Gear Repair for Helicopters and Wind Turbines via Isotropic Superfinishing

Vincent Cline
Project Engineer II
REM Research Group
Brenham, TX, USA

Lane Winkelmann
Director of R&D
REM Research Group
Brenham, TX, USA

Justin Michaud
CEO
REM Surface Engineering
Brenham, TX, USA

ABSTRACT

The wind turbine, aerospace, and helicopter gear industries recognize the importance of surface finish and surface texture for maximizing component and system performance. Optimizing surface finish and surface texture has been shown to reduce failure rates and increase operating safety margins. Isotropic superfinishing in the form of chemically accelerated vibratory finishing has been utilized to increase the performance of new wind turbine, aerospace, and helicopter gears for many years. The wind turbine gearbox industry has also used isotropic superfinishing as a method of repairing damaged gears for over a decade. The aerospace and helicopter gear industries have only minimally employed this technology as a repair technique. As the aerospace and helicopter industries scrap many gears due to only minor surface damage, further consideration of isotropic superfinishing as a repair tool is warranted. This paper will summarize the technical capabilities, recent advancements, and economic benefits of using isotropic superfinishing to repair wind turbine, aerospace, and helicopter gears. With this information, the aerospace and helicopter gear industries will be better positioned to evaluate isotropic superfinishing's potential to recover otherwise scrap gears and thereby reduce sustainment costs.

NOTATION

Abral = a proprietary, abrasive vibratory finishing process
AEO = all engines operative
OEI = one engine inoperative
CAVF = chemically accelerated vibratory finishing
CF = contact fatigue
hp = horsepower
IGA = intergranular attack; also described as grain boundary etching
ISF = isotropic superfinishing via chemically accelerated vibratory finishing
ksi = kilopounds per square inch
Media = solid objects which provide the required rubbing medium in a CAVF process
OEM = original equipment manufacturer
psig = pounds per square inch gauge
R/SCF = rolling/sliding contact fatigue
Ra = per ISO 4287, the arithmetic average of the micro surface deviations from the mean line of the surface profile
Rmr = per ISO 4287, the material ratio of the surface profile
RPM = revolutions per minute
Rz = per ISO 4287, the average of the five adjacent sampling lengths within the evaluation length of the largest peak deviation and the depth of the largest valley deviation within that sample length
SR = scoring resistance
STBF = single tooth bending fatigue
UTS = ultimate tensile strength
VDC = vapor deposition coating
µin = microinches
µm = micrometers

INTRODUCTION

For years, the aerospace, helicopter and wind turbine gearbox industries have utilized isotropic superfinishing in the form of chemically accelerated vibratory finishing (CAVF) to maximize performance and mitigate component failures—for the purpose of simplicity, the process of using CAVF to achieve an isotropic superfinish shall henceforth be referred to as "ISF". These industries have recognized the relevance of surface finish and surface texture to component and system performance. In aerospace and helicopter gear applications as with wind turbine gear applications, reliability is critical, overhaul is extremely costly, operation is in variable temperature and load conditions, compact designs and planetary configurations are common, and the cleanest metals, highest quality heat treatments, and most advanced manufacturing processes are required. Thus, the utilization of advanced surface finishing technology is logical.

However, there is a notable divergence between the aerospace, helicopter and wind turbine gearbox industries in regards to the use of ISF for the repair of used gears. For over a decade, the wind turbine gear industry has taken advantage of ISF to repair used wind turbine gears. Conversely, the helicopter and aerospace gear industries have not widely pursued this option. Rather, many aerospace and helicopter gears are removed from service and scrapped due to only minor surface damage.

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It is the authors' view that this component scrap rate could be reduced via the application of ISF as a repair tool. Further, it is logical, based on existing technical data, to conclude that the use of ISF as a repair tool would have an additional benefit of extending repaired component life beyond the expectations of traditionally manufactured (ground) gears. Either individually or in combination, these benefits would result in a reduction of aircraft sustainment costs.

This paper will provide a comprehensive summary of past component performance studies thereby succinctly detailing the benefits and validations of ISF. Additionally, process advancements and capabilities related to ISF as a gear repair tool will be explained and juxtaposed against alternate repair techniques. Case studies of used wind turbine gears will be presented to lend credence to the aforementioned studies. Lastly, the economic benefits from the direct recovery of otherwise scrap gears as well as the follow-on benefits of ISF related performance enhancements will be discussed.

ISOTROPIC SUPERFINISHING

Isotropic superfinishing is a term that, in the broadest sense, describes any process that is achieves a "superfinish" while also generating an isotropic surface texture. Applications such as aerospace, helicopter and wind turbine gearing are increasingly requiring improved surface finishes and surface treatments to increase operational performance and safety margins. This trend has resulted in more attention being given to various superfinishing technologies. Given these facts, it seems important to clearly establish both what isotropic superfinishing is, what studies and validations exist relative to isotropic superfinishing, and to which specific process embodiments these studies and validations are attached.

The term isotropic is generally borrowed from material sciences. It describes a form of matter that possesses equal physical properties in all directions. In combination with superfinish or superfinishing, the term isotropic describes a surface, and, as such, it is only being applied in reference to the texture of the surface itself and not to any subsurface features. The important characteristic which the term isotropic is seeking to describe is a differentiation of the surface texture as compared to machined surfaces which are inherently periodic or anisotropic. In order to be truly isotropic, a gear's surface must be refined in a manner such that all directional machining marks are removed (cross hatch patterns would generally not be considered isotropic). Currently, the only processes capable of generating such a surface are relatively low-energy, media-based processes such as vibratory tumbling, CAVF, and the like. A primary limitation of higher energy processes such as honing and polish-grinding is the inability to generate an isotropic surface.

Defining what classifies as a superfinish is, unfortunately, not an agreed upon standard within the aerospace, general gear, or manufacturing industry at large. Some OEM's have defined a superfinish as a surface having an Ra of < 16 µin (~0.4 µm). However, most aerospace specifications that utilize isotropic superfinishing as an operation step will have an Ra target < 4 µin (~0.1 µm). For the purpose of this paper, the generalized aerospace definition of a surface having an Ra of < 4 µin (~0.1 µm) shall be applied to the term superfinish. Therefore, in this paper, isotropic superfinishing shall be defined as a process that produces a non-directional surface texture via the removal of all grinding or machining lines while also creating a surface with an Ra of < 4 µin (~0.1 µm).

CAVF is a finishing process that has been described in some detail in various articles and papers. It is perhaps best explained in Ref. 1. CAVF is capable of producing isotropic superfinishes on gear flanks and other engineered surfaces such as bearings and airfoils. As referenced in the introduction, in this article, CAVF when it is used as an isotropic superfinishing process shall be referenced as ISF. ISF typically differs from "mirror-polishing" processes in that it generates a unique, non-directional texture on the surface of the component being processed. Mirror-polishing processes would have essentially no texture and exhibit no discernable features under high magnification inspection. The importance of this difference will be apparent in the subsequent technical performance data review.

All data presented on ISF in this paper is based on processes designed and provided by REM Surface Engineering. The authors would caution against the association of the conclusions from this paper (and other studies) relative to process viability and component safety of CAVF process from other suppliers. Validation testing would be advised to ensure no undue risk is introduced to the manufacturing or repair process. Additionally, it is not recommended to associate the benefits that are linked to ISF processed surfaces with surfaces possessing similar Ra or Rz measurements which lack an isotropic texture. Surface texture must also be considered relative to any performance correlations. Certainly, periodic surfaces with similar Ra or Rz measurements should not be assumed to perform in a similar fashion as isotropic surfaces. Again, independent performance validation testing should be performed.

PROCESS VALIDATION

ISF has been extensively studied, albeit across many individual initiatives. An important aspect of many of these studies is the verification of the process technology and the specific processes themselves as having no detrimental impact of the component that is being processed. These same verifications will be important when considering ISF as an aerospace or helicopter gear repair operation.

As ISF is a chemical process, it is logical for there to be concerns relative to hydrogen embrittlement and intergranular attack (IGA). Additionally, because ISF occurs after the final shaping step of grinding or machining, evaluation of any gear geometry or profile change is a common concern. Lastly, determining what, if any, changes to surface hardness occur as a result of ISF is an important qualification parameter.

Intergranular Attack

A joint evaluation of ISF was conducted by REM Surface Engineering (hereafter REM) and the Rolls-Royce Corporation in Ref. 2. The study began because IGA was detected on some test specimens which had been treated by one of REM's ISF aerospace gear processes. Examples of IGA are shown in Fig. 1.

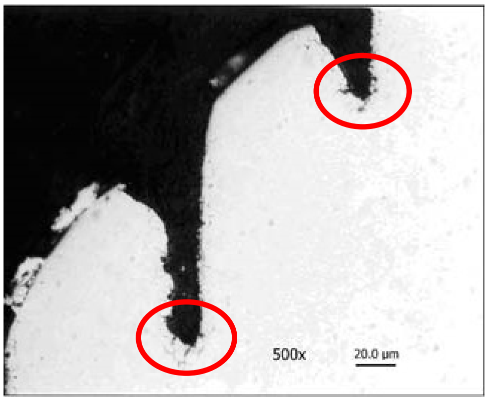


Fig. 1 Photomicrograph at 500X. Circles show visible IGA in the valleys of machining lines (Ref. 2).

In order to determine if ISF caused the previously detected IGA, AISI 9310 Falex V-Blocks were manufactured to Rolls-Royce's gearshaft specifications, processed by ISF, sectioned, and examined. No IGA or corrosion pitting was detected as shown by Fig. 2. Thus, the risk of IGA being caused by ISF was disproven. In recent years, this specific area of concern regarding ISF has ceased to be prevalent amongst new adopters of the technology.

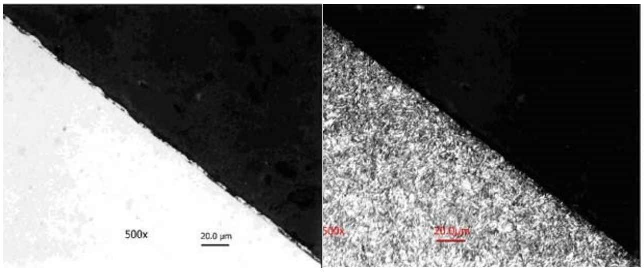


Fig. 2 Post ISF photomicrographs of the polished (left) and 3% Nital Etched (right) V-Block sections showing no IGA (Ref. 2)

Hydrogen Embrittlement

The evaluation of ISF for any risk of hydrogen embrittlement has been conducted numerous times by various OEMs as well as by REM relative to its aerospace and other gear processes. One such study is cited in Ref. 3 in which case carburized specimens of both AISI 8620 and SAE 9310H were evaluated using slow strain rate testing to determine comparative ultimate tensile strength (UTS) ratings. No statistical difference was found between the baseline and ISF processed specimens as shown in Figure 3, and therefore, the conclusion was drawn that ISF had no link to increased hydrogen embrittlement risk. Additionally, the authors can attest that dozens of OEM controlled tests for hydrogen embrittlement have been conducted as a part of process qualification and ongoing production quality control. All such studies have resulted in the same conclusions—that ISF does not generate hydrogen embrittlement.

