The Fundamentals of Surface Engineering by Superfinishing using a Chemically Assisted Vibratory System

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Metal gears are manufactured to their rough dimensions by some combination of metallurgical and machining steps. However, the grinding processes used to finish gears leave microscopic surface features that influence gear life. Therefore, additional processes are needed to eliminate these features while preserving the required geometric accuracy. Recent experimental results indicate that improved part surface finish, via superfinishing, can reduce contact fatigue in gears by a factor of 3, as well as enhance the bending fatigue life of their teeth by at least 10%.[1] An improved surface finish also helps to maintain a fully elastohydrodynamic lubricant film that will prevent metal-to-metal contact in mating parts and will virtually eliminate contact wear and pitting fatigue. Such improvements reduce the downtime and cost for repair and maintenance. Additional benefits of superfinishing include an increase in load bearing capacity, a decrease in noise and a decrease in coefficient of friction between mating surfaces that can reduce the amount of frictional losses inherent in any power transfer system which will lead to reduced operation and sustainment costs. Furthermore, this improved gear performance provides an opportunity to reduce component weight in new designs. This article reviews the process techniques, tests, results and benefits of applying this superfinishing process.

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Introduction

Both the AMMTIAC** initiated Surface Engineering Center (SEC-Alion) and the Engineered Surfaces Center at the University of North Dakota (ESC-UND) have been actively pursuing engineering solutions for weapon systems life extension through further development of the Chemically Accelerated Vibratory Surface Finishing (CAVSF) process or superfinishing. Previous Alion research demonstrated what effect superfinishing had on critical components of weapon systems and discovered that significant advantages result from superfinishing high class (AGMA Class 13) aerospace gears. These advantages include an increase in part longevity of up to 300% and an increase in load bearing capacity in excess of 10%.[1] This successful research motivated Tier 1 DoD suppliers to install and implement the superfinishing process for manufacturing weapon systems components. Even though the benefits are obvious, the science behind the process was not greatly understood. The DoD and other Tier 1 suppliers were interested in discovering more of the science behind the superfinishing process. This task, along with validating a second superfinishing source, was undertaken by the SEC/ESC. Since its inception in October 2005, the SEC/ESC has independently validated these performance increases with a second superfinishing supplier and developed more understanding on how the superfinishing process works. The SEC/ESC plans to continue development of surface engineering solutions through the use of laser, cold spray and plasma vapor deposition systems.

** *The Advanced Materials, Manufacturing and Testing Information Analysis Center (AMMTIAC), Rome, NY (http://ammtiac.alionscience.com/); formerly The Advanced Materials, Processing and Testing Information Analysis Center (AMPTIAC).*

Figure 1—Superfinishing cell at SEC/ESC, Grand Forks, ND.

Equipment

Equipment used to perform the superfinishing process at the SEC/ESC in Grand Forks, ND, consists of a vibratory bowl with control panel and dosing station (Fig. 1). The dosing station is programmable to control the variable parameters of the treatment chemicals. The bowl is filled with ceramic media of various sizes and shapes to perform the mechanical abrasion. A zero discharge effluent waste treatment unit was also setup to process the waste water.

Technique

In the CAVSF process (Fig. 2), an acid is allowed to flow under a controlled rate through a vibratory bowl that is filled with small pieces of a ceramic media. This acid softens the outer layer of the metal, creating a salt layer or "conversion coating." The microscopic peaks are exposed to the media first and the conversion coating on those peaks is sloughed off as the media vibrates past it. The newly exposed substrate comes into contact with the acid again and the conversion coating reforms on the new peaks. This process repeats until all the peaks have been worn down and only the valleys remain. After an amount of time has elapsed (60 to 120 min), the bowl is rinsed and a burnishing agent is introduced into the bowl. This burnishing agent neutralizes the residual conversion coating and imparts a luster to the surface of the material.

The physical process of treating a part remains, to a slight degree, imprecise. A relatively complex setup procedure is used for R&D purposes than would be used for production. The bowl is initially run with some variety of acid, a metal test piece (of the material to be treated) and an amount of "spare" metal added for the purpose of achieving bowl chemistry equilibrium. This spare metal is added until the color on the test piece turns a dark black color. Once this color is achieved, a paper towel is used to attempt to wipe the conversion coating off the surface of the part.

