Superfinishing Gears—The State of the Art

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Introduction

Superfinishing the working surfaces of gears and their root fillet regions results in performance benefits. For example, in 1987, Tanaka et al. showed that an appreciable increase in surface durability could be achieved when gear pairs were finished to a mirrorlike surface using a cubic-boron-nitride (CBN) wheel (Ref. 1). Since that time, it has been further established that superfinishing gears to a low surface roughness can reduce friction, pitting fatigue, noise, operating temperature, bending fatigue, metal debris and wear (Refs. 2–9).

Superfinishing hardened gear surfaces using conventional techniques, such as grinding and/or honing, however, has several serious drawbacks. Not only are such processes costly and time consuming, but there is always the risk of permanently damaging the gear by either destroying the tooth profile or introducing grind burn. In addition, such superfinishing methods can routinely achieve a roughness average (R_a) of only 6.0–12 µin., whereas there is technical data strongly supporting that a smoother surface is even more beneficial (Refs. 1–8).

For the past several years, chemically accelerated vibratory finishing has been used to successfully superfinish high quality gears to a roughness average (R_a) between 1.0 and 3.0 µin. The aim of this article is to identify and dispel two common misconceptions about this technique.

Figure 1—SEM images of test specimens superfinished with ceramic (top) and plastic (bottom) non-abrasive media.

Description of the Superfinishing Process

Before proceeding further, it is important to explain how this process works and how it is radically different from conventional machining. The following is a brief overview of the chemically accelerated vibratory finishing process using high density, non-abrasive ceramic media.

Vibratory machines. The process is carried out in vibratory finishing bowls or tubs. These relatively inexpensive and durable machines are basically unchanged in design since their introduction more than 40 years ago. Vibratory finishing machines are available in sizes from 0.5 to 250 cubic feet of working capacity. This means gears can be finished ranging in size from less than two inches in diameter to more than six feet in diameter and quantities from one to thousands at a time.

High density, non-abrasive ceramic media. **(Ref. 10)** The process utilizes high density, non-abrasive ceramic media in the vibratory finishing machine. It is considered non-abrasive since it does not contain discrete abrasive particles and alone is unable to abrade material from the hardened surface of the gears being processed. The media is selected from a range of shapes and sizes best suited for maintaining the geometry of the gears. No finishing occurs on a surface where media is unable to contact and rub. By selecting a media that has a uniform probability of contact across all surfaces, especially across the tooth flanks, the tooth profile and lead are not adversely affected, even with AGMA Q12 gears (Ref. 11). One important advantage of the high-density ceramic media is that it has essentially no attrition during usage. The process is consistent for thousands of hours of production because the size and the shape of the media remains constant.

Process chemistry. The unique and significant feature of the process is the surface leveling/smoothing mechanism utilized to achieve the surface finish. A reactive chemistry is used in the vibratory machine in conjunction with the media. When introduced into the machine, this chemistry produces a stable, soft conversion coating across the asperities (peaks and valleys) of the gears.

The rubbing motion across the gears developed by the machine and media effectively wipes the soft conversion coating off the “peaks” of the gear’s surfaces, thereby removing a micro-layer of metal. The “valleys” are left untouched since the media bridges over them and cannot wipe the conversion coating. The conversion coating is continually re-formed and wiped off during this stage, producing a surface leveling/smoothing mechanism. This mechanism is continued in the vibratory machine until the surfaces of the gears are free of asperities. At this point, the reactive chemistry is rinsed from the machine with a neutral soap. The conversion coating is wiped off the gears one final time to produce the mirrorlike surface.

It is important to note that the reactive chemistry producing the conversion coating is only mildly acidic, having a nominal pH of 5.5, and the process is normally carried out at ambient temperature. Thus there is no possibility of hydrogen embrittlement or grind burn, as is common with mechanical grinding or honing operations.

When a number of gears are processed simultaneously, all are exposed to the same mechanical and chemical environment such that every tooth of every gear is processed identically. This eliminates the need for 100% final inspection.