Property	AISI 8620 Baseline	AISI 8620 ISF	SAE 9310H Baseline	SAE 9310H ISF
UTS Mean (ksi)	217.4	221.1	223.4	224.3
UTS Standard Deviation (ksi)	5.7	9.4	11.6	20.5

Fig. 3 Slow Strain Rate (ASTM G129 and ISO 7539) Hydrogen Embrittlement Testing Results (Ref. 3).

Geometry, Profile, and Hardness

Gear geometry is critical to component and system performance. Any post-grinding operation step that affects the gear flank must maintain the profile and geometry to within design allowances. Thus, the evaluation of ISF relative to how it changes gear geometry or profile is a common area of study. One such study was conducted on AGMA Quality Q12 gears of both AISI 9310 spiral bevel and Pyrowear® 53 spur gears in Ref. 4. The results from this study established that the material removed during ISF was within design tolerances and therefore maintained the AGMA Quality Class rating.

Many such studies, both public (Ref. 1 and Ref. 5) and proprietary (for the purpose of part specific qualification) have been conducted. In all such studies, it has been found that there is strong material removal uniformity associated with ISF. The process relies on the ability of the specified media to rub the gear flank where the conversion coating has formed thereby removing a microscopic amount of metal from the gear surface (see Ref. 1 for more details). Due to the geometric limitations created by the generally "v-shaped" nature of gear teeth, any type of vibratory tumbling or media-based process will tend to finish the "open" addendum portion of a gear flank more than the "restricted access" dedendum. This tendency is exacerbated with abrasive only processes, making them generally unsuitable for gear processing or any application in which shape alterations must be minimized. Experience has shown that "mirror-polishing" operations will struggle to maintain component geometry due to their generally abrasive-only nature. While ISF may take off slightly smaller amounts of material from the dedendum than from the addendum, due to the lower force requirement to achieve material removal created by the conversion coating, this differential is drastically smaller than with abrasive deburring or polishing processes. In most applications, the difference has been found to be almost immeasurable (several microns). It is typically only in very tight pitch gear applications where any consideration must be given to the differential finishing rates. Even in these tight pitch applications, unless there is a relatively high material removal requirement, no design changes would be necessary. As shown in several of the referenced articles and studies (Ref. 3, 4, 5, 9), any finishing rate differential has been shown to be well within existing design tolerances. One specific reference showed via tooth contact pattern analysis that the extremely minor material removal variations had no detrimental impact to gear operation (Ref. 5). Further, technology advancements to media selection and overall processing setup have led to improvements and even greater processing uniformity such that aerospace gears with a diametral pitch of 96 have been successfully processed via ISF while maintain all necessary tooth form parameters.

The last element to consider in the technical validation of ISF is the verification that the process does not alter the surface hardness. Ref. 3 showed no change in the HRC of aerospace quality case carburized gears. Numerous proprietary studies as well as comparative performance results in studies, such as Ref. 4 and Ref. 5, have served to validate this conclusion.

In summary, based on multiple studies and evaluations, all of the standard concerns associated with ISF have been overcome. Additional, repair specific process validations will be discussed later.

ISF BENEFITS

ISF has been utilized on various wind turbine gearbox variants as well as numerous aerospace and helicopter platforms. Helicopter models such as the Sikorsky S-76 and S-92, the Bell 427, 429, and 525, and the AgustaWestland AW189 have all been publicly associated with the use of isotropic superfinishing. As discussed, ISF produces surfaces completely devoid of grinding or machining lines and which possess flank Ra measurements of < 4 µin (~0.1 µm). It is worth noting briefly that both Ra and Rz are limited measurements that, on their own, do not necessarily provide a comprehensive evaluation of the quality of a surface. This observation is discussed further in Ref. 6 where it is noted that the ability to correlate performance relative to contact fatigue based solely on measurements such as Ra and Rz becomes increasingly problematic when comparing planarized, isotropic surfaces with periodic surfaces such as those produced by machining operations (including precision grinding).

The growing utilization of ISF is directly linked to the multitude of benefits that the process provides to gears, bearings, and the like. To aid in the later discussion of ISF as a gear repair tool, a succinct summary of these benefits will be provided here. Additional details on these benefits can be found in the respective references. For comparative purposes, a ground and honed surface is shown in Fig. 4—note the directional lines and distressed metal zones that have been created by these machining processes.

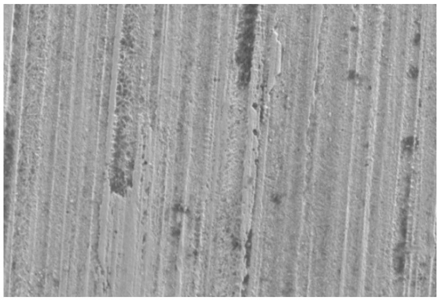


Fig. 4 SEM micrograph (1000X) of a ground and honed specimen

This distress metal layer is commonly worn-off during a break-in cycle or in subsequent operation, introducing unnecessary containments into the lubricant. While not necessarily a primary benefit in aerospace, helicopter or wind turbine gear applications, the elimination of the break-in step or period for gears processed via ISF is a unique characteristic that would not translate to surfaces finished solely by grinding or honing. This characteristic was first explored in Ref. 7. and Ref. 8. See Fig. 5 for an example of a post ISF surface; note the absence of machining lines and distressed metal as well as the mild, non-directional scratch pattern that has been produced; this scratch pattern is the "texture" that differentiates ISF from mirror-polishing processes.

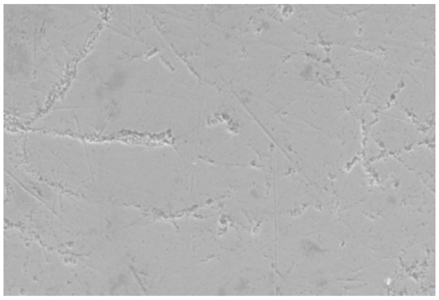


Fig. 5 SEM micrograph (1000X) of a post ISF specimen

Nearly all of the benefits associated with ISF can be linked to the improvement in the surface condition as a result of the removal of all distressed metal and the periodic machining lines coupled with the impartation of the low roughness, isotropic surface texture shown above. These changes to the surface result in, among other benefits, a reduction in friction, an improvement of the load distribution across the gear flank, and the removal of failure initiation sites on the gear surface.

Contact Fatigue Resistance

Contact fatigue resistance was one of the first areas in which ISF was evaluated for potential improvements to gear performance. The study described in Ref. 4 actually began as an evaluation of vapor deposition coatings (VDC) for the extension of gear life. R/SCF testing yielded an average increase in statistical life of 22% for VDC's relative to baseline specimens; the ISF specimens exhibited an average increase in statistical life of 950% over the same baseline specimens. Additionally, the ISF specimens demonstrated the capability of carrying 28% higher contact stresses for at least three times the life of the baseline specimens. These results caused the study to pivot away from VDC's, and to expand the testing relative to isotropic superfinishing.

ISF was then tested on gears via a power circulating pitting fatigue testing apparatus. The results showed that ISF resulted in a 300% increase in gear life over baseline gears (see Fig. 6).

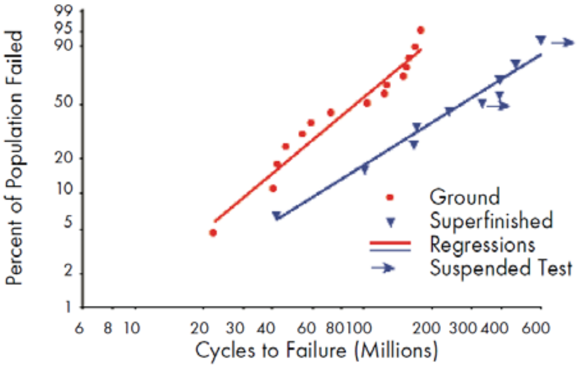


Fig. 6 Graph of Surface Fatigue Data (Ref. 3)

A similar contact fatigue oriented study utilizing R/SCF testing compared ISF to baseline, ground and Abral processed specimens (Ref. 3). The results overwhelming favored ISF over the Abral process as well as the baseline specimens—shown in Appendix A. This conclusion is especially interesting as it highlights the importance of not only reductions in surface roughness, but also the importance of the isotropic surface texture that is generated by ISF. The Abral processed components tended to be largely devoid of texture as compared to the ISF processed surface shown in Fig. 5 (see Fig. 7 for comparison). Similar performance differentials have been seen in other proprietary studies whereby texture-less or mirror-polished surfaces with equal or even lower Ra and Rz values have performed worse in contact fatigue and scuffing testing as compared to ISF processed surfaces with residual isotropic texture.

Additional contact fatigue resistance testing has yielded similarly impressive results. Specifically, FZG micropitting evaluations (detailed in Ref. 12) have been conducted in which gears treated by ISF did not exhibit micropitting after the completion of both the loading and endurance stages. Profile form deviation was only approximately 0.00002 of an inch (0.5 µm) at the completion of the endurance testing for the ISF FZG gears as opposed 0.001 of an inch (28 µm) for the baseline FZG gears. These results are especially impressive when one considers that FZG micropitting gears (which were used for this testing) are specifically designed to induce micropitting.

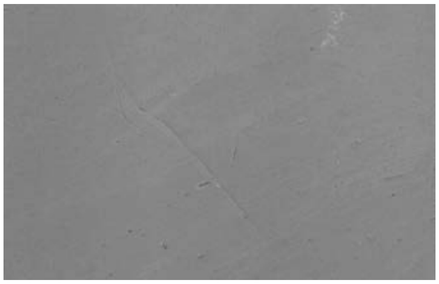


Fig. 7 SEM micrograph (500X) of a surface generally devoid of texture

Scuffing Resistance

Scuffing or scoring is a primary failure concern in aerospace and helicopter gearing due to the high loads and high speeds under which these components operate. Interestingly, although not often cited as a primary failure mode concern, scuffing can occur in wind turbine gearboxes despite the relatively slow speeds of operation as compared to helicopters; this occurrence is sometimes referred to as slow speed scuffing. Nevertheless, the study of scuffing or scoring resistance relative to ISF has been primarily contained to aerospace and helicopter gears.