Equilibrium is reached when the dark color does not change after the wipe-down step and a minimum of the conversion coating can be seen on the paper towel. After the equilibrium is reached, a timer is started and the actual pieces to be superfinished are added. Most process times fall between 60 and 120 min though process times can range widely depending on initial surface finish, desired final surface finish and allowable material removal. The part is removed from the process from time to time and is observed under a low-magnification (~40×) microscope. The part will begin to exhibit a shiny appearance beneath the black color. Once this shininess is obtained and any residual grinding lines or other surface anomalies are removed, the initial "acid cycle" is terminated and a rinse of purified water enters the bowl. This rinse continues for approximately 15 min. After the rinse cycle, a burnishing solution is administered and continues until all of the conversion coating has been removed and a deep luster is restored to the surface of the processed part.

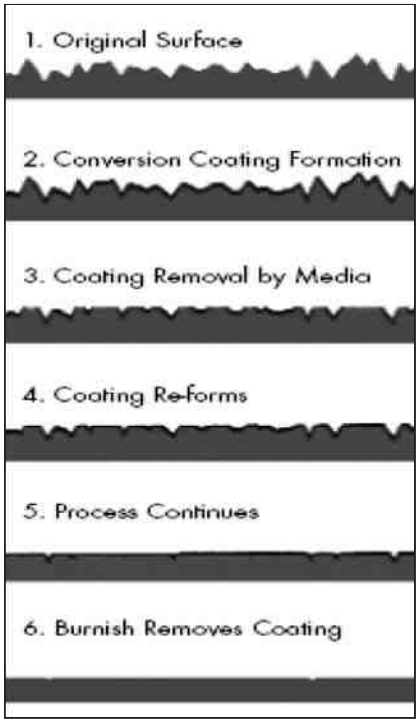

Figure 2—Superfinishing schematic (Courtesy of REM Chemicals).

An effluent stream is a by-product of the superfinishing process. This effluent stream contains the removed conversion coating as well as a small amount of ceramic from the media as it breaks down. The high amount of metals in the effluent stream mandate that processing is done to obtain appropriate city and state water limit values (as per Grand Forks, ND standards). This effluent is collected as it exits the bowl and is stored in a holding container until it can be processed by the low-volume, zero-discharge effluent evaporator. A 55-gal stainless steel barrel is then filled with this effluent and is placed in the evaporator. The temperature is raised in the barrel until the effluent begins to boil. The effluent boil is allowed to continue until all of the water has evaporated. The sludge that remains can then be collected and disposed of by a local chemical handler.

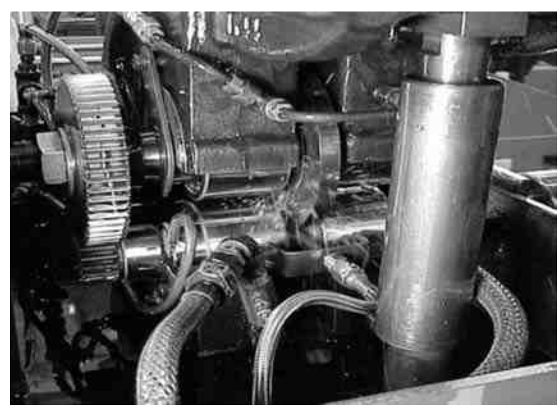

Figure 3—R/SCF test.[1]

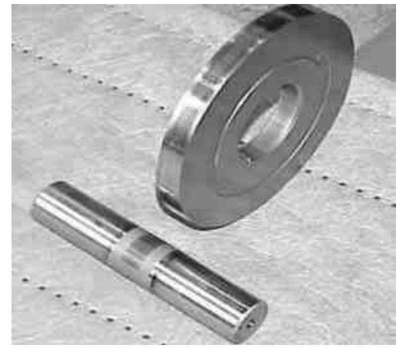

Figure 4—R/SCF test coupons.[1]

Tests

The objective of this project was to verify that the superfinishing process would be beneficial to aerospace transmissions. As *in-situ* testing was initially cost prohibitive, it was decided that a series of screening tests be run to first validate the postulates of superfinishing. The first test that was conducted was the Rolling Sliding Contact Fatigue (R/SCF) Test (Figs. 3 and 4). It was chosen because it could deliver an accurate analysis of the process at a fraction of the cost of actual gear testing. This screening test is used to determine contact fatigue resistance and is designed to reproduce the contact stresses that occur in transmissions under load.

