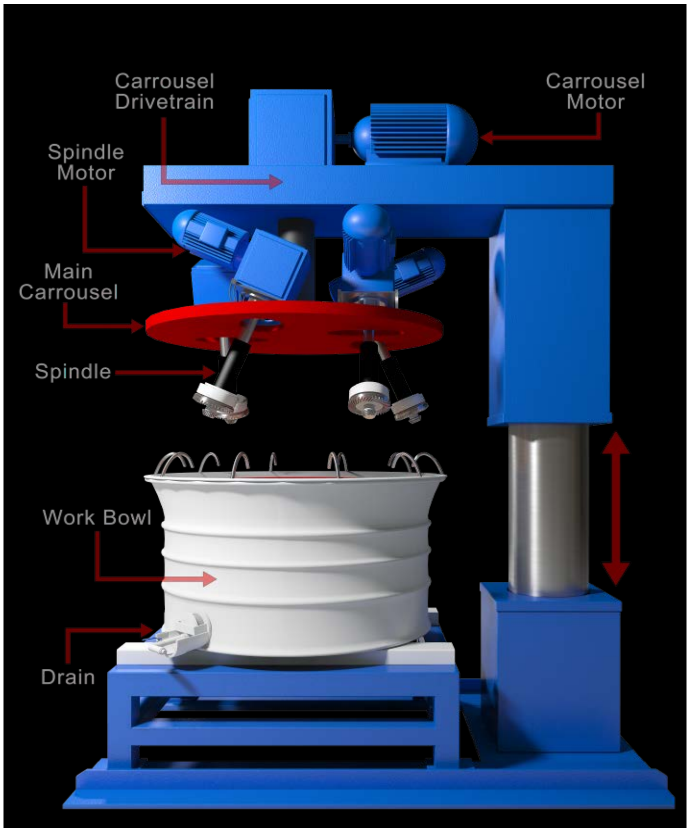


Figure 3. 3D image of the drag finisher showing the component parts.

Description of the Magnetic Fixture

As previously mentioned, the ring gear 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.[x] A plastic fixture sized to fit the dimension of the particular rear axle gears is fastened to a steel shaft as shown in Figures 4 and 5. This has the added benefit of preventing stock removal from the backside of the gear.

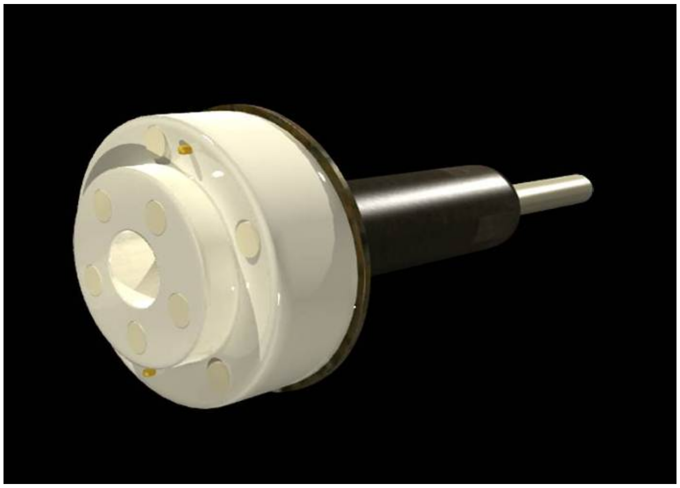


Figure 4. The small circles are the location of supermagnets placed around the larger plastic cylinder to hold the ring gear in place.

Similarly, the small circles on the smaller cylindrical section are the location of supermagnets to hold the pinion to the fixture.

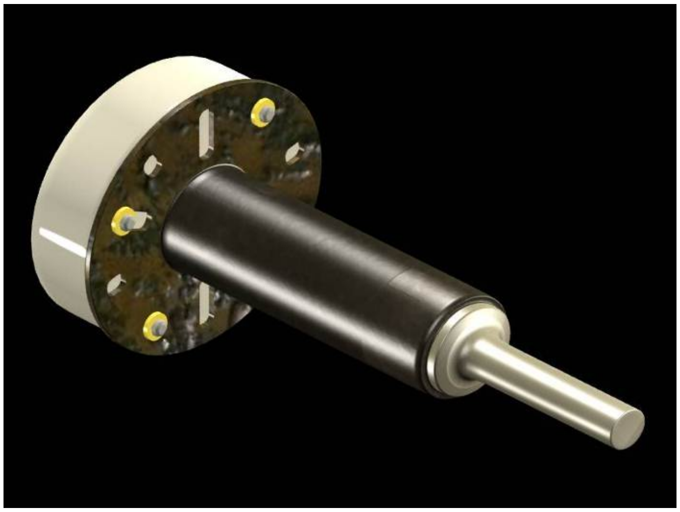


Figure 5. The plastic magnetic fixture attached to spindle and shown above.

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 so strong that the ring and pinion cannot 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.

Figure 6. 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 8.

Figure 7. The spindle is attached to the drag finisher with the ring gear and pinion gear held by the magnetic force to the plastic fixture.

The specifications of the drag finishing machine are shown in Table 1.

Operation	Programmable with full automation capabilities
Dimensions (L x W x H)	8.5 ft x 9.8 ft x 11.8 ft) (2.6 m x 3.0 m x 3.6 m)
Work Bowl ➢ Diameter ➢ Media load ➢ Vibratory Motor ➢ Wear-resistant Liner	 4.4 ft 30 ft^3 1.2 hp polyurethane
Main Carousel ➢ Drive Power ➢ Carrousel Movement	 10 hp CW/CCW
4 Work Stations with Independent Drive ➢ Drive Power ➢ Spindle Movement ➢ Spindle Angle	 4 x 2.0 hp CW/CCW Adjustable
Maximum Workpiece Dimensions ➢ Diameter ➢ Height	 17 in. 15 in.