Given the improvements shown by ISF in contact fatigue studies, coupled with the aerospace and helicopter industries' interest in the technology, scuffing resistance testing was a logical next step in the technical qualification of ISF. The University of Cardiff, in conjunction with REM, carried out twin disc scuffing testing detailed in Ref. 13. This study tested baseline (ground), ISF processed with texture, ISF processed without texture, and zinc-chip processed (similar to the Abral process) specimens. The processing parameters used to produce the "with texture" specimens resemble the current embodiments of ISF for aerospace and helicopter gears. The "with texture" specimens far and away out performed all other specimens, mirroring the above referenced contact fatigue testing results. These "with texture" specimens survived all twelve, three minute loading stages, culminating with a maximum load of 4,150 N and a subsequent thirty minute endurance cycle conducted at this maximum load. Baseline specimens failed at 2,320 N, and the generally texture-less specimens failed between 3,450 and 4,150 N—none reached the endurance testing.

Additional scuffing resistance testing conducted in conjunction with Sikorsky on actual gears (Ref. 14) yielded similarly impressive results. As with other studies, no detrimental alterations to gear profile were found post ISF.

Results of the testing, conducted at 285 ksi, showed that ISF processed gears were able to withstand at least 60° F higher lubricant supply temperatures than their baseline counterparts prior to scuffing.

From these studies, the conclusion can be made that ISF significantly increases gear scuffing resistance. When combined with the contact fatigue resistance benefits, the application of ISF to wind turbine, aerospace, and helicopter gear applications is valuable option for increasing operating safety margins relative to these failure modes or categories.

Extreme Conditions and Oil-Out

In the helicopter industry, "oil-out", "loss of lubricant", and "extreme conditions" testing is critical to aircraft certification. Such testing is necessary due to the implications of gear failure during flight. Thus, testing of ISF has been conducted relative to these types of events on several occasions.

The exceptional R/SCF testing results in Ref. 3 led to subsequent loss of lubricant testing. Because this testing had not been planned within the original scope of experiments, an already used but un-failed ISF specimen was employed in the testing. This specimen (of SAE 9310H) survived the entire thirty minute, no lubricant cycle at 400 ksi before failing via scuffing when the loading was subsequently increased to 425 ksi. While not a perfect comparison, an AISI 8620 specimen was tested as a pseudo-baseline (there were no un-failed SAE 9310H baseline specimens); this AISI 8620 specimen failed in under a minute in the loss of lubricant R/SCF testing at the 400 ksi load.

In a separate study, Bell Helicopter conducted a series of extreme conditions tests (Ref. 5) utilizing a Bell 427 main rotor gearbox (MRGB). This testing was comprised of a series of low oil pressure tests and a high temperature tests simulating both AEO and OEI events. Low oil pressure testing culminated in a thirty minute AEO test run at 550 hp, 6000 RPM, 230° F oil temperature and oil pressure between 25 – 30 psig (minimum oil pressure is specified as 40 psig). Visual inspection via viewing ports showed no evidence of scoring or other anomalies after this testing. Subsequently, high temperature testing was conducted, culminating in a thirty minute AEO test run at 550 hp, 6000 RPM, oil pressure at 55 psig, and oil temperature between 245 – 250 ° F (maximum oil temperature is specified as 230 ° F). Visual inspection, again, via the viewing ports showed no indication of scoring or other damage. Final disassembly and visual inspection verified the viewing port inspections: that the ISF processed gears exhibited no scoring or signs of damage despite a combined sixty minutes of extreme conditions testing.

These results further strengthened the value of ISF as a method of enhancing operating safety margins in helicopter and other high load gear applications—both high load and high speed such as aerospace and helicopter gears and high load and low speed such as wind turbine gears.

Bending Fatigue, Load Carrying Capacity, Noise, and Operating Temperature Reductions

Additional benefits that have been studied relative to ISF include: bending fatigue, load carrying capacity, vibro-acoustic noise, and operating temperature.

Increased bending fatigue resistance has been associated with even small improvements to root fillet roughness (Ref. 4). Machining lines are, logically, a common failure initiation point for bending fatigue, assuming there are no subsurface flaws on the specimen being tested. STBF and rotating beam testing has shown that surfaces which are completely devoid of machining lines (which typically run in parallel to the likely direction of fracture in gears) have increased bending fatigue resistance as compared to machined surfaces (see Ref. 15 and Fig. 8). Some caution should be offered here given the difficulties that can arise in seeking to achieve a machining line free condition in the root fillet of a gear; however, the benefits to bending fatigue should not be discounted and advancements in ISF should be sought to fully take advantage of this potential benefit.

Fig. 8 Gear displaying root fillet finishing

Load carrying capacity is another benefit that is linked with the isotropic superfinish that ISF generates. This benefit is linked primarily to an intrinsically obvious improvement in load distribution on the surface of a gear flank. A machined surface (as shown in Fig. 4 and again in Fig. 9 and Fig. 10) has a much lower surface area with which to distribute the working load during gear mesh as it is largely limited to the tops of the peak asperities generated during grinding. This high-pressure loading at a microscopic level contributes to the lower surface durability results from machined surfaces.

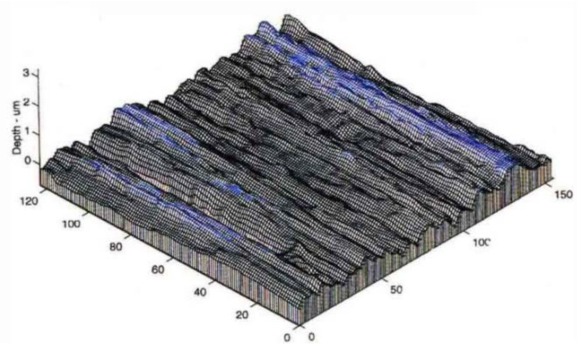


Fig. 9 Topographical map of a honed surface

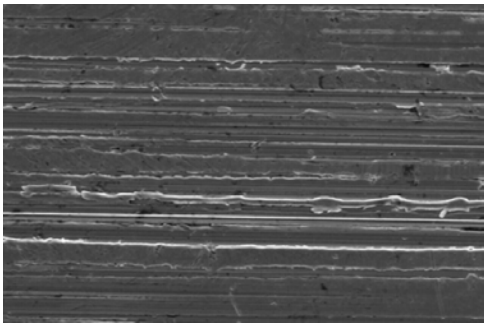


Fig. 10 SEM micrograph (500X) of a ground surface

Any improvement to a ground surface in the form of planarization and roughness reduction will serve to improve the load distribution, thereby lowering the contact pressure between the two mating gear flanks. However, as mentioned above, machining lines can act as failure initiation points for bending fatigue and have been theorized to be the initiation sites for micropitting (Ref. 16). Therefore, incomplete removal of machining lines (see Fig. 11) is likely to result in a significantly reduced improvement in load carrying capacity as well as contact and bending fatigue resistance. Processes that achieve only partial planarization such as polish grinding are likely to suffer from these limitations. Proprietary testing has even shown that extremely smooth surface finishes (Ra < 4 µin/~0.1 µm) which retained a periodic surface texture yielded early failures in advanced alloys and were outperformed by legacy alloys such as SAE 9310 and Pyrowear® 53 components which had full isotropic superfinishes. The maximum benefit to load carrying capacity achievable via surface roughness and texture modification (not considering compressive stress imparting processes like shot peening) is through the complete removal of machining lines (see Fig. 12 and Fig. 13).

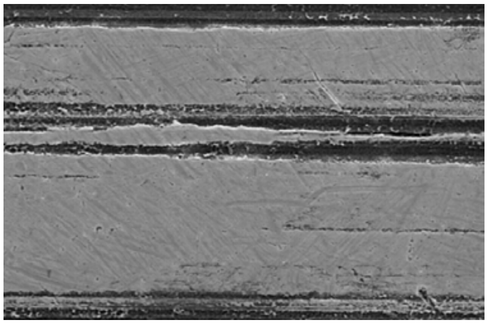


Fig. 11 SEM micrograph (500X) of a partially refined and planarized surface with residual machining lines (from the same surface as Fig. 10)

Noise and operating temperature reductions via the reduction of surface roughness are also benefits associated with isotropic superfinished surfaces. Ref. 3 displays an interesting study conducted on variable speed spherical roller bearings in which a baseline, honed bearing was tested against a bearing which had ISF applied only to the rollers and a bearing which had ISF applied to both the rollers and the races. The study was conducted to measure operating temperature differentials between the three bearings. The ISF processed bearing experienced operating temperatures which were reduced by as much as 40° F in higher load stages (see Fig. 14).

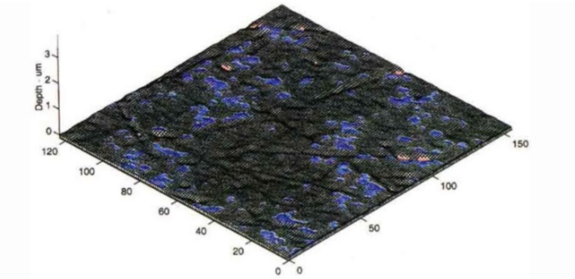


Fig. 12 Topographical map of ISF surface (from the same surface as Fig. 9)

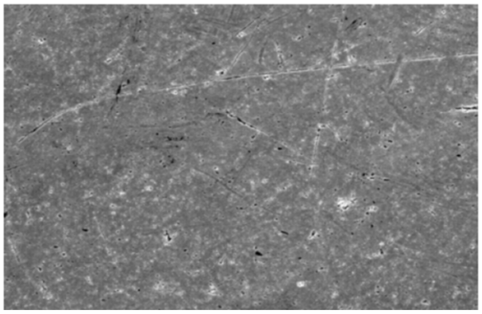


Fig. 13 SEM micrograph (500X) of ISF surface (from the same surface as Fig. 10 and Fig. 11)

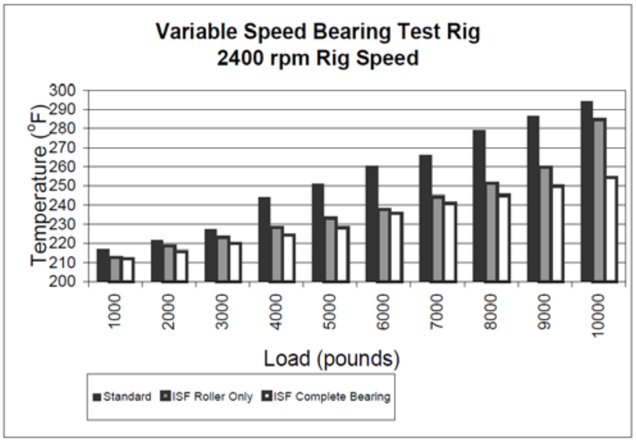


Fig. 14 Operating temperature comparison of standard honed, ISF roller only, and ISF complete bearing under increasing loads (Ref. 3)

Similar temperature reduction results have been found in gear applications. Hot weather, rear axle pickup truck testing has shown temperature reductions on the order of 40 – 50° C. Ref. 11 cites reductions in operating temperature of ISF processed Boeing CH-46 transmission gears of 20 – 30° F, and similar results are cited in Ref. 17 for Sikorsky S-76 main transmission gears.