Initial testing observed that cycles to failure in the superfinished samples increased by 950% as compared to the baseline samples (Fig. 5). It was also observed that superfinished samples could carry 28% higher contact stresses for three times longer than baseline before failure occurred.[1] A second set of data from a second source of superfinishing is currently being obtained.

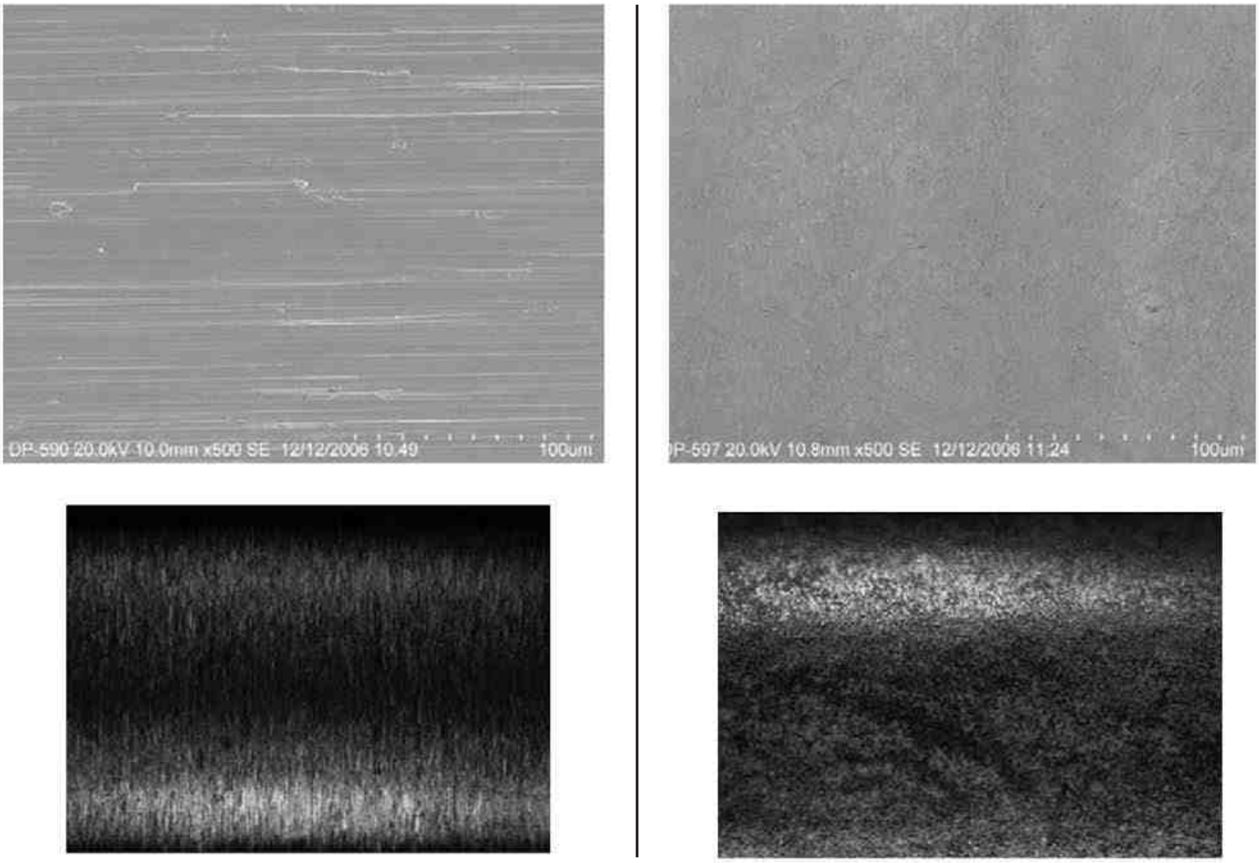

Figure 5—Before (L) and after (R) superfinishing under SEM (Top - 500×) and optical (Bottom ~50×) Microscope.