Depending on the choice and concentration of the active chemistry, the process can be controlled to remove stock at a rate of 0.00005 to 0.00040 in./hr. Therefore, aerospace gears with an AGMA quality of Q12 or greater and an initial R_a of 12 µin. or OEM automotive gears with an initial R_a of 60 µin. can be superfinished to a low surface roughness in approximately 1.0 hour.

Health, safety and environmental considerations. The chemicals used to produce the superfinished gears of alloy steels are non-toxic and are classified as non-hazardous by 49CFR (Federal Hazardous Material Transportation Law). Such products have been supplied to a wide variety of industries for more than 15 years without any health or safety incident.

The waste produced by the process is classified as non-hazardous according to the Environmental Protection Agency (EPA), but the waste may require standard metals precipitation to meet local and state discharge regulations.

Gear Industry Acceptance

As with any new technology, initially there were some serious technical questions that needed answering. This was especially true for gears used in aerospace or military applications where any failure could be catastrophic.

Metallurgists had apprehensions that gear alloys exposed to an acidic chemistry would produce hydrogen embrittlement and/or intergrannular attack. Both in-house and outside testing quickly dispelled such fears and demonstrated that this process is metallurgically safe. The results have been presented elsewhere, and these concerns no longer seem to be an issue (Refs. 8–9).

However, other misconceptions about the process have surfaced from time to time. It is the purpose of this article to identify and explain two common misconceptions.

Misconceptions

Misconception No. 1. Gear teeth having a mirrorlike surface will not have the proper lubrication properties. Residual machine lines or a dimpled surface are required for oil retention.

Two basic facts are known about the correlation between surface roughness and tribological properties:

1.) If two mating surfaces are too rough, boundary or mixed lubrication occurs. The resulting metal-to-metal contact produces a higher operating temperature, increased friction and increased wear.

2.) On the other hand, if the two mating surfaces are too smooth,

Table 1—Specifications of Scuffing Specimens.

Property	Specification
Material	AMS 6260 (SAE 9310 Air Melt)
Heat Treatment	Carburized
Surface Finish after Grind (RMS)	16 µin. max.
Hardness (HRC)	60–63
Effective Case Depth (in.)	0.036–0.042
Core Hardness (HRC)	36–41
Diameter	3.0 in.
Crowning radius of disks with transverse radius of curvature	12.0 in.

Table 2—Testing Parameters of Two-Disk Apparatus.

Peripheral Velocity of Fast Shaft (ft./sec.)	65.62
Peripheral Velocity of Slow Shaft (ft./sec.)	16.21
Mean Entraining Velocity (ft./sec.)	42.49
Sliding Velocity (ft./sec.)	52.49

Table 3—Number of Test Specimens Finished in Each Type Of Media.

Media Type	No. of Specimen Sets
Non-abrasive ceramic	3
Non-abrasive plastic	2

Table 4—Results of Scuffing Tests.

Test	Ground	Ceramic			Plastic	
Scuffing Load (lbs.)	522	933*	933*	933*	776	776

* No scuffing occurred at maximum testing load and 30 minutes hold time.

Table 5—Specifications of SAE 8620 Carburized Rolling/ Sliding Contact Fatigue Specimens.

Property	
Material	SAE 8620
Hardness (HRC)	60–61
Roughness Average (R_a) (µin.)	26

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then adhesive forces become appreciable, again resulting in high friction and wear. Anyone who has held two clean, highly polished flat steel surfaces together knows just how strong this force can be.

There is no argument among gear designers that removing the peaks from the working surfaces of gears is beneficial. After all, if the peaks are left in place, there must be a traditional run-in period when friction and operating temperature are high, and metal debris is generated, which causes further damage to the lubricant, gears, bearings, or all three.

In addition, since these peaks are fractured or sheared from the surface during the traditional run-in, initiation sites for future contact fatigue are seeded. So the question arises: What type of surface is needed to obtain optimum performance?