Ref. 17 also notes reductions in gear friction leading to reductions in vibro-acoustic noise at various gear mesh locations of multiple decibels. Ref. 5 attributed one overall decibel reduction of cabin noise to the isotropic superfinish imparted by ISF.

In summary, there are a great many benefits that have been studied and are now attributed to ISF in gear applications. Overall, these benefits make a strong argument for the implementation of ISF in the wind turbine, aerospace, and helicopter gear industries. Thus, if it is possible for ISF to be employed as a repair tool, there are strong potential benefits to future gear performance in addition to the value derived from recovering an otherwise scrap component.

REPAIR VIA ISF

The wind turbine industry has been very successful in utilizing ISF to repair used, damaged gears. Wind turbine gears suffer from a variety of failure modes, many of which are also common in aerospace and helicopter gearing. Notable failure modes include micropitting (sometimes called gray-staining), scuffing (sometimes called scoring), and FOD damage (see Fig. 15, Fig. 16 and Fig. 17 for examples). To date more than 400 wind turbine gearboxes have had components repaired via ISF.

Fig. 15 Example of Micropitting on a Wind Turbine Sun Pinion

Fig. 16 Example of Scuffing on a Wind Turbine Intermediate Pinion

Unlike with new component applications, the performance benefits that are associated with ISF are not the primary driver for its use in wind turbine gear repair. Rather, the primary arguments for ISF in the wind turbine repair market are based on economics and lead times. The alternatives to ISF in the wind turbine gear repair industry are primarily regrinding (or kiss grinding as it is sometimes called) and component replacement. If the damage is particularly minor and not prevalent on the gear, hand working of the gear may be possible via abrasive tools or stones, but this technique has obvious limitations in wind turbine gear repair. While all of these alternate techniques have their uses, in situations where the option to use ISF exists, it is typically the superior method of repair (for reasons that are discussed below).

Fig. 17 Example of FOD Damage on a Wind Turbine Annulus Gear

The aerospace industry differs from the wind turbine industry in terms of its gear repair options. Wind turbine gears benefit from having, proportionally, a great deal of material stock that can be utilized (i.e. removed) in a repair process. Some wind turbine planetary gears may have as much as 0.01 of an inch (~254 µm) material tolerance per flank. Aerospace and helicopter transmission gears typically have less than 0.0002 of an inch (~5 µm) of material tolerance per flank. As such, in many cases the option of regrinding is not available. Thus, aerospace gear repair options may be limited to basic hand working or component replacement.

Regrinding

Regrinding can be a useful repair technique in the event adequate stock is available to be removed from the component. Regrinding will typically require the removal of at least 0.003 of an inch (~76 µm) from each side of the gear tooth resulting in a diameter reduction of 0.006 of an inch (~152 µm). This amount of stock removal is typically acceptable on wind turbine gears, but it would typically take helicopter transmission gears out of tolerance. In researching aerospace and helicopter gear repair practices, general industry feedback was that the regrinding of gears is not common. Some anecdotal references where discovered relative to the regrinding of only the active flanks, but these comments were generally followed with skepticism as to the efficacy of the practice and the actual use of these reworked components. Ultimately no evidence was found that flight critical gears are being reground. However, in the wind turbine industry there are certain scenarios where regrinding is, in fact, the best option for gear repair. These scenarios include situations where:

A. The existing tooth form or profile has been substantially altered
B. The existing tooth form or profile is deemed to be less than optimal as per its original design
C. The depth of damage on the gear tooth exceeds 0.003 of an inch (~76 µm)

In scenario A, it is likely that the gear will not be able to be recovered as a substantial profile shift would likely require very high levels of material removal. In both scenarios A and B the reason for utilizing regrinding over ISF is very simple—ISF is a process that has been fundamentally designed not to alter existing tooth shape and profile. As noted above, maintaining component geometry is one of the critical characteristics for the use of ISF on precision components such as gears, bearings, and airfoils. Therefore, any scenario in which there is a desire to alter an existing gear tooth profile—be it the correction of a profile loss or microgeometry alterations—ISF is not the right solution. In scenario C, the reason to use regrinding over ISF is, again, a simple one—regrinding will be more efficient due to the amount of material that must be removed. One of the strengths of ISF is its controllability and reliability. As an example, a specified ISF process for the repair of wind turbine planet gears is known to remove 0.0002 – 0.00025 of an inch (~5 – 6 µm) per hour of processing time. It is worth noting that ISF processes for use on wind turbine gears are typically tailored towards larger and faster material removal rates as compared to ISF processes for aerospace and helicopter gears. Given this fact, a wind planet gear with heavy pitting or FOD damage having a depth of 0.004 of an inch (~101 µm) would require approximately eighteen to twenty-two hours of processing time for complete damage removal via ISF (including the time necessary for the burnishing cycle). In most cases, such a cycle time would be inefficient as compared to regrinding.

In essentially all other instances, ISF will be equal, or more typically, a better option than regrinding. The arguments for ISF over regrinding in scenarios where gear profile alteration or substantial stock removal is not necessary can be made solely on the grounds of economics and lead times. Regrinding prices, obviously, vary from company to company, but industry research in the US has yielded a price range of $7,000 - $10,000 to regrind all nine gears in a ~2MW single stage wind turbine planetary gearbox. Comparatively, ISF is publicly referenced at being able repair all nine gears in up to a ~2.3MW planetary gearbox for under $6,000. The advantages that allow ISF to be more cost competitive than regrinding have to do with the nature of the process. Grinding equipment is fundamentally designed to produce medium to high volume runs of the same exact component. Given the range to wind turbine gearbox suppliers and the design variations across these manufacturers and gearbox models, regrinding will inherently struggle with equipment setup and changeover issues—not to mention the potential for setup losses. Conversely, there is essentially no changeover time for any of the nine planetary gearbox components when using ISF, and ISF has no risk of setup losses. As a gentle, ambient temperature process, ISF has no need for post-processing crack or nital-etch inspection—both a cost savings and a major health, safety, and environmental advantage. Lead time is another advantage that ISF offers over regrinding. US wind turbine gear regrinding lead times tend to run between six and twelve weeks; published lead times for wind turbine gear repair via ISF range between two and four weeks in most cases, with the actual gear processing time for a complete planetary gearbox taking only two to three days.

Moving beyond the basic justifications for using ISF over regrinding in the wind turbine gear repair market, one must now consider the add-on benefits of an ISF surface as compared to a ground surface. Typical wind turbine gear surface quality targets for ISF are:

- Ra = 2 -8 µin (0.05 – 0.20 µm)
- Rz = 8 – 32 µin (0.20 – 0.80 µm)
- Rmr (16 µ in/0.4 µm) > 99%

Surface quality for a reground gear will tend to be on an order of magnitude of three to five times higher for the Ra and Rz measurements and derivatively lower for the Rmr. Reground gears will not have the added benefit of the isotropic surface texture imparted by ISF. Lastly, the performance benefits associated with ISF will apply to repaired components, and one would derivatively expected ISF repaired gears to outperform new, non-ISF processed gears.

New Component Replacement

New component replacement is a requirement whenever the damage found on a gear exceeds the allowable stock removal, or the damage is otherwise too severe to be repaired. Hence, there is an obvious place in the wind turbine, aerospace and helicopter industries for new component replacement. By using ISF, the subset of gears that require replacement can be reduced. This reduction in the gear scrap rate is linked to the controllability of ISF relative to material removal. Aerospace, helicopter, or wind turbine gears that lack adequate remaining stock to be reground or have damage deeper than is feasible to hand work, have the potential to be repaired via ISF due to its controllability. Material removal rates for wind turbine planet gears are cited above, but for aerospace and helicopter gear applications, ISF can be tailored to match their much smaller tolerance bands. A typical ISF helicopter transmission gear process will have a material removal rate of 0.00005 of an inch (~1 µm) per half hour. This level of control opens the possibility to repair many aerospace and helicopter gears that would currently be scrapped per existing practices.

According to Ref. 9 and Ref. 10, current practices for the evaluation of helicopter gears involve visual inspection utilizing 10x magnification as well as the use of a sharp scriber traversing over any identified damage. If the scriber is snagged by the damage, then the gear is identified as scrap. This method identifies very minor damage. Commonly, helicopter gears are scrapped due to only minor micropitting or FOD damage (see Fig. 18, and Fig. 19)

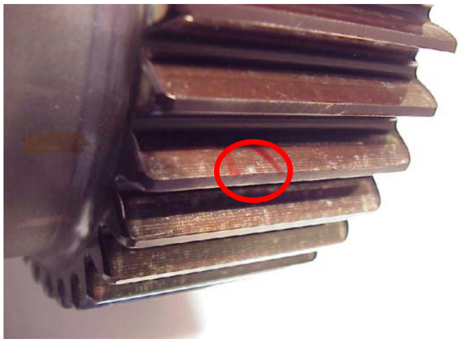


Fig. 18 Boeing CH-46 Sun Gear with identified FOD damage (Ref. 9)

The FOD damage illustrated in Fig. 18 was measured to have a depth of 0.00006 of an inch (~1.5 µm), and in general, it was hypothesized that much of the damage caught by the scriber method would have a depth of less than 0.0002 of an inch (~5 µm). Given the referenced ISF material removal rates, the complete repair of this damage should be achievable. Of course, maintaining critical geometry and meeting performance requirements must be linked with such efforts, but this will be discussed later. It is unclear how many gears could be salvaged given current inspection intervals, but the economic benefits of the recovery of even a small percentage of gears (also to be discussed later) make strong arguments for further consideration of this approach. Ref. 11 cites the potential for the recovery and reuse of greater than 50% of the scrap gears at the Naval Air Depot at Cherry Point via processes like ISF. Even ignoring the potential cost savings that ISF represents, when one considers that it is not uncommon to have lead times in excess of one year for replacement helicopter components, the time savings that ISF can provide is considerable; outsourced ISF processing is estimated to require less than two months including initial process customization and less than one month for components with existing fixed processes.