In an additional effort, the Rolling Sliding Contact Fatigue tester of V-Tech International (ZF-RCF) was utilized to validate the superfinishing process as well (Fig. 6). Although the initial test specimens displayed 200% life improvement from the baseline samples, it was discovered that the coupons used in testing had been manufactured incorrectly. Consequently, a new set of coupons has been manufactured and at the time of this report are undergoing the ZF-RCF test.

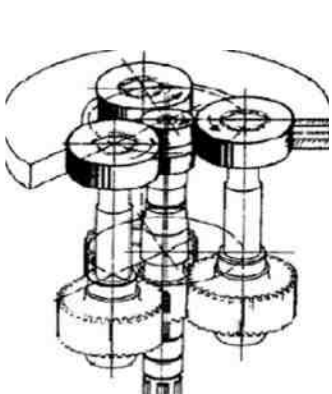

Figure 6—ZF-RCF test schematic.

Further testing will be conducted to more accurately correlate the results of the R/SCF test with the ZF-RCF test. Currently, the R/SCF test quantifies failure by examining pit size. The ZF-RCF test uses an eddy current test apparatus to verify crack propagation and it is believed that this test is capable of delivering high cycle fatigue results with a lower degree of scatter.

After the positive initial R/SCF screening, further analysis was recommended. Because of the goal of implementing the superfinishing technology in existing transmissions, data on gear geometry and profile change as well as actual gear testing was desired. The profile and geometry were evaluated using a coordinate measuring machine (CMM) and the gears used were made from Pyrowear® X53 Alloy.

Twelve spiral bevel gears of AGMA Class 12 were used in the initial test followed by an independent investigation of the superfinishing effect on one AGMA Class 10 spur gear in a separate effort. The spiral bevel gears were analyzed using a Zeiss/Höflter CMM by Arrow Gear Company (Downers Grove, IL) while the spur gear was measured by a Zeiss CMM at Concept Machine Tool Sales (Minneapolis, MN). Before and after measurements of hardness and surface roughness were taken and the results remained positive. Superfinishing was observed to remove between 0.00015[1] and 0.00013 in. from the tooth surface. As such, the superfinished gears remained within their specified tolerance. Therefore, AGMA Quality Class was maintained in both the Class 12 and Class 10 specimens.

Due to the positive outcomes of the initial screening and subsequent gear geometry evaluation, actual gear testing via a Power Circulating Pitting (contact) Fatigue Test as well as a Power Circulating Bending Fatigue Test (Fig. 7) were completed at the Gear Research Institute (GRI) at Penn State. AISI 9310 gear steel was initially evaluated due to its ubiquitous nature as an aerospace gear material and was analyzed in the form of eight sets of spiral bevel gears provided by Army Research Lab (ARL) personnel associated with NASA's Glenn Research Center. While initial testing made available fast and economical results, the data was determined not to be useful for statistical verification. It did, however, pave the way for further testing by demonstrating that gears that had been superfinished performed at least as well as gears that remained in the "as-ground" state.

A new set of 15 spur gears made from Pyrowear® X53 were destined for testing and of these, eight sets were used as baseline samples while the remaining seven were first superfinished then tested. Fifteen tests were conducted on the baseline samples and totaled 1.5 billion stress cycles. It should be noted that every baseline sample failed due to surface fatigue on one or more teeth. Ten tests were administered to the superfinished gears and comprised 2.9 billion stress cycles. Eight of the ten tests resulted in surface fatigue on one or more of the teeth. The results of these tests can be seen in Fig. 8. The "as-ground" gears were characterized by an arithmetical mean surface roughness (R_a) of 9 to 12 μ-in. with an average time-on-test of 100 million cycles. Because every specimen underwent surface failure, no tests were suspended. The superfinished samples displayed R_a values of between 2 and 3 μ-in. While eight of the tests resulted in surface fatigue failure, two of the tests were suspended. One test still exhibited no failure at 333 million cycles and the other test was suspended at 600 million cycles without failure. The resultant average time-on-test was 300 million cycles and superfinishing displayed a significant 300% improvement in surface contact fatigue resistance when compared to the baseline. It should be noted that high cycle fatigue test data have an inherently high degree of scatter even though extra precautions were taken to ensure that all test samples were identical through every process of manufacturing, superfinishing (when applicable), testing and evaluation. This improvement has been statistically calculated to the 90% confidence interval.[1]

