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Repair of Helicopter Gears

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American Gear Manufacturers Association

TECHNICAL PAPER

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Abstract

In order to reduce costs by extending the operational life of the sun and input pinion gears of a helicopter transmission, scraped gears were subject to a superfinishing process. This process was found to remove minor foreign object damage by uniformly removing a minimal amount of material on the gear teeth, while meeting original manufacturing specifications for geometry. The process also resulted in enhanced surface quality and did not exhibit detrimental metallurgical effects on the surface or sub-surface of the teeth. The process was also found to eliminate gray staining, an early precursor to pitting. This paper describes the results of the helicopter gear repair project and includes the geometry and metallurgical evaluations on the repaired gear. Further effort to characterize the durability and strength characteristics of the repaired gear is ongoing.

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Background

At each depot level maintenance interval (900 hours flying time for the Input Pinion and 1800 hours flying time for the Sun Gear) the gears are thoroughly visually inspected. This inspection is carried out with up to 10x magnification, and gears are either, scrapped, returned to service, or subjected to remediation based on the inspection findings.

Figure 1 shows typical minor FOD. Remediation is accomplished by hand polishing with 400 grit paper in accordance with approved repair specifications. The intent of this process is that no (i.e., so little as to be negligible) material is removed, and that the gears are not "reworked." Figure 2 shows typical gray staining and early stages of pitting. These gears are routinely reassembled into the transmission with potential premature pitting failure developing as a result.

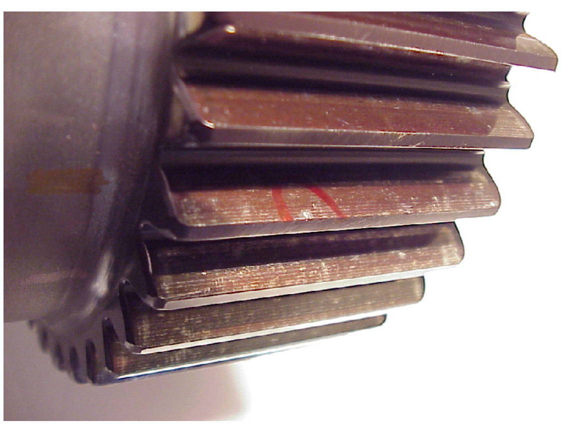


Figure 1. Sun Gear with minor FOD, area circled in red

CH–46 Aft transmission Sun Gears and Input Pinion gears are being scrapped at a rate of over $1.2 million per year. The Sun Gears are by far the higher dollar value item, and most of this effort is directed at evaluating superfinishing as a method to salvage some of these gears and reintroduce them into the transmission.

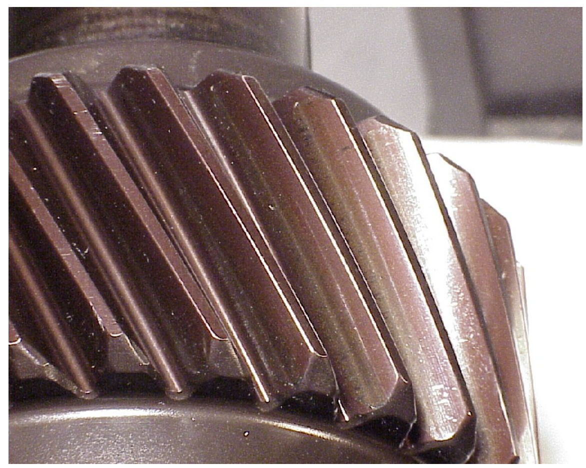


Figure 2. Input Pinion with early pitting (gray staining) on drive flanks below pitch line

Review of Superfinishing Processes

There are several commercial methods currently available to superfinish the surface of parts that results in a non–directional, isotropic, surface finish. These remove small amounts of material uniformly over the surface of the parts, and can eliminate some minor surface defects. Typically, these processes are used to impart a mirror, or near–mirror finish to machined parts. It is proposed to use one of these methods to uniformly process gears that are deemed suitable for remediation without introducing non–uniformities in surface topography while doing so. Three of the commercially available mass finishing processes were evaluated as a part of this effort. There were: MFI (Mass Finishing, Inc.), Extrude Hone, and REM Chemicals, Inc.

A summary of the main characteristics of these processes is tabulated in Table 1.