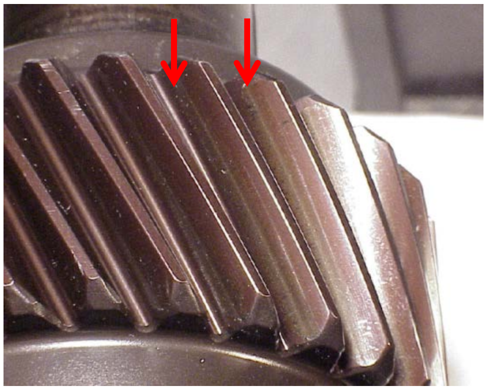


Fig. 19 Boeing CH-46 Input Pinion with identified micropitting below the pitch line (Ref. 9)

As noted, wind turbine gears tend to have a great deal more tolerance available. As such, it would seem less likely for these components to be scrapped. While condition monitoring and scheduled maintenance have come a long way from the early days of mega-watt class installations, wind turbine gears still tend to be allowed to operate for longer than recommended periods despite initial problem detection. This practice is understandable given the double edged cost of wind turbine downtime—the wind turbine is both not generating revenue and is accumulating costs via the required technicians, crane use, and gearbox repair costs. Unless an owner operator has spare gearboxes (somewhat of a rarity) or is working with a repair operation that offers exchanges, the wind turbine that is undergoing repairs is likely to be down for multiple months. While the short-term perspective lends itself towards pushing a wind turbine gearbox beyond initial problem detection, a longer term perspective would offer another conclusion.

If a wind turbine gearbox is taken offline upon early problem detection, it is likely that the damage present on the gear flanks would be very minor, perhaps on par with or only slightly heavier than the damage exhibited in Fig. 18 and Fig. 19 (see Fig. 17).

In such a scenario, ISF could be used to repair this relatively minor damage, removing perhaps 0.0002 to 0.0004 of an inch (~5 – 10 µm) of material from each tooth flank. Assuming that the gear had 0.005 of an inch (~127 µm) of available stock for removal, a reasonably conservative estimate, this gear would still have over 0.004 of an inch (~100 µm) of available stock for future repairs. While the contact fatigue and scuffing resistance increases associated with ISF would suggest that it is unlikely that either of these two failure modes would occur once the gear was put back into service, there is still the possibility of abrasive wear, corrosion, fretting, or FOD damage occurring. In such an event, the gear could be repaired via ISF at least once more, if not multiple times, depending on the depth of new damage. This possibility of multiple repairs via ISF could effectively extend a gears life many times over—calling into the question the value of pushing the gearbox after initial problem detection.

On the other end of the spectrum, if a wind turbine gear was made to the lower end of minimum size tolerances, it is likely that regrinding would be considered too aggressive of a repair technique. As in the helicopter gear example, given the enhanced controllability of ISF as compared to regrinding, these components need not be scrapped, provided that the remaining material tolerance is in excess of the depth of material damage. Even in the event the depth of damage is beyond that acceptable material removal limits, if the portions of damaged gear flank are not pervasive (as may be the case with FOD damage), it may be possible to repair the gear down to the minimum tolerance limit and simply leave behind some negative damage. While this practice may not result in the same increases in subsequent gear life, the option may be preferable in some cases to the scrapping of the component.

Hand-Working

Repair practices on helicopter gears that display visual damage but pass the scriber test currently tend to be limited to hand-work. Ref. 9 notes that 400 grit sand paper is used to repair minor FOD and micropitting damage with the goal being reduction or removal of the damage without actually taking off enough material to count as rework. Other versions of hand-stoning or hand-dressing have been recounted as the means of repairing very minimally damaged aerospace and helicopter gears. These techniques are, unfortunately, very limited in their capabilities.

Hand-working is less common in the wind turbine gear repair industry. Given the size of the components and the typically available levels of excess gear stock, hand-work is generally not a very efficient option for gear repair. However, if machine availability or capability does not exist to meet a repair shop's required deliver time schedule, or if material removal limits eliminate regrinding as an option, it is not unheard of for operators to be asked to hand-dress a wind turbine gear. Unlike in the aerospace practice, where the amount of material being removed is miniscule, hand-dressing in the wind turbine industry may require the removal of 0.001 of an inch (~25 µm) or greater. In such instances, the uniformity of repair and the maintenance of the tooth profile must be considered. Clearly, an automated and controlled process such as ISF represents a superior solution.

ISF REPAIR CAPABILITIES

The position has been stated that ISF is both in many cases a superior gear repair option in the wind turbine industry and a means of recovering many aerospace and helicopter gears that would otherwise be scrapped. However, while the concept has been effectively proven in the wind turbine industry via the hundreds of gears that have been put back into service post ISF, the viability in the aerospace and helicopter industry must be addressed in an alternative manner since there is no such industry data in existence. It is worth noting that to date, no ISF repaired wind turbine gears have been found with recurrent contact fatigue or scuffing damage.

Process Validation on Used Helicopter Gears

Ref. 9 and Ref. 10 make a very compelling case for the viability of ISF as an aerospace and helicopter gear repair tool in the manners suggested above. Ref. 9 provides a particularly helpful table (see Appendix B) which describes the changes to tooth geometry, or more accurately lack of changes, to the Boeing CH-46 Sun Gear and Input Pinion shown above.

As noted in Appendix B, both components met spec after the noted damage was completely removed. One can see that the Input Pinion required more processing in order to remove all of the micropitting that was observed. Despite the additional material removal, all size changes were well within the design tolerances of the gear. Fig. 20 and Fig. 21 display the post ISF appearance of the two component types.

Fig. 20 Boeing CH-46 Sun Gear post ISF (Ref. 9)

As a part of this testing, additional gears of these two types were sectioned and processed. Upon analysis of these sectioned gear teeth it was confirmed that surface hardness depth to 50 HRC and the core hardness all met OEM specification—further validation of the fact that ISF does not affect these properties. Grain structure analysis showed consistency with properly heat treated SAE 9310 with no evidence of grain boundary etching (IGA) or hydrogen embrittlement—another validation of earlier claims on OEM components. Lastly, compressive residual stress was measured on a post ISF Sun Gear via X-Ray diffraction; the measurements confirmed a significant amount of compressive residual stress was present (108.7 +/-2.4 ksi) and verified that ISF does not detrimentally affect compressive stress.

Fig. 21 Boeing CH-46 Input Pinion post ISF (Ref. 9)

Performance Validation on Used Helicopter Gears

Confirmation that ISF was able to repair without otherwise damaging or degrading the quality of helicopter gears is important, but it is only half of the required validation. While ISF has been proven effective in enhancing the performance of new components, there is an obvious need, given the criticality of the application, to verify the performance of these repaired components. Ref. 10 undertook this exact effort via the testing of CH-46 Mix and Main gearboxes. The testing criteria included Single Tooth Bending Fatigue (STBF), power re-circulating Contact Fatigue (CF) tests, and Scoring Resistance (SR) tests. Additionally, all failure locations were examined to determine any correlation between the failures of the repaired component to the original damage.

STBF results showed that ISF repaired gears performed as well as, and in most cases better than, new baseline gears (see Appendix C). On average, slightly over 5% increases on the ISF repaired gears were seen on required loads to achieve 10%, 50%, and 90% failure rates as compared to new baseline gears (see Fig. 22).

Failure Rate	"New" CH-46 Gears	Repaired CH-46 Gears
90%	43,737 lbs	46,071 lbs
50%	38,778 lbs	40,837 lbs
10%	33,808 lbs	35,603 lbs

Fig. 22 Load for corresponding failure rates of new vs. ISF repaired CH-46 Spur Pinions (Ref. 10)

CF testing yielded a similar performance results, with the ISF repaired gears showing superior performance as compared to the new baseline components (see Appendix D). Additionally, the G50 life (in cycles) for varying confidence levels displayed increases across all levels for the ISF repaired gears as compared to the new baseline gears (see Fig 23). Referring back to the earlier discussion regarding the reduction of operating temperature, the ISF repaired gears operated at about 20 – 30 degrees F cooler than the new baseline gears on the pitting test rig (Ref. 11).

Confidence	"New" CH-46 Gears	Repaired CH-46 Gears
95%	0.23X106	0.6X106
50%	1.4X106	2.5X106
5%	5.0X106	6.8X106

Fig. 23 G50 life analysis in cycle by confidence level of new vs. ISF repaired CH-46 Intermediate Pinion driving Collector Gear

Evaluation of failure locations after the pitting testing on the repaired gears showed that all failures occurred at one edge of the face width—which would correspond to testing expectations based on the offset loading strategy. Considering that the original damage to these gears was distributed across multiple gear flank locations, it is reasonable to conclude that the original damage, pre ISF, had no impact on the pitting failures of these gears.

Lastly, SR testing showed that the ISF repaired gears were able to operate at consistently higher lubricant temperatures as compared to new, baseline gears (see Appendix E). On average, the ISF repaired gears were able to operate at >40% higher lubricant temperatures, indicating superior scoring resistance.

Additional details on this testing can be found in Ref. 10. In general, this performance testing validates and corresponds with much of the data that has been gathered on OEM ISF processed gears and their measured performance enhancements.

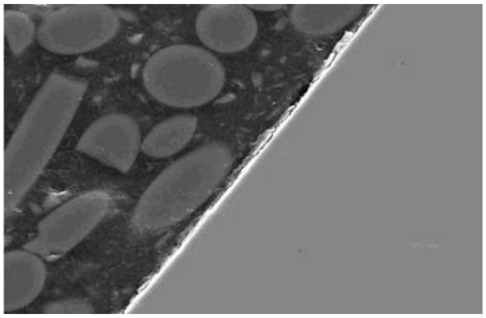


Fig. 24 Surface showing complete IGA removal by ISF (1000X)

It is worth noting that Ref. 2 found ISF to be an effective tool for the removal of IGA. So, while Ref. 9 and Ref. 10

focused primarily on the removal of micropitting and FOD damage, IGA or general corrosion should also be considered as potentially repairable via ISF (see Fig 24 and Fig. 25). In fact, any surface damage not judged to have detrimentally altered the hardness of the gear and any gear still possessing accurate geometry and profile should be considered potentially repairable by ISF.