Table 1. Description of the mini-drag finisher.

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 7. 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 isotropic superfinished simultaneously.

Isotropic 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. It also should be noted that a planarized surface having a 0.2 micron Ra will give almost the same fuel efficiency performance as a 0.1 micron surface. This again allows one to produce suitable gears for the OEM automotive industry with regards to fuel efficiency. On the other hand, if one desires to take advantage of using a lower viscosity lubricant, it is recommended that the isotropic superfinished surface be approximately 0.1 micron R_a.

The parameters used to isotropic superfinish the hypoid gears discussed in this paper are given in Table 2.

Test Parameters	
Main Carousel Speed	55%
Main Carousel Rotation	CW
Spindle Speed	100%
Spindle Rotation	CW
Spindle Depth	650 mm
Spindle Angle	20º
Media Description	Non-abrasive Ceramic
Accelerated Chemistry	FERROMIL® FML-7800
Bowl Temperature	50-52 °C
Process Time	8.0 min.

Table 2. Drag Finisher parameters used to isotropic superfinish the hypoid gears.

The gears were isotropic superfinished in the drag finisher for only 8.0 minutes using a heated accelerated chemistry. Only a very light conversion coating was present on the gears indicating that the media rubbing was sufficient to keep up with the more aggressive chemistry. The surface roughness of the convex and concave sides of the ring gears and pinion were measured using a stylus profilometer. A typical surface trace along with the average R_a is presented in Table 3. The drive sides of the gears had an average surface roughness of less than 0.1 micron R_a. The pinion coast side also achieved a <0.1 micron R_a, and even the coast side of the ring gear had a 0.21 micron R_a.

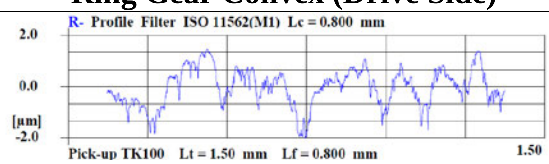
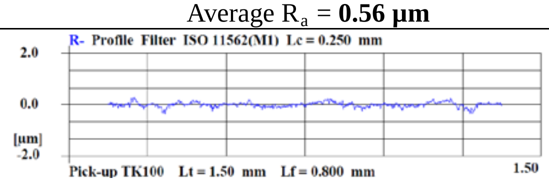
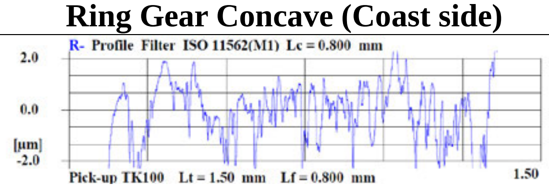
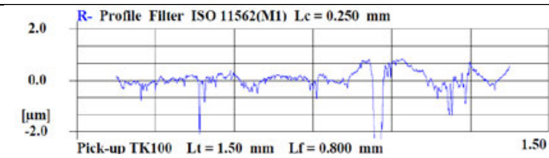
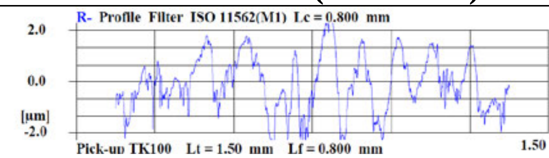
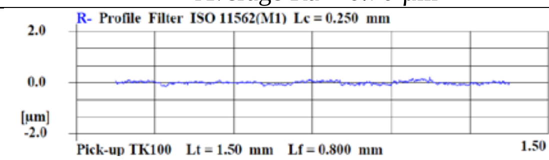
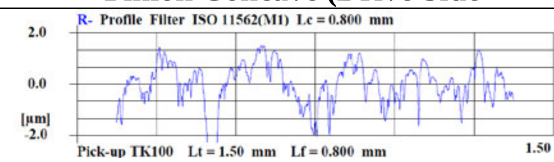
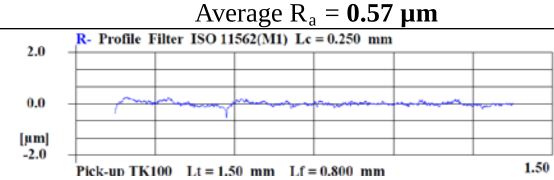
	Ring Gear Convex (Drive Side)
Before	 Average R_a = **0.56 µm**
After	 Average R_a = **0.09 µm**
	Ring Gear Concave (Coast side)
Before	 Average Ra = **0.86 µm**
After	 Average Ra = **0.21 µm**
	Pinion Convex (Coast Side)
Before	 Average Ra = 0.70 µm
After	 Average Ra = **0.06 µm**
	Pinion Concave (Drive Side
Before	 Average R_a = **0.57 µm**
After	 Average R_a = **0.07 µm**

Table 3. Typical; before and after surface traces of the concave and convex sides of the ring gears and pinions after isotropic superfinishing for only 4.0 minutes.

Drag finishing has been used to isotropic 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. Multiple commercial automotive tests of isotropic superfinished axles, when compared to standard commercial production have consistently shown a 0.5% increase in axle efficiency. This can be equivalent to over 1.0 g/km of CO_2 reduction when lower viscosity lubricants are incorporated in the axle.

CONCLUSIONS

1. Isotropic superfinished gears can make a significant improvement to reducing friction and thus reducing greenhouse gas emissions (GHG).
2. The drag finisher is a commercial production ready machine that can achieve isotropic superfinishing on the drive and coast side of rear axle gears to less than 0.1 micron R_a.
3. Isotropic superfinishing the hypoid gears increases fuel efficiency and reduces CO_2 emissions.

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