Table 1. Evaluation of Superfinishing Processes

Process	REM Chemicals, Inc.	Mass Finishing, Inc.	Extrude Hone
Hydrogen embrittlement	None – See Note 1	N/A (not an acid process)	N/A (not an acid process)
Selective etching at grain boundaries	None – See Note 2	N/A (not an acid process)	N/A (not an acid process)
Process effect on residual stress	None – See Note 3	No data available	Adds slight compressive residual stress
Material removal	Depends on surface finish before processing. For aerospace quality gears, stock removal is approximately 0.0001" per surface.	Varies. For aerospace quality gears very, very little material is removed (no quantitative value available).	Can be controlled to nearest 0.0001".
Finish achieved	Bright finish (about 2 micro-inch R_a). Can also control process to remove less material and target any required finish.	Bright finish (can go to 0.02 micro-inch R_a). Can also control process and target any required finish.	Depends on finish before processing. Can reduce R_a by 8:1. Limit about 4-6 micro-inch R_a
Effect on temperature of running gears	Reduces temperature in automotive & aerospace transmissions.	No data available.	No data available.
Process time (qualitative)	Rapid	Slow	Slow
Experience in superfinishing gears	Significant	Minimal	Minimal
Processes are applicable to the following materials:			
Case hardened	Yes	Yes	Yes
Through-hardened	Yes	Yes	Yes
Non-hardened	Yes	Yes	Yes
Non-ferrous	Yes	Yes	Yes
Plated	Yes. Removes plating.	Yes. Can remove or burnish plating.	Yes. Can remove or polish plating (if plating is thick and uniform enough).
Black oxide coated	Yes. Removes black oxide coating.	Yes. Can remove or burnish black oxide coating.	Yes. Can remove or polish black oxide coating (if coating is thick and uniform enough).

Notes:
1. REM Chemicals, Inc. has conducted studies that verify the mild acids (pH = approximately 5.5) used in their process, coupled with the other details of the process, do not cause hydrogen embrittlement.
2. REM Chemicals, Inc. has conducted studies that show their process does not selectively attack grain boundaries.
3. REM Chemicals, Inc. has measured residual stress on parts before and after processing and verified their process has no measurable effect on residual stress.
(Results of the studies noted above can be obtained from REM Chemicals, Inc.)

The MFI process is a vibratory honing process. The hardness and texture of the abrasive media can be controlled to achieve any desired surface finish, down to a bright mirror finish (0.02 micro-inches R_a). With proper media selection, thin coatings can be polished without being removed. This is a time consuming operation. The Extrude Hone process involves honing the surface of the part with putty like media charged with abrasive particles. This is a cutting process rather than a burnishing/honing process. The surface finish that can be achieved is a function of the surface finish before processing with the functional limit for finest finish is approximately in the 4 to 6 micro-inches R_a range. This method requires tooling specific to each part to ensure uniform stock removal. The REM Chemicals process is a chemically accelerated vibratory finishing technology. A mildly acidic phosphate solution produces a soft conversion coating, which is easily removed by the rubbing of the non-abrasive media. he exact blend of chemicals and the size and shape of the media are selected on the basis of the material being processed, the size and shape of the part, and the desired final surface finish.

The MFI process requires long process time to produce fine finishes. The Extrude Hone process requires special tooling to ensure uniform stock removal, and can produce only a moderately fine finish. Thus, of the three processes evaluated, the REM Chemicals process offers the best advantage in producing a fine finish (1-2 micro-inches R_a range), rapid processing time, and controlled, minimal~~,~~ stock removal. Based on this analysis (a detailed analysis was not considered a part of the effort) and considerable experience with the REM Chemical's process for superfinishing gears[1,2,3], it was selected for this effort.

Pre-Finishing Evaluations

Two Sun Gears and two Input Pinions that had been scrapped due to major FOD were provided for examination. These gears also exhibited minor FOD (edge not detectable with the point of a sharp probe, a typical example is shown in Figure 1) and early pitting (gray staining, a typical example is shown in Figure 2) was detected on the Input Pinions, making these gears good candidates to investigate repair procedures.

<u>Metallurgical Characterization Pre-Superfinishing</u>

A metallurgical section was cut from one of the sun gears through an area with minor FOD damage. This section was polished, and examined for evidence of sub-surface cracking resulting from the dislocation when the foreign object passed through the mesh. A high magnification photomicrograph of this section is shown in Figure 3. No evidence of sub-surface cracking could be detected. Thus, damage of this limited magnitude is a satisfactory candidate for remediation by superfinishing the surface.