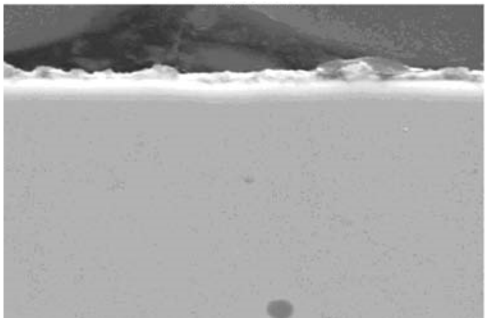


Fig. 25 Surface showing the complete removal of IGA (5000X)

Overall, the conclusion from this data is that ISF repaired gears performed at least as well as, and in most cases better, than newly manufactured, ground gears. Given that these newly manufactured gears are acceptable to use in flight critical applications, it would be logical to conclude that ISF repaired gears that maintain original manufactured design tolerances should be acceptable for use as well.

Standard Components

As the data discussed above and contained in the relevant references proves the validity of ISF as a gear repair tool for the wind turbine, aerospace, and helicopter gear industries, it is necessary to examine the potential component types to which ISF has been or could be applied. In a standard single stage planetary wind turbine gearbox, all nine gears would be considered standard components: planet gears; sun, intermediate, and high speed pinions; high speed and low speed helical gears, and ring or annulus gears (see Fig. 26 for some examples of these components). Similarly, standard aerospace gears and pinions have been processed for over fifteen years (see Fig. 27, Fig. 28, and Fig. 29).

Fig. 26 Post ISF wind turbine gears (top) sun pinion, (bottom left) planet, (bottom right) low speed helical gear

Fig. 27 Bell 427 input pinion post ISF

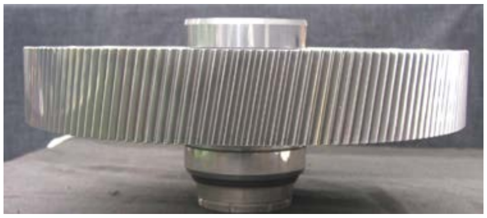


Fig. 28 Bell 427 bull gear post ISF

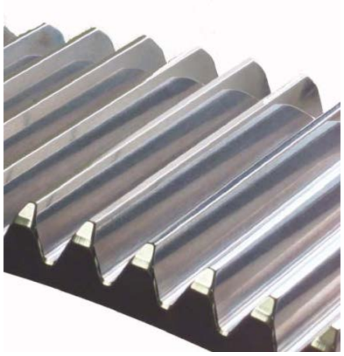


Fig. 29 Sikorsky S76 third stage bull gear close-up post ISF

Nitrided Components

One of the areas of advancement for ISF in repair work in recent years is with nitrided components. In wind turbine gear design, the annulus is occasionally heat treated via gas nitriding as opposed to the more typical technique of through hardening (see Fig. 30 for an image of a lightly damaged, nitrided wind turbine annulus). Gas nitrided parts are typically not able to be reground due to their relatively shallow case depth. Assuming a newly manufactured and nitrided gear has a residual case depth after white layer removal of between 0.002 and 0.006 of an inch (~50 – 150 µm), is it easy to understand why one would not want to risk regrinding such a component during an overhaul. However, given the controllability of ISF, removing surface damage while maintain the nitriding case layer does not present an excessive challenge. Wind turbine annulus gears can cost more than $15,000 even for small MW class gearboxes; thus, the savings potential created via ISF for such applications is immense. As nitrided annuluses and other components are not uncommon in aerospace and helicopter applications, the benefits achieved in the wind turbine industry are easily translatable.

Fig. 30 Nitrided wind turbine annulus with mild flank damage

Complex, Multi-Feature, and Assembled Components

With the initial success of ISF as both a repair tool and on new components, more complex applications inevitably arose. In wind turbine gearing, some planetary designs call of integral bearing races on the inner diameter bore of the planet gears (see Fig. 31).

Fig. 31 Wind turbine planet gear with integral bearing race

When such components need to be repaired, there can be challenges posed on two fronts. First, the bearing surface is likely to have much tighter material removal tolerances than the gear flanks, potentially eliminating the possibility of repair overall. Secondly, if repair is possible, it will have accomplished via two independent machining operations—thereby increasing the cost of repair significantly. However, by utilizing ISF, where all surfaces that are exposed to the process are repaired simultaneously, both the material removal limitations and the two step repair process challenges are addressed.

The ability to simultaneously finish gear flanks and bearing surfaces is not limited solely to wind turbine applications. As advances in the customization of the material removal rate have been achieved, the ability to finishing both bearing surfaces and gear flanks on helicopter gearshafts has become much more common (see Fig. 32 for an example component). While typically applied on OEM components as a cost savings (via the elimination of final bearing honing), the crossover application to helicopter gear repair is fairly easy to see, provided accommodations can be made to account for the reduction in bearing surface diameter. If no material removal can be accommodated on the bearing surface, then advances in fixturing and process aid technology now allow for the complete masking of these surfaces resulting in no undesirable material removal.

Fig. 32 Helicopter pinion with bearing surface

While not particularly common in wind turbine applications (see Fig. 33 and Fig. 34), the application of ISF to multi-gear shafts and double helical gears is a growing area of application in the aerospace and helicopter industries. Much like the advantage offered by ISF in processing bearing and gear flanks simultaneously during repair operations, the ability to process multiple independent gears on a single component offers considerable cost savings.

Fig. 33 Aerospace double helical gears

A further area of demonstrated capability for ISF in the wind turbine industry that could be explored in aerospace and helicopter applications is that of assembled components. In a typical wind turbine planetary design the intermediate pinion and the high speed helical gear will be interference fit to one another—this part combination is sometimes referred to as the intermediate assembly (see Fig. 34). The separation of these two parts is, at best, costly and, at worst, results in the scrapping of one or both of the components. By utilizing clever fixturing techniques to generate desirable component motion in the vibratory vessel, intermediate assemblies can be processed in their combined state, thereby eliminating the risk of scrapping one of the parts during disassembly, and generating a cost savings by combining what would otherwise be two regrinding operations into a single ISF cycle.

Fig. 33 Clipper Liberty gearbox double helical pinion and bull gear assembly

Another example of processing of assembled wind turbine components can be seen in the processing of the low speed helical gear. This gear typically has a coupling mated to its inner diameter, sometimes referred to as the hollow shaft (see Fig. 35). ISF is able to process and repair damage to the flanks of the low speed helical gear without requiring the removal of the hollow shaft component, again, offering operational costs savings and a risk reduction.

Fig. 34 Wind turbine planetary gearbox intermediate assembly

Fig. 35 Wind turbine low speed helical and hollow shaft assembly

ISF in Extreme Applications

Component size and new alloys are the final areas where ISF as a technology has been pushed for advancement. Early gear applications were limited to components of less than ~20 inches (~500 mm) in diameter. However, over the years and certainly with the advent of wind turbine gear processing, this upper limit has expanded greatly. The largest components processed to date include annulus gears in excess of 90 inches (~2.3 meters) and double helical bull gears weighing in excess of 10,000 lbs. (~4,550 kgs.)—see Fig. 36). Process capabilities have also expanded in terms of precision capabilities and smaller, tighter pitched gears. ISF has successfully processed several thousand gears with diametral pitches of 64 – 96. Many of these gears are no larger than the tip of one's finger (see Fig. 37), but demand precision refinement in the same manner as helicopter transmission gears.

Fig. 36 Clipper Liberty gearbox double helical bull gear; approximate weight of 10,000 lbs. (~4,550 kgs.)

Fig. 37 Spur gear with diametral pitch of 64

As the gear industry has pushed beyond materials such AISI 8620 and SAE 9310, the ISF technology has been pushed to accommodate increasingly complex, high hardness, high temper resistance materials such as Pyrowear® 53, Ferrium® C61, and Ferrium® C64.

In summary, ISF has a wide range of repair capabilities beyond basic gear types, sizes and metallurgies. This breadth of capability serves to further increase the value of investigating its application as an aerospace and helicopter gear repair tool further.

CASE STUDIES

To provide further information on and evidence of the efficacy of ISF as a repair tool and an overall gear upgrade, several case studies are discussed below.

Ground Gear Damage and Failures

The drawbacks of ground gears versus isotropically superfinished gears have been discussed, so an example of a

~2 MW wind turbine gearbox where some of the components were processed by ISF and some were not is an interesting example to review. In this gearbox, a partial isotropic superfinish was applied to the planet gears and to the sun pinion. This "partial" finish means that a true isotropic surface was not achieved as residual grinding lines were present; in this instance, the OEM's manufacturing preferences simple did not specify for the generation of a "full" isotropic superfinish. No additional finishing beyond final grinding was applied to any of the other components in this gearbox design. The gearbox was taken out of service due to a bearing failure and was estimated to between three and four year old in terms of service life (a relatively new gearbox). Fortunately for this case study, no significant FOD damage occurred, so a visual inspection of the progression of contact fatigue was able to be performed. Fig. 38 below shows an image of the intermediate pinion. Evidence of early stage micropitting was found in the dedendum of the gear. It is also interesting to note the well-defined edge to the contact pattern on the gear teeth. Fig. 39 shows a wider image of this same gear.

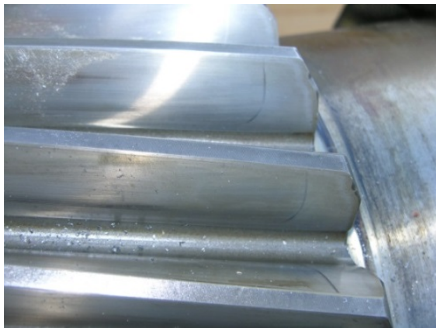


Fig. 38 Close-up of used, ground intermediate pinion – note light micropitting and defined edge contact pattern

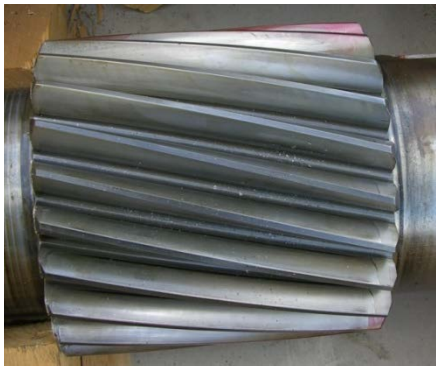


Fig. 39 Used, ground intermediate pinion

Partial ISF OEM Field Results

As noted, the sun pinion in this gearbox was ISF processed by the OEM, but the surface refinement was carried out only to a partial finish thereby not entirely removing the grinding lines. The sun pinion displayed no significant contact fatigue damage during visual inspection. Given the quality of its surface as compared to the ground, intermediate pinion and the relatively low number of operating hours on the gearbox, this result is not surprising (see Fig. 40). However, two notable differences from what would be expected on a gear of this age for a fully isotropically finished component are: the evidence of a defined contact pattern edge and visually discernable roughness variations on the gear flank (see Fig. 41).