A study to investigate bending fatigue followed the pitting fatigue tests, and results are shown in Figure 8. The GRI at Penn State continued their evaluation of the superfinishing process by conducting Power Circulating Bending Fatigue Tests. 14 sets (28 total) of Pyrowear® X53 spur gears were created with special undercuts in the root fillet to ensure that any failure that occurred was due to bending and not surface fatigue. Of these tests, seven were conducted with as-ground roots while seven sets were tested with as-ground then superfinished roots. To gain appropriate signal-to-noise (S/N) curves, the gears were tested at multiple stress levels. One as-ground sample was tested at each 153, 164 and 175 ksi load levels while four samples were tested at the 158 ksi load level. These tests lasted between 0.1 and 11 million cycles. One set of the superfinished samples was tested at 185 ksi and six sets were tested at the 175 ksi load level. The superfinished samples ran from 0.2 to 8 million cycles while one sample surpassed the 9 million cycle mark.[1]

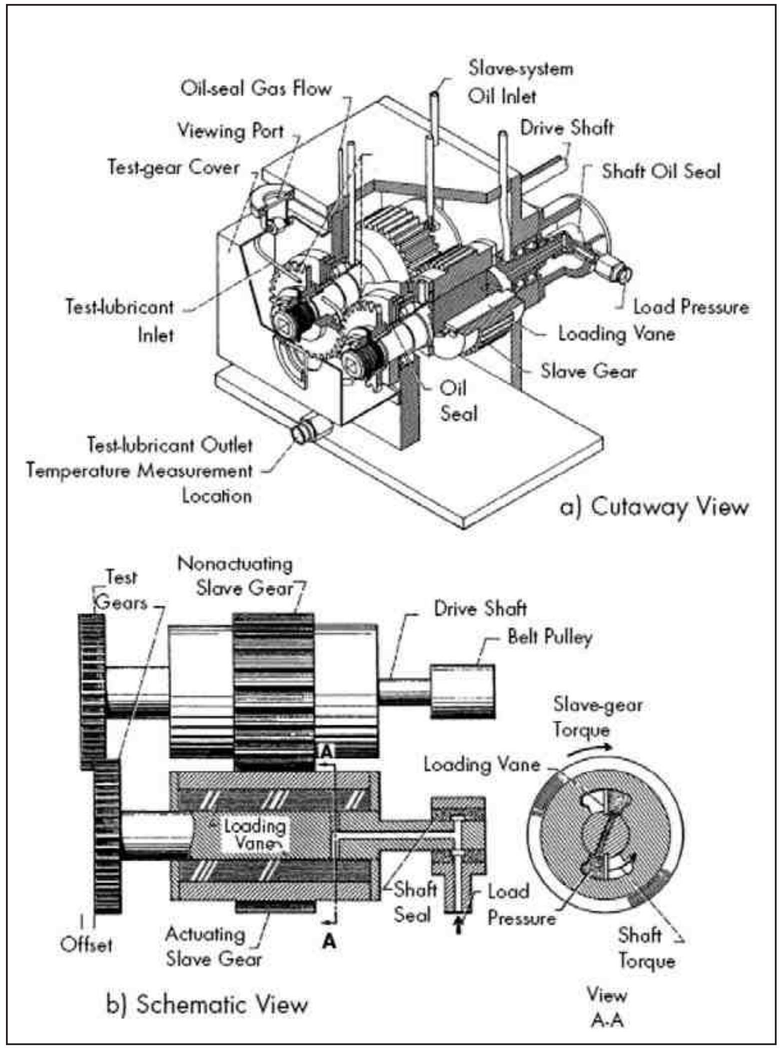

Figure 7—NASA Glenn Research Center's contact fatigue test apparatus.[1]

Surface defects attributed to premature surface failures prevented the desired bending failure from being analyzed. These surface failures were consistent with nonmetallic inclusions therefore significant statistical observations on bending failure could not be made. It can be noted, however, that since all specimens were made from the same bar of material, the tests do portray an accurate reflection of the improvements in bending performance that can be obtained through superfinishing.