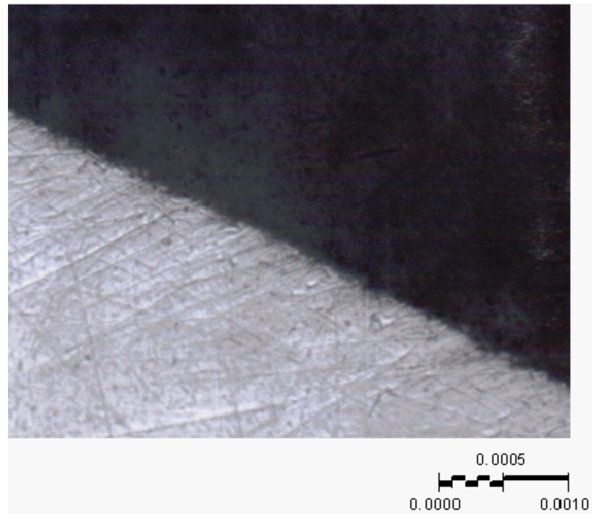


Figure 3. High magnification photomicrograph of section through area on Sun Gear with minor FOD. No sub-surface cracking associated with the damage is evident.

A metallurgical section was cut from one of the Input Pinions through an area with early pitting (gray staining). A high magnification photomicrograph of this section is shown in Figure 4.

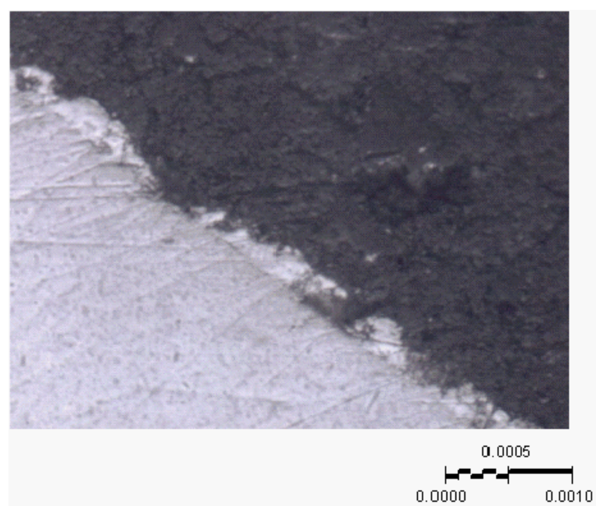


Figure 4. High magnification photomicrograph of section through area on Input Pinion with early pitting (gray staining). Damage is confined mainly to the surface with only minor (less than 0.0001 inch) penetration into the substrate.

Examination of the polished section showed that the early pitting (gray staining) was confined mainly to the black oxide coating and penetrated less than

0.0001 inch into the substrate. Again, damage of this limited magnitude is a satisfactory candidate for remediation by superfinishing the surface. The REM Chemicals process will remove the coating, and can be controlled to remove the top 0.0001 inch of the substrate.

Dimensional Characterization Pre-Superfinishing

A comprehensive dimensional characterization was conducted on one Sun Gear and one Input Pinion. Standard dimensional characterization of gears involves checking profile, spacing, index, run out, and thickness variation at the center of the face width. To get a more complete picture of the effect of REM Chemicals superfinishing on the gears for this effort, these items were measured at the center of the face width and 1/4 inch from the ends of the face for each gear. On the Input Pinion, these measurements were conducted on each of the right hand and left hand helices. The results of the dimensional characterization prior to superfinishing and after superfinishing is presented comparatively in Table 2 in the following text.

Surface Roughness Characterization Pre-Superfinishing

Surface roughness measurements were conducted on one of the sample Sun Gears, prior to superfinishing. A surface roughness of 7 micro-inches R_a and 18 micro-inches R_a was measured along the lead direction and along the profile direction, respectively.

Based on the fact that the damage exhibited on both the Sun Gear and Input Pinion was satisfactory for repair by superfinishing the Sun Gear, the Input Pinion, and a segment from the second Sun Gear, which had been sectioned for metallurgical examination, were sent to REM Chemicals, Inc. for superfinishing. The segment of the sectioned gear was sent to provide a sample for metallurgical characterization and residual stress measurement after superfinishing. REM Chemicals, Inc. masked all areas on the gears except the teeth. Processing was carried out using media and chemicals that REM Chemicals, Inc. has determined are suitable for processing AISI-9310 steel gears of the general size and configuration of the gears for this effort.