Fig. 40 Used, partial isotropic superfinish sun pinion

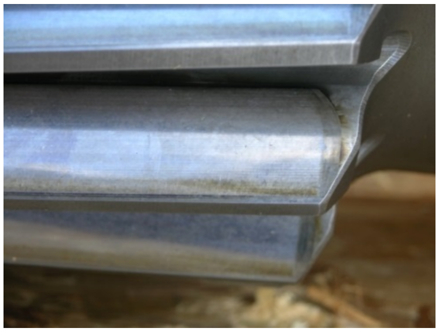


Fig. 41 Close-up of used, partial isotropic superfinish sun pinion – defined edge contact pattern

A fully isotropically finished gear would be expected to have a completely uniform surface appearance and little to no discernable contact pattern. It is also worth noting that some minor, straight-line discolorations were observed in the dedendum of multiple gear teeth. Microscopic inspection was not possible due to the promised lead time on the components, but based on Errichello's micropitting theory involving hydraulic lubricant pressure, it would not be entirely surprising if these straight-line discolorations were in fact the very early stages of micropitting. Had the sun pinion be fully isotropically superfinished, no such cracks (grinding lines) would have existed to allow for this hydraulic propagation.

Fig. 42 and Fig. 43 show the post ISF repair condition of these two components. Note the complete removal of the contact pattern and the creation of full isotropic superfinishes on both components.

Fig. 42 Close-up of ISF repaired sun pinion

Fig. 43 Close-up of ISF repaired intermediate pinion

Full ISF OEM Field Results

In a separate scenario, a ~1.5MW gearbox was taken out of service where the entire first stage had been be processed by ISF to a full isotropic superfinish. This gearbox was estimated to be approximately five years old in terms of service life. The first stage gears exhibited absolutely no evidence of wear or even a contact pattern (see Fig. 44 and Fig. 45). The visual inspection of these gears showed no difference as compared to newly manufactured and ISF processed components in terms of the gear flanks themselves. The difference between this planet gear as compared to the used, ground intermediate pinion and the used, partial isotropically superfinished sun pinion shown above is substantial. The visual comparison itself is a strong argument for the efficacy of ISF, even ignoring all of technical studies and benefit validations that support its value as an engineering upgrade.

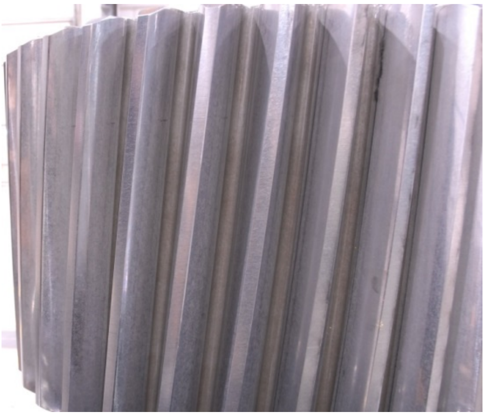


Fig. 44 Used, full isotropic superfinish planet gear

Fig. 45 Close-up of used, full isotropic superfinish planet gear

WIND TURBINE, AEROSPACE, AND HELICOPTER SUSTAINABILITY COSTS

Sustainability costs, as they are referred to in the aerospace and helicopter industries, and operations and maintenance costs (O&M) in the wind turbine industry are essentially different terms for the same concept—how much does it cost to keep these assets functioning. ISF be employed as a gear repair tool in all three of these industries for the purpose of reducing sustainment and O&M costs.

As the wind turbine industry trends towards the back end of the theorized “bath tub lifecycle curve”, owner-operators will have substantial O&M challenges to face. The ability to repair gears cost effectively while simultaneously upgrading the components during the repair process would offer significant advantages for wind farm profitability. With replacement wind turbine gearboxes costing well over $100,000 in most cases and individual components costing $5,000 and up, it would be highly advisable for these owner-operators to be very proactive in their condition monitoring and component inspections. Given modern condition monitoring capabilities, ISF should be able to repair the vast majority of wind turbine gear damage; taking advantage of operational efficiencies via the repair of assembled components, as well as the repair of nitrided components and components that have low material removal allowances will serve to further reduce wind farm O&M costs. The proven performance advantages of ISF processed gears would serve to lower the ongoing O&M costs for these gearboxes. Furthermore, an improved surface finish on wind turbine gears opens up the possibility of lubricant and filtration optimizations for further performance enhancements. Outsourced ISF processing facilities for wind turbine gears exist in the US and Europe. Alternatively, full process installation costs are estimated to be approximately $500,000. Given the technical and economic advantages, ISF would seem to be a superior repair operation to regrinding, hand-working, and new component replacement.

In aerospace and helicopter gearing, the possibilities and economic impact of using ISF as a repair are arguably even greater than those in the wind turbine industry. The scrap rates of aerospace and helicopter gears are clearly very high. The current repair practices of hand-dressing gears with 400 grit sand paper is arguably inferior to the controllability and uniformity that ISF can offer which, in turn, opens up the possibility to repair gears with more significant (although still minor) surface damage. Aerospace and helicopter gears tend to cost as much if not more than their larger wind turbine counter parts. The annual procurement costs for the part numbers tested in Ref. 10 are known to have been several million dollars (Ref. 11), with the individual component costs ranging from ~$5,000 to ~$30,000 each. Thus, recovery of even a small portion of these and other aerospace or helicopter gears offers a significant and immediate sustainment cost reduction. Lead times for replacement gears in the aerospace and helicopter industries are extremely long, in many cases exceeding twelve months. This lead time dynamic results in the need to maintain greater inventories of spare components. ISF as a repair tool would reduce the needed volume of spares due to its short lead time (even when considering the requisite gear inspection procedures and operations). The add-on benefits of improved component performance and increased operating safety margins post-ISF repair will facilitate longer operating periods between overhaul, further reducing sustainment costs. Similar to wind turbines, outsourced processing options exist in both the US and Europe for the repair of aerospace and helicopter gears. ISF processes lend themselves well to “frozen planning” operations whereby processes can be established and locked, giving engineering revision control to the requisite party. Further these fixed processes can be easily incorporated underneath a primary repair center’s certifications, simplifying the qualification process. Lastly, as with wind turbines, full process installation can be obtained for less than the cost of a single grinding machine, while offering considerably greater component processing flexibility and no required dangerous EH&S post-process inspection techniques (such as nital etch).

CONCLUSION

1. ISF is an established technology for use on new wind turbine, aerospace, and helicopter gears.
2. ISF is an established technology for the repair of used, damaged wind turbine gears.
3. All required process validations of ISF in order to establish that it does not detrimentally affect gears including testing for IGA, hydrogen embrittlement, alterations to gear profile, hardness, and the like have been successfully completed.
4. ISF has been shown to have strong performance enhancements relative to: contact fatigue, scuffing (or scoring) resistance, extreme conditions or oil-out performance, bending fatigue, load carrying capacity, operating temperature, and noise.
5. ISF repaired helicopter gears have been verified to perform as well as and in most cases better than newly manufactured, ground components relative to contact fatigue, scuffing resistance, and single tooth bending fatigue.
6. ISF has the ability to process complex, multi-feature components, assembled components, nitrided components, new and exotic alloys, components that are extremely large, extremely small, and gears that are extremely tightly pitched.
7. ISF is a superior repair tool to regrinding provided damage does not exceed ~0.003 of an inch (~76 μm) due to its flexibility, controllability, lower costs, and the superior surface it generates.
8. ISF can repair wind turbine, aerospace, and helicopter gears that lack adequate stock to be reground.
9. ISF is a superior repair tool to hand-working due to its efficiency and uniformity of finishing as well as its lower labor requirements.
10. ISF has much shorter lead times than regrinding or new component replacement in wind turbine industry.
11. ISF has significantly shorter lead times than new component replacement in the aerospace and helicopter industries
12. ISF does not require dangerous and environmentally hazardous post-process inspections such as nital etch.
13. ISF can facilitate the reduction of spare part inventory due to its shorter lead times and greater component salvage capabilities.
14. ISF can extend the average time between overhaul due to contact fatigue and scuffing resistance.
15. ISF offers significant sustainment and O&M cost savings to the aerospace, helicopter and wind turbine industries.