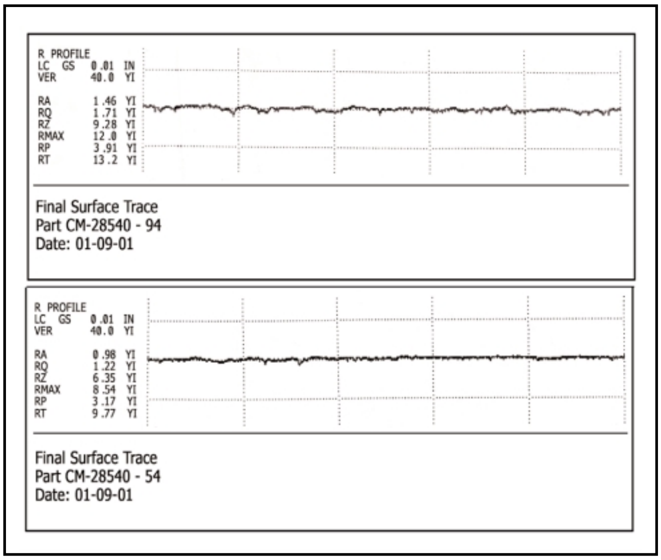


Figure 2—Surface roughness profiles of test specimens superfinished with ceramic (top) and plastic (bottom) non-abrasive media.

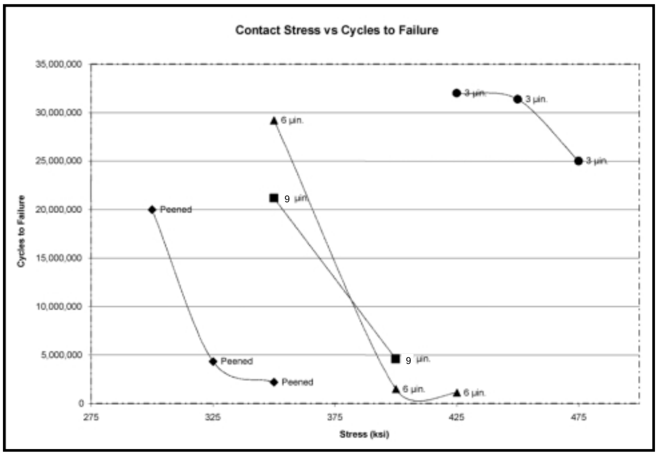


Figure 3—Results of rolling/sliding contact fatigue testing.

Table 6—Surface Treatment of Specimens Tested.		
	R_a (µin.)	Surface Treatment
Baseline	22	Shotpeened, 230 Hard Cast Shot, 0.012–0.015 Almen “A,” 200%
Group I	8.8	Superfinished using chemically accelerated vibratory finishing in non-abrasive ceramic media
Group II	5.9	
Group III	2.6	

In an attempt to answer this question, two experiments were conducted by independent gear research laboratories: Cardiff University’s engineering school in Wales, U.K., and The Pennsylvania State University’s Gear Research Institute in State College, Pennsylvania, U.S.A.

Scuffing. At Cardiff University, scuffing specimens and testing were provided by the engineering school’s R.W. Snidle. The specifications of the specimens are given in Table 1.

A special two-disk machine was used for the testing with the aim of simulating gas turbine gearing conditions as closely as possible. The ratio of the speeds of the two shafts may be preset from unity (pure rolling) up to a value of almost five. In the work reported here, the ratio for the speeds was 4.24, which gives a slide/roll ratio of 1.24. One shaft is supported on fixed bearings, and the second shaft is mounted on a swinging yoke.

Scuffing is caused by running the disks at constant speed and increasing the load between them at 3-minute intervals. The maximum load that is normally applied to the contact is 933 lbs., which produces a corresponding maximum Hertzian pressure of 247 ksi. The testing parameters are given in Table 2.

Two groups of scuffing specimens were superfinished using chemically accelerated vibratory finishing. One group was processed using non-abrasive ceramic media, while the other was processed using non-abrasive plastic media. Table 3 lists the number of test specimen sets finished in each type of media.