Table 2: Dimensional Changes Due to Super Finishing

Parameter	Sun Gear P/N 107D2256-7	Meet Spec	Input Pinion P/N A02D2059-	Meet Spec
Tooth Thickness	Reduced 0.00014	Yes	Reduced 0.0003	(1)
Lead	Added crown and taper – total variation less than 0.00005 per flank.	Yes	None Measurable	Yes
Profile	Increased Tip Relief 0.0001	Yes	Increased Tip Relief 0.0001	(2)
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	(3)
Tooth Thickness Variation	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 inch per degree roll.	(4)

Notes:
(1) Tooth thickness of Input Pinion was below minimum OEM specification before super-finishing.
(2) Profile on drive flank of Input Pinion did not meet OEM specification due to excess tip relief before super-finish. Profile on coast flank met OEM specification before and after super-finish.
(3) Maximum tooth spacing variation on the Input Pinion exceeded OEM specification before super-finishing. Super-finishing was not able to correct the tooth spacing error.
(4) There were select areas on the Input Pinion with profile hollow (reverse curvature) in excess of OEM specification before super-finish. Super-finishing generally corrected this.

Superfinishing Process Details

REM Chemicals process is produced in vibratory finishing bowls or tubs. A proprietary active chemistry is used in the vibratory machine in conjunction with high-density, non-abrasive ceramic media. When introduced into the machine, this active chemistry produces a stable, soft conversion coating on the surface of the metal gears being processed. The rubbing motion across the gears developed by the machine and media effectively wipes the conversion coating off the asperity peaks of the gears surfaces, but leaves the valleys untouched. (No finishing occurs where media is unable to contact or rub.) The conversion coating is continually re-formed and rubbed off during this stage producing a surface smoothing mechanism. This process is continued in the vibratory machine until the surfaces of the gears are free of asperities. At this point, the active chemistry is rinsed from the machine with a neutral soap. The conversion coating is completely rubbed off the gears to produce the isotropic superfinished surface. In this final step, commonly referred to as burnishing, no metal is removed.

The gears used in this study were superfinished in a 10 cubic foot vibratory bowl using non-abrasive high density ceramic media (3 mm x 6 mm angle cut cylinders) and a proprietary active chemistry. A witness coupon was processed simultaneously along with the gears. After 1.25 hours, 0.00010 inch of stock was removed from the witness coupon. The gears were then burnished for 2.0 additional hours. After burnishing the gears were immersed in a rust preventive, dried and returned for evaluation.

Post-Superfinishing Evaluations

Metallurgical Characterization Post-Superfinishing

A metallurgical characterization was conducted on a section cut from the segment of a Sun Gear that was superfinished. The hardness profile obtained in this characterization is shown in Figure 5. Surface hardness, depth to 50 HRC, and core hardness meet OEM Specification. A high magnification photomicrograph of the near surface microstructure is shown in Figure 6. The structure is fine grain tempered Martensite with about 15% retained Austenite and finely distributed carbides. This structure is consistent with properly heat treated SAE 9310, and shows no evidence of degradation (grain boundary etching, hydrogen embrittlement, etc.) due to the superfinishing process.

Dimensional Characterization Post-Superfinishing

Figure 7 shows profiles and leads on the Input Pinion before and after superfinishing. The results of comparing detailed dimensional characterizations show that the material removed by the REM Chemical superfinishing process was minimal and relatively uniform. Some non-uniformity and more material removal were caused in areas where the media used in the superfinishing process was able to move more freely. The sun gear has a large flange to support the bevel ring gear. This flange acted as a baffle and restricted the flow of the media at one end of the face width. Lead traces and tooth thickness measurements show that there was more material removal at the end of the face away from this flange. However, since the amount of material removed was so small, the changes in shape introduced by this variation were well within the lead tolerance for this gear. The input pinion had no restriction to cause non-uniform movement of media along its axis. In this case the superfinishing process introduced no measurable variation in lead. For both gears, the superfinishing process tended to round off sharp corners – causing tip relief to increase. Table 2 shows a detailed summary of the dimensional changes introduced by superfinishing.