AUTHOR CONTACT INFORMATION

Lane Winkelmann – lwinkelmann@remchem.com
Vincent Cline – vcline@remchem.com
Justin Michaud – jmichaud@remchem.com

APPENDICES

Appendix A

Sample	Contact Stress (ksi)	Test Duration (million cycles)	Failure Mode
Ground/Honed Baseline			
#1	400	3.6	Pitted
#2	400	4.2	Pitted
#3	400	3.5	Pitted
Abral #1	400	44.0	Pitted
Abral #2	425	1.0	Plastic Flow
ISF #1	400	20.0	**No Failure**
Same specimen and load roller sequentially tested at each stress level.	425	20.0	**No Failure**
	450	22.4	**No Failure**
Cumulative Result	400-450	**62.4**	**No Failure**
ISF #2	400	5.0*	**No Failure**
Same specimen and load roller sequentially tested at each stress level.	425	5.0*	**No Failure**
	450	20.0	**No Failure**
Cumulative Result	400-450	**30.0**	**No Failure**

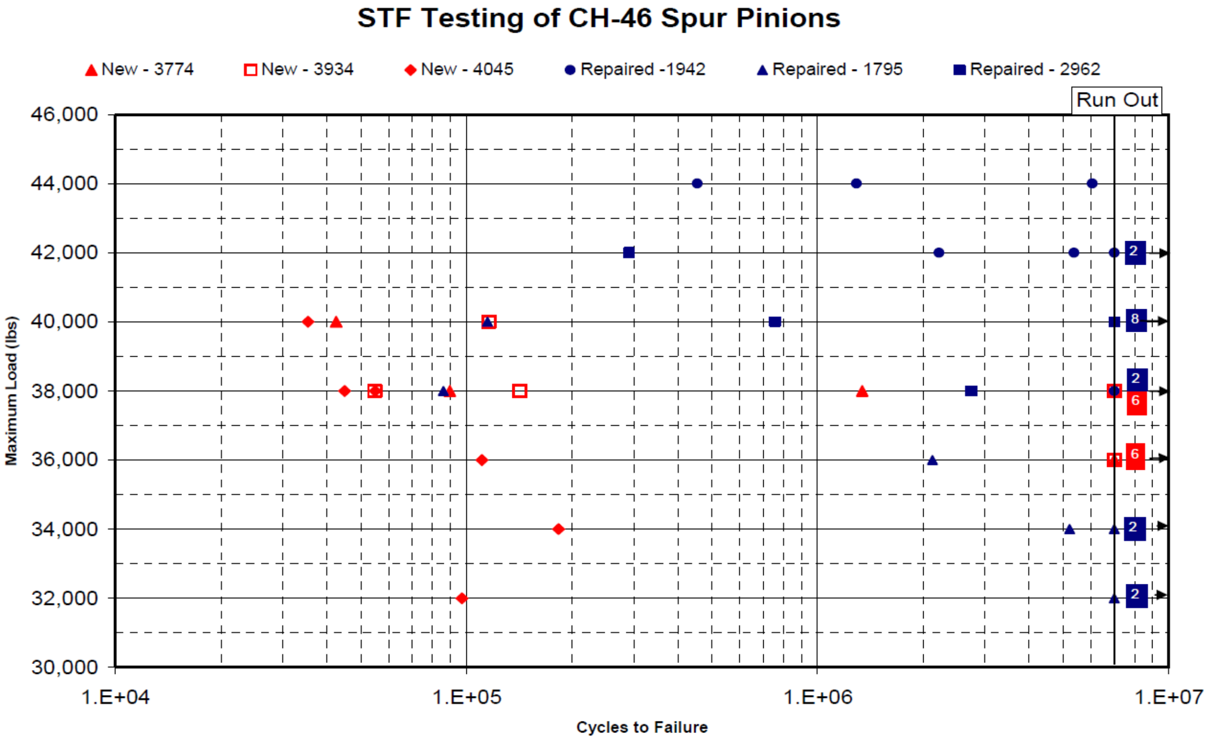
R/SCF testing results of SAE 9310H (AMS6265) case carburize specimens comparing ISF and Abral processed specimens against baseline ground and honed specimens (Ref. 3)

Appendix B

Dimensional Change Evaluation of Isotropic Superfinishing on Helicopter Gears				
Parameter	Sun Gear P/N 107D2256-7	Meet Spec	Input Pinion P/N A02D2059	Meet Spec
Tooth Thickness	Reduced 0.00014 in (0.0036 mm)	Yes	Reduced 0.0003 in (0.0076 mm)	Yes
Lead	Added crown and taper - total variation less than 0.00005 in (0.0013 mm)	Yes	None Measurable	Yes
Profile	Increased Tip Relief 0.0001 in (0.0025 mm)	Yes	Increased Tip Relief 0.0001 in (0.0025 mm)	Yes
Index Variation	None Measurable	Yes	None Measurable	Yes
Pitch Line Runout	None Measurable	Yes	None Measurable	Yes
Tooth Spacing Variation	None Measurable	Yes	None Measurable	Yes
Tooth Thickness Varation	None Measurable	Yes	None Measurable	Yes
Profile Hollow	None Measurable	Yes	Broke the edges of areas with reverse curvature, reducing the maximum to less than 0.000075 in (0.0019 mm) per degree of roll.	Yes

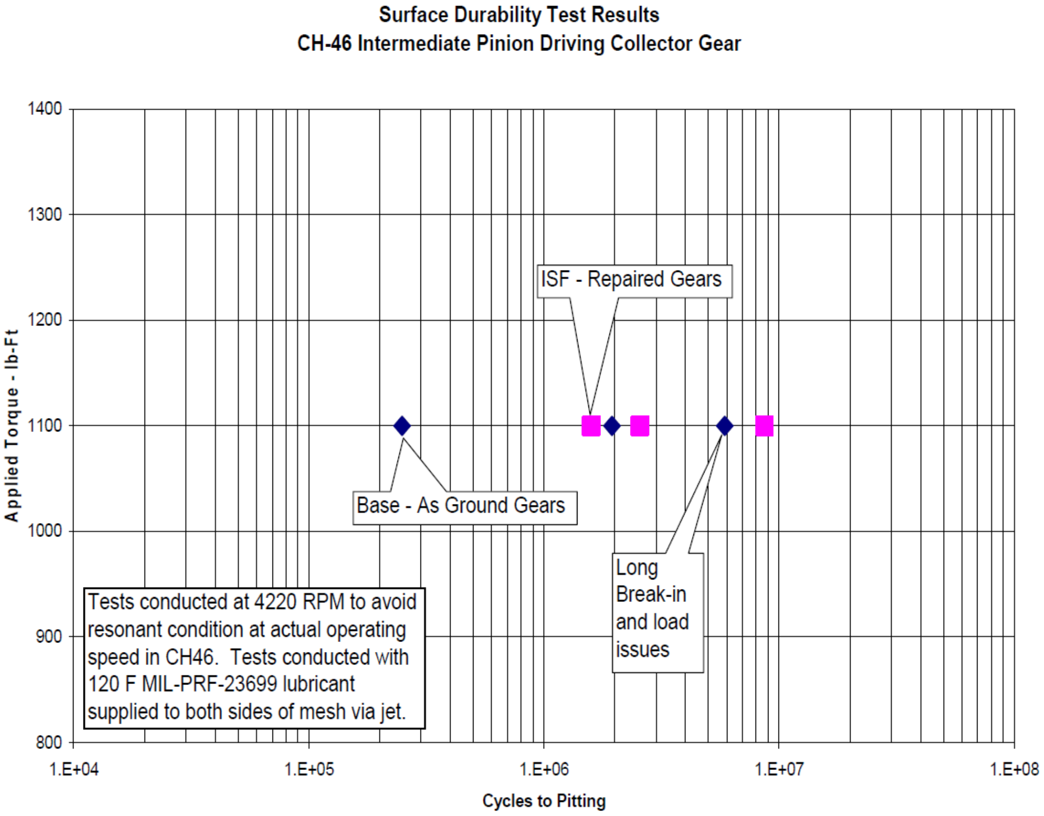
Dimensional Changes due to ISF on a Sun Gear and Input Pinion from a Boeing CH-46 (Ref. 9)

Appendix C



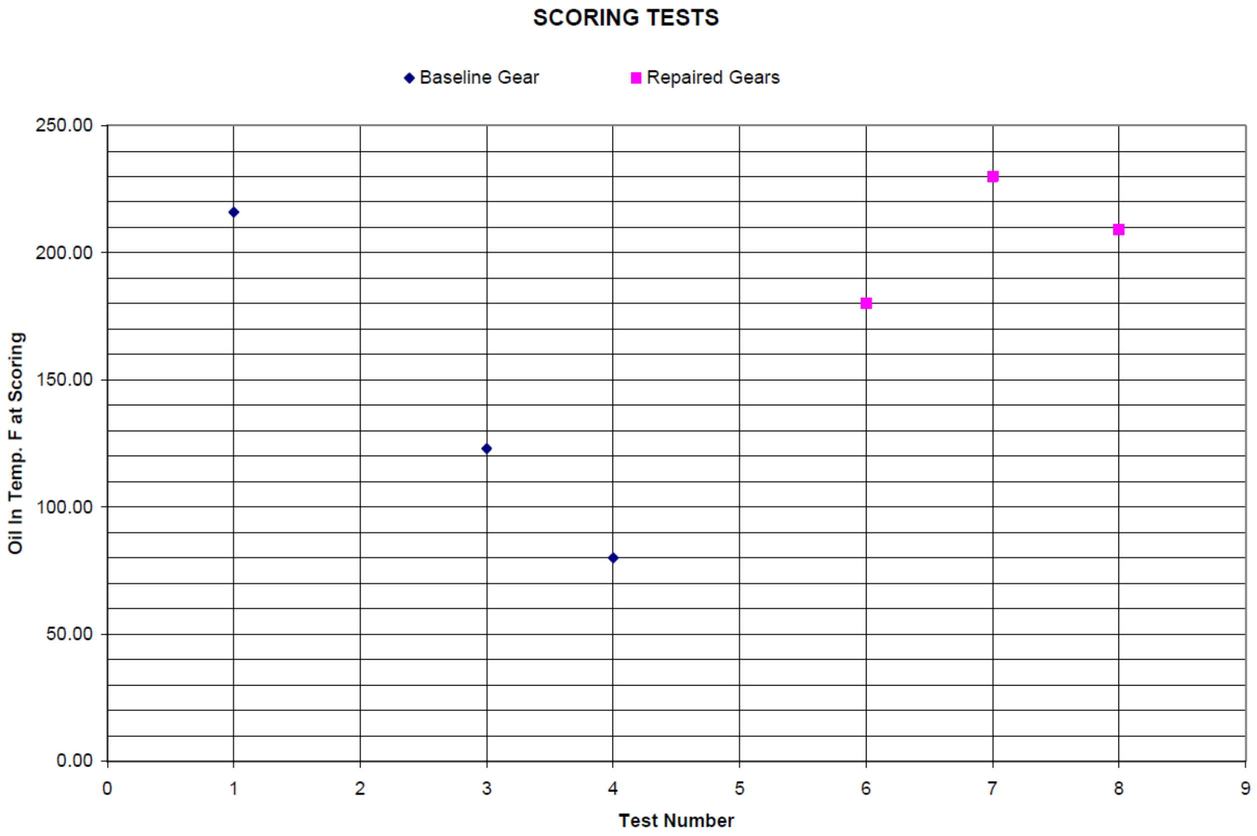
STBF cycles to failure comparison between new, baseline and ISF repaired CH-46 Spur Pinions (Ref. 10)

Appendix D



Pitting tests of new vs. ISF repaired CH-46 Intermediate Pinion driving Collector Gear (Ref. 10)

Appendix E



Scoring test results, lubricant temperature at scoring of new vs. ISF repaired CH-46 gears (Ref.10)

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The ISF notation is used with the permission of REM Chemicals, Inc. as it is a registered trademark.

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