The two surfaces are both mirrorlike in appearance to the naked eye, but the Scanning Electron Micrograph (SEM) images at 500X clearly show that the surfaces are quite different (see Fig. 1). Typical profilometer traces along with the surface measurement parameters for these surfaces are shown in Figure 2 and are consistent with the SEM images. The ceramic media causes scratches and dings on the surface, while the plastic media produces a very smooth surface. Prior to testing, it was anticipated that the surface processed using the plastic media would significantly outperform that produced with the ceramic media.

The surface formed with the ceramic media is typical of the isotropic surface produced with non-abrasive ceramic media. This surface has undergone thorough evaluation over the past several years and has demonstrated that it can increase performance, resulting in reduced friction, lower operating temperature, better contact fatigue resistance and less wear (Refs. 8, 12–13).

Scuffing test results. The results of the testing are summarized in Table 4. Surprisingly the more highly textured surface using the non-abrasive ceramic media was vastly superior to the ultra-smooth surface of the non-abrasive plastic media with regards to scuffing. Even more remarkable is the fact that the highly textured surface did not scuff even at the maximum loading of the test and even after the test was allowed to continue for an additional 30 minutes.

Therefore, it is now evident that two mirrorlike surfaces with low R_a’s can perform quite differently. As predicted, too smooth of a surface without microtexture does not perform as well as the smooth but textured surface. The microtexture created by the non-abrasive ceramic media is essential to obtaining optimum performance benefits from surface finishing.

Rolling/sliding contact fatigue. At The Pennsylvania State University, rolling/sliding contact fatigue tests were performed at the Gear Research Institute and were sponsored by the institute's Vehicle Bloc.

Case carburized SAE 8620 rolling/sliding contact fatigue specimens were fabricated without any grinding/honing after carburization. The specification of these specimens is given in Table 5. The baseline specimens were shotpeened after carburization. Two sets of seven specimens each and a third set of four specimens were finished using chemically accelerated vibratory finishing with high density, non-abrasive ceramic media. The sets were processed after carburization to a low, medium and high level of surface finish (see Table 6).

The rolling/sliding contact fatigue testing was done under the conditions shown in Table 7. The results are listed in Table 8 and are shown graphically in Figure 3.

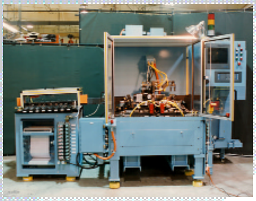
In this study of SAE 8620 specimens, the maximum benefit for performance is achieved by refining to a line-free, isotropic condition with an $R_a < 3.0$ µin. It is postulated that this process not only improves performance because it removes the peaks from the working surface and creates a microtexturing, but it also removes any damage to the metal surface caused by grinding, honing or carburization.

Another interesting observation is that even the partially finished specimens still well outperformed the baseline shot-peened specimens. Specimens receiving the full finish (i.e., line-free with an $R_a < 3.0$ µin.) performed as well as aerospace specimens from an earlier study manufactured from SAE 9310. In that study, the aerospace specimens were ground/honed after heat treatment and then superfinished. It should also be mentioned that there were three other sets of specimens superfinished to an $R_a < 3.0$ µin. and tested by rolling/sliding contact fatigue over a two-year period. All had extremely good contact fatigue and wear resistance (Ref. 14).

In conclusion, the most desirable surface has an $R_a < 3.0$ µin. and has microtexturing to facilitate lubrication, as shown in Figure 1's top image. This microtexturing, with its extremely shallow dings and random scratch pattern, is inherent to chemically accelerated vibratory finishing using high density, non-abrasive ceramic media. Residual machine lines or deep dimples are not essential, and in fact are detrimental insofar as these can contain damaged metal or act as stress raisers leading to contact and/or bending fatigue.

Misconception No. 2. The relationship between surface roughness parameters and component functionality is not well understood and requires advanced mathematics and sophisticated software. Therefore, there is no simple method of determining what surface will give the desired performance benefit.

This misconception arises because of the extreme difficulty to characterize a surface. Today there are about 57 different surface roughness parameters described in current standards for 2-D pro-



filometry and 14 parameters for 3-D topographic analysis. This being the case, it would be difficult to predict the performance of a given surface.