The samples were reprocessed to further analyze root fillet behavior as a function of bending fatigue resistance. The initial as-ground condition of the gears displayed root roughness values between 12 and 16 μ-in. while the flanks maintained an R_a value of between 9 and 12 μ-in. It was noted that the superfinishing process preferentially affects tooth flanks while leaving the roots in nearly the same condition as the as-ground specimens. This topic was addressed and the gears were processed a second time to specifically achieve an adequate surface finish in the root fillet of the gears. After this subsequent processing, the roots maintained a surface finish of between 6 and 9 μ-in. GRI reported that any small surface finish improvements will serve to minimize fracture initiation sites through the reduction of stress risers. The data in this experiment was deemed too insufficient for statistical reliability, but the results imply that superfinishing can increase bending resistance failure by at least 10%. Through this test it was also noted that superfinishing virtually eliminated wear.[1]

Subsequent experimentation has verified that uniform surface finishing can be optimized through the mixing of a variety of different media to ensure that every surface from root to tip is affected at the same rate

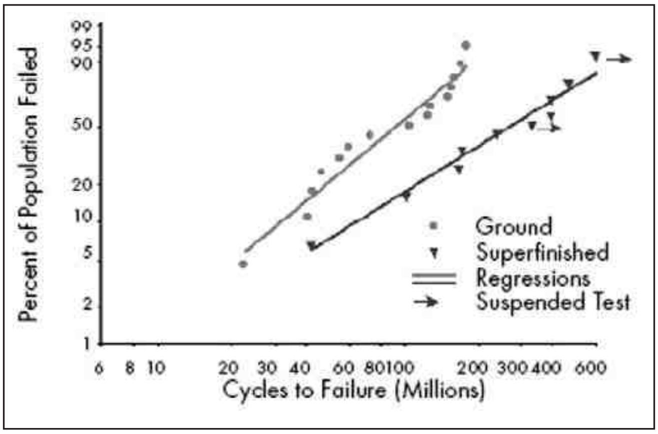

Figure 8—Surface fatigue data.[1]

Figure 10—Superfinished gear (L) and as ground (R).

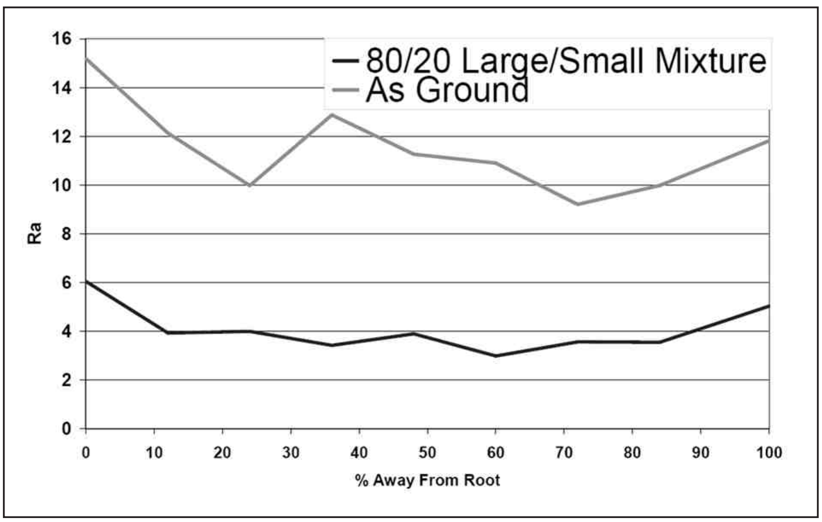

Figure 9—Graph of surface finish as function of media mixture.

(Fig. 9). Preliminary testing indicated that a combination of 80 vol% 5/16" angle cut cylindrical composition 10 media mixed with 20 vol% 1.7mm × 5mm, k-polish cylinder high-density media resulted in a more uniform average surface roughness as compared to other combinations of media. This media mixture was optimized for a 1" diameter bar steel coupon with one single cut-out made to replicate the tooth of a gear. Although preliminary, it can be concluded from this test that media mixture can be optimized for any tooth geometry to obtain removal rates and surface finishes that maintain uniformity throughout the profile.