Surface Roughness Post-Superfinishing

Surface roughness was measured on the superfinished Sun Gear. The measurements were 3 micro-inches R_a and 12 micro-inches R_a along the lead direction and along the profile direction, respectively. While this is a considerable improvement over the original surface roughness, the REM Chemicals process is capable of significantly better surface quality if more material can be removed. Figures 8 and 9 show the Sun Gear and Input Pinion after superfinishing. These figures clearly show that superfinishing removed minor FOD and early pitting (gray staining). They also show the near mirror finish obtained by the superfinishing process (the apparent markings on tooth flanks are not shadows, but are reflections of adjacent teeth).

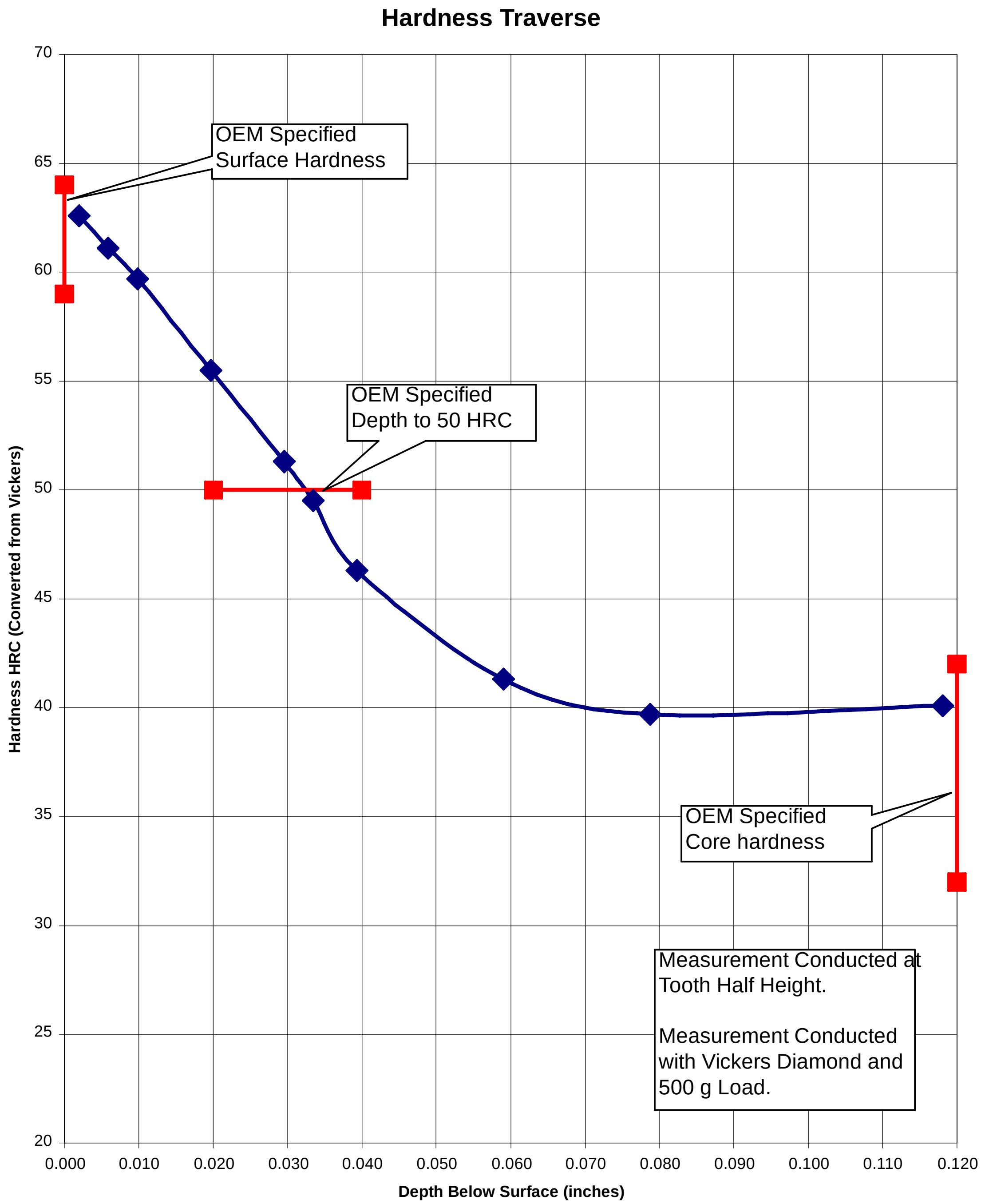


Figure 5. Hardness traverse taken on segment cut from Sun Gear after REM Chemical superfinishing. OEM specifications for surface hardness, depth to 50 HRC, and core hardness are met.