In the previous section, it was found that a surface having an $R_a < 3.0$ µin. generated by chemically accelerated vibratory finishing using high density, non-abrasive ceramic media gave excellent performance on test rigs designed to simulate gear performance. This again is attributed to the fact that the non-abrasive ceramic media consistently gives the microtextured surface that facilitates lubricant retention.

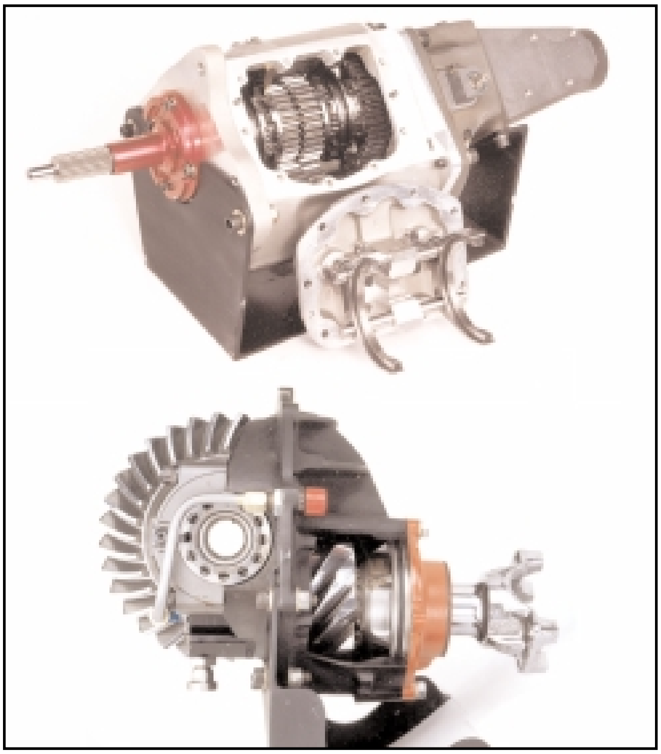


Figure 4—NASCAR transmission and differential that are superfinished with chemically accelerated vibratory finishing using high density, non-abrasive media. Courtesy of Tex Racing.

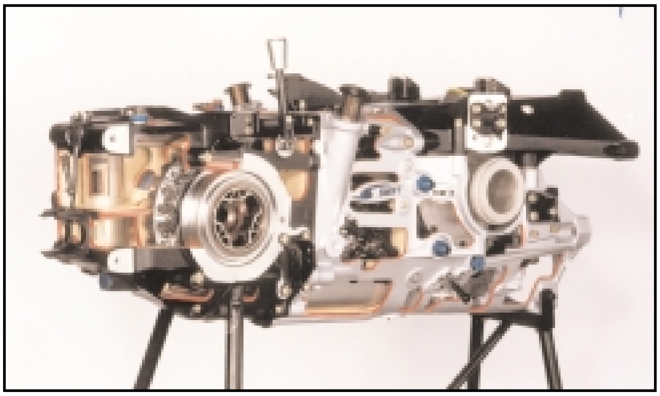


Figure 5—IndyCar™ transmission that is superfinished with chemically accelerated vibratory finishing using high density, non-abrasive media. Courtesy of Swift Racing Technologies.

Table 7—Parameters of Rolling/Sliding Contact Fatigue Testing.

Testing Parameters	
RPM of Test Rig	1,330
Runout (cycles)	30×10^6
Negative Sliding (%)	43
Temperature (°F)	200

Field performance using this superfinishing process over the last five years supports the validity of the test rig data and the use of only roughness average as the measurement parameter to ensure proper finishing. Various job shop facilities across the country routinely use this superfinishing process on transmission and differential gears for the automotive racing industry.

For example, all NASCAR racing teams use this process as well as many of the IndyCar™ series teams. Figure 4 is an example of a NASCAR transmission and differential superfinished by this process. Note the mirrorlike surface of the tooth flanks.