Results and benefits

Though experimentation continues, the initial benefits of superfinishing are proving persuasive. Average surface roughness can be taken from 10 to 12 μ-in. down to 2 to 3 μ-in. while mean peak-to-valley heights (R_z) of between 90 to 120 μ-in. can end up less than 30 μ-in. These low surface finishes have proven to extend part life by as much as 300% in actual gear testing with an additional benefit of enhanced bending fatigue resistance of at least 10%. Additionally, material removal of 0.00013 to 0.00015 in. has been observed and uniformity from tip to root can be manipulated through the implementation of specifically tailored media mixtures depending on an individual gear profile. All of these benefits can be realized while simultaneously adhering to stringent AGMA Gear Quality tolerances.

Additional research will be undertaken by the SEC/ESC to develop novel solutions for wear and corrosion resistance through the application of new technologies. Such technologies include cold spray, laser and plasma vapor deposition.

Conclusions

Superfinishing is a robust and repeatable process and thus far, has demonstrated itself to be a beneficial and promising surface finishing solution (Fig. 10). This solution is one that could result in substantial increases in transmission performance by allowing the production of lighter, stronger and more reliable systems. The superfinishing technology is an effective part of a broad campaign to increase system life and reduce sustainment costs. Although this effort has been primarily concerned with military aerospace gears, superfinishing has the potential to improve any system where pitting fatigue resistance and bending fatigue resistance are critical design factors. Other prime examples include bearings and races, but the potential exists to apply this technology to a wide variety of high performance machinery components that are subjected to frictional forces.

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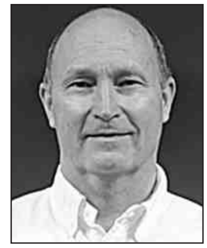

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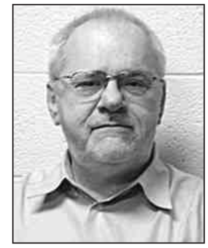

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About the Authors

Jarrod Schell is a Mechanical Engineer as a part of Alion Science and Technology's Surface Engineering Center for the past two and a half years, where his research has been focused on extending the life and improving the reliability of military weapons system components. Current projects include Chemically Accelerated Vibratory Surface Finishing (CAVSF) and the use of Cold Spray and Laser Technologies to develop and enhance wear and corrosion resistant coatings. Prior to joining Alion, Mr. Schell accumulated experience in CNC programming, laser technologies and manufacturing. Mr. Schell graduated from the University of North Dakota with a B.S. in Mechanical Engineering and is currently pursuing an M.S. in the same field.

Benjamin Hoiland is a Research Engineer at Alion Science & Technology, and has been with the company since 2005. Mr. Hoiland now leads the group of research engineers at the Surface Engineering Center. The center's focus is to increase the life and improve the reliability of Army equipment housings, frames, chassis, other parts with complex geometries, specific materials of construction and load bearing elements through the application of advanced production process technology to the fabrication of replacement or new parts. Mr. Hoiland received a Bachelor of Science degree in Mechanical Engineering from the University of North Dakota.

Damian Wilmot, a Mechanical Engineer at Alion, has been employed at the Alion Science & Technology Surface Engineering Center since its origination in 2005, where his focus has been on the research and development of emerging surface technologies. These technologies extend the life and improve the reliability of military weapons systems components. Prior engineering experience has included work in the design, manufacturing and foundry industries. Mr. Wilmot received a Bachelor of Science in Mechanical Engineering from North Dakota State University.

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Dr. D. Bryce Mitton is Director of the Engineered Surfaces Center within the School of Engineering and Mines at the University of North Dakota. Dr. Mitton was previously employed as a Research Associate and was the Senior Research staff member within the H. H. Uhlig Corrosion Laboratory at MIT, where he was Co- PI on a variety of projects. In 1979, he graduated "Cambrian Scholar" from Cambrian College of Applied Arts and Technology in Canada and subsequently was involved in an investigation of corrosion associated with high level nuclear waste containment at the Atomic Energy of Canada Limited (AECL). Dr. Mitton received a M.Sc. in Corrosion Science and Engineering in 1984, was awarded a Part-Time Teaching Assistantship in 1985, and a Ph.D. in Corrosion Science and Engineering in 1990 from The University of Manchester Institute of Science and Technology (UMIST) in England. He has diverse research experience, more than 70 publications, including book chapters and invited papers, and has both consulting and teaching experience.