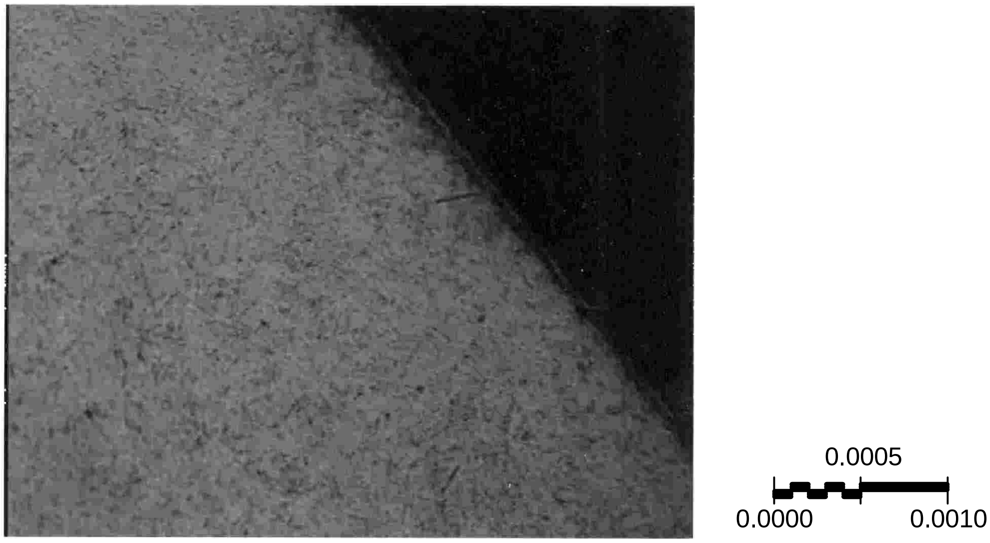
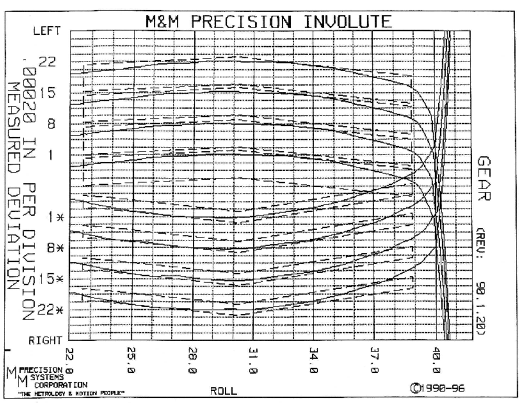
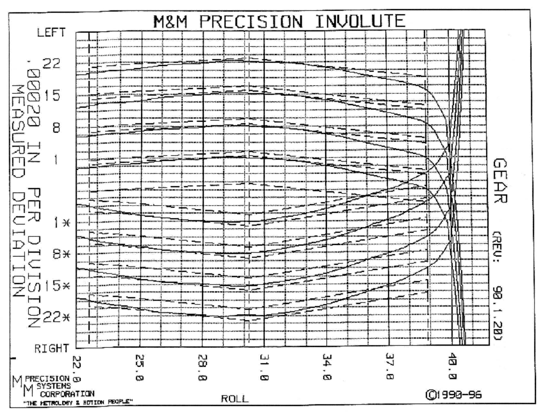


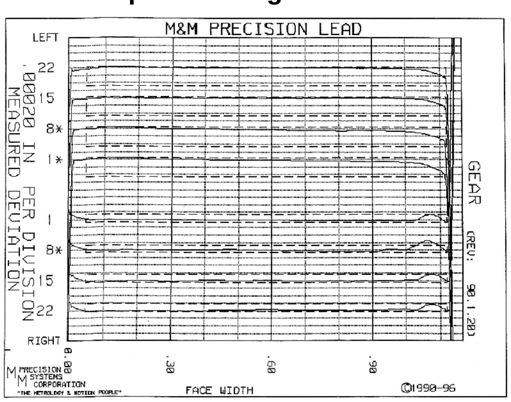
Figure 6. High magnification photomicrograph of near surface microstructure on Sun Gear from a section cut after super-finishing. The structure is fine grain tempered Martensite with about 15% retained Austenite and finely distributed carbides. This is consistent with properly processed AISI 9310. The apparent line parallel to the tooth surface is an artifact of the mounting and does not represent material degradation.