Figure 5 is an example of an IndyCar transmission superfinished by this process. The superfinished gears can be glimpsed through an opening beneath the Swift logo. In Europe, the process is used by several Formula 1 cars. No transmission or differential problems have been attributed to this process. In fact, post-race inspections of the gears show little to no indications of usual wear or pitting patterns. An example of this is shown in Figure 6.

The standard finished (ground) gear has been run for 500 miles in a typical race transmission. The contact pattern is clearly marked by pitting and wear. The superfinished gear, on the other hand, shows no contact pattern, wear or micropitting at all after being run for the same 500 miles in the same transmission.

Similarly, gears finished for aerospace companies such as Westland Helicopters Ltd., Sikorsky Aircraft Corp., and Rolls-Royce Gear Systems and for automotive companies such as DANA Corp., Ford Motor Co. and GM Powertrain have all shown performance improvements after superfinishing with this process using only the R_a as a criterion for proper finishing (Refs. 15–17).

A few examples of these improvements reported by aerospace companies are: sustained operating temperature reductions of 5°F while using an external oil cooler, reductions in vibro-acoustic noise of up to 7 dB, increases in bending fatigue resistance of approximately 10 percent and significant increases in contact fatigue resistance. Improvements reported by automotive companies include elimination of the initial run-in temperature spike followed by a reduction of the sustained operating temperature by up to 50°F, significantly less wear and much lower coefficients of friction.

Summary

Superfinishing gears using chemically accelerated vibratory finishing with high density, non-abrasive ceramic media brings about a surface textured property that facilitates lubrication. The superfinished surface will be free of stress raisers, damaged metal and peak asperities, all of which reduce the life of the gears. These gears will experience reduced friction, lower operating temperature, less wear, better scuffing resistance, and better contact fatigue resistance. Laboratory and field testing supports the conclusion that only the R_a needs to be monitored during the process to attain proper surface finishing. An R_a of < 3.0 µin. will ensure optimum performance benefits (Refs. 6–9, 12–17). ⚙

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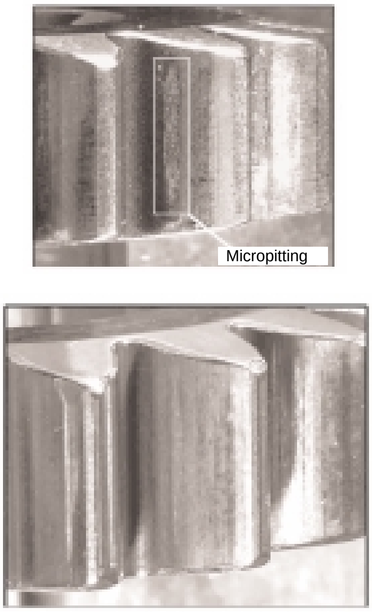

Figure 6—Two gears that each completed 500 miles of use in an automotive racing transmission. The top gear had the standard ground finish while the bottom gear had been superfinished with chemically accelerated vibratory finishing with high density, non-abrasive ceramic media. Note there is no wear or micropitting at the contact area on the superfinished gear.

Table 8—Rolling/Sliding Contact Fatigue Results for Various Levels of Surface Finish.

Surface Finish	Contact Stress (ksi)	Cycles to Failure (10^6)	Mean (10^6)
Shotpeened $R_a \approx 22$ µin.	300	12.0	20.0
	300	28.0	
	325	3.1	4.3
	325	3.7	
	325	6.2	
	350	2.2	2.2
$R_a \approx 8.8$ µin.	350	5.6	21.2
	350	26.0	
	350	31.9	
	400	1.4	4.6
	400	2.8	
	400	4.1	
	400	10.0	
$R_a \approx 5.9$ µin.	350	25.0	29.2
	350	32.4	
	350	30.2	
	400	1.2	1.5
	400	1.7	
	425	0.9	1.1
	425	1.4	
$R_a \approx 2.6$ µin.	425	32.0	32.0
	450	31.3	31.3
	450	31.5	
	475	25.0	25.0