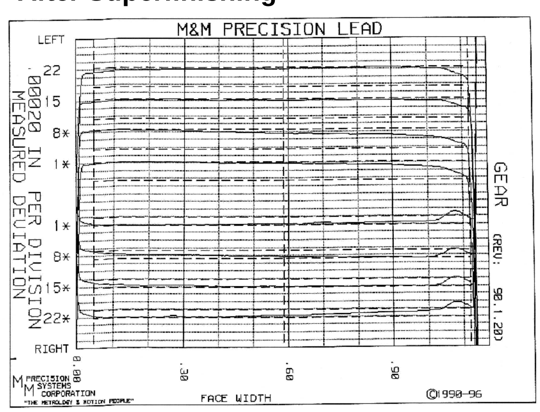
Before Superfinishing



After Superfinishing



Before Superfinishing



After Superfinishing

Figure 7. Profiles and leads of an Input Pinion, before and after superfinishing.

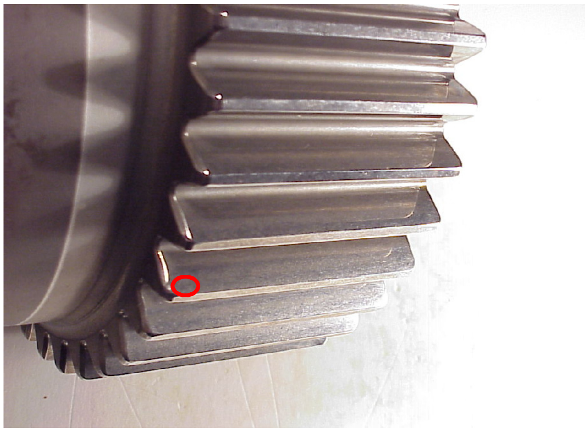


Figure 8. Sun Gear after super‐finishing showing that the process eliminated minor FOD. The area circled in red is one of the areas with major FOD that caused this gear to be scrapped.

Figure 9. Input Pinion after super‐finishing showing that the process eliminated early pitting (gray staining).

XRD Residual Stress and Retained Austenite Measurement Post–Superfinishing

The balance of the sample segment cut from a Sun Gear was sent to Lambda Research for measurement of residual stress and retained austenite via X–Ray diffraction after superfinishing. These parameters were measured with X–Rays passing parallel to the axis of the gear to obviate the need to remove teeth for beam access. A compressive residual stress of 108.7 +/–2.4 ksi and a retained austenite of 3.1 +/–0.1 % were measured. The measurement confirms a significant amount of compressive residual stress which is favorable for fatigue life and confirms the premise that the REM Chemicals process does not unfavorably impact the residual stress condition of the gear tooth.

Conclusions

Minor damage (FOD, micro–pitting) can be uniformly removed without degrading gear performance. The REM Chemicals superfinishing process is a random isotropic process that removes a relatively uniform, very thin layer of material that can eliminate shallow (less than 0.0001 inch deep) surface imperfections. The characterizations performed in this effort show that this process does not degrade gear dimensional or metallurgical properties below OEM specifications for new gears, provided the used gears meet these specifications, and the tooth thickness is on the order of 0.0003 inch above the low specified limit.

Surface durability testing conducted on cylindrical specimens shows that the resulting improved surface provides extended durability and operating life[(4)]. This is to be verified on CH–46 gears in a current project, improved surface finish on gear teeth is anticipated to extend operational life and reduce maintenance costs. While the maximum benefit will accrue only if the mating pair of gears are superfinished, superfinishing only one of the gears will provide a portion of the benefit.

Based on the results of this Repair Technology project, the REM Chemicals superfinishing process is highly recommended for remediation of minor FOD. Further, the uniform material removal by the REM Chemicals process also resulted in the removal of gray staining which is an early stage of pitting. Removal of gray staining is anticipated to cause enhanced pitting resistance in the gear teeth, resulting in extended life of the gear. The improved quality of surface obtained will also enhance the pitting resistance with additional operational life for the gear.

Based on the encouraging results in this study, a further project to establish the strength and durability of used gears that have been repaired by REM Chemicals superfinishing is in progress and data obtained in this project will be available next year.

Acknowledgements

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