Technical Area: Mechanical Systems

Repair of Helicopter Gears-Phase II

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Abstract

In order to reduce sustainment costs, by extending the operational life of the gears of the CH-46 (Sea Knight) transmission, scrap gears were subject to a select super finishing process. This select process, known as the Isotropic Super Finishing (ISF) process, was found to remove minor Foreign Object Damage (FOD) by uniformly removing a minimal amount of material (0.0002 inch/flank or less) on the gear teeth, while meeting all original equipment manufacturer (OEM) specifications for dimension and geometry. The process also resulted in enhanced surface quality and did not exhibit any detrimental metallurgical effects on the surface and sub surface of the gear tooth.

The ISF process was also found to eliminate gray staining, which is an early precursor to more severe micro-pitting/pitting. The removal of this feature and the high surface quality obtained is anticipated to provide extended operational life of the gear, with commensurate reduction in gear replacement costs. While the maximum benefit will accrue only if the mating pair of gears are super finished, it is anticipated that super finishing only one of the gears will provide a portion of the benefit.

This paper describes the results of the U.S. Navy Manufacturing Technology (ManTech) helicopter gear repair project and focuses on the comparative strength and durability evaluations conducted on repaired gears and new gears, obtained from a qualified Navy vendor. The results obtained demonstrate that the repair and reuse of a portion of the scrapped gears is highly feasible.

Background

Military repair facilities, like the Fleet Readiness Center (FRC) at Cherry Point North Carolina, routinely overhaul helicopter gear boxes at periodic intervals. Transmission gears are visually scanned for any damage. If damage is detected a sharp scriber is traversed over the damage. If the scriber is snagged, the gear is scrapped. For the CH-46 Sea Knight aircraft this process is executed for all the gears in the fore and aft transmission and the Mix box. A schematic of the Mix box is illustrated in Figure 1.

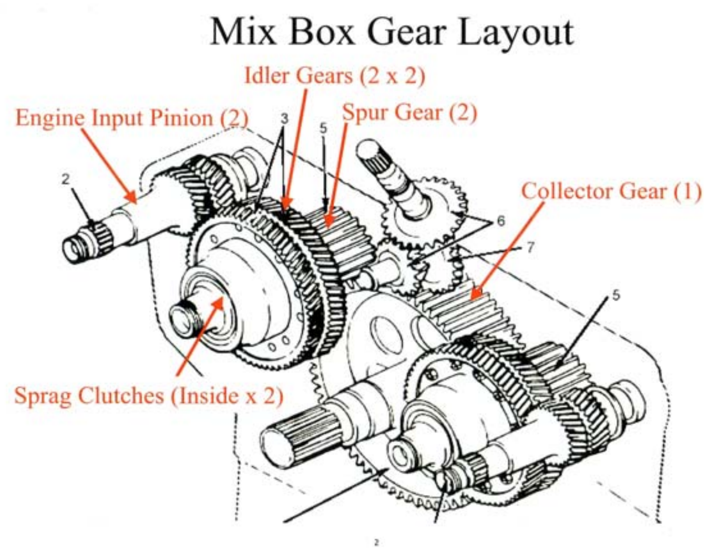


Figure 1: Mix Box Schematic

Costs for replacement gears are high. In the Mix box, the cost of the individual gears range from $6000, for the cheapest gear, to almost $30,000 for the most expensive gear. Typical gear tooth damage encountered are FOD and gray staining. A typical FOD on a gear is illustrated in Figure 2.

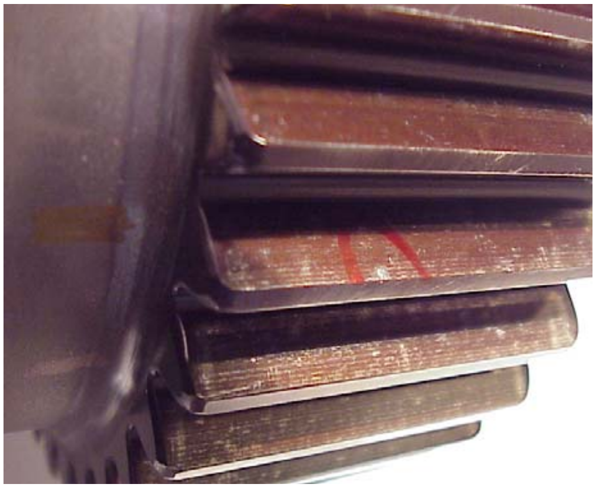


Figure 2: Typical FOD on Gear

A cross section profile of a FOD on a scrapped gear is illustrated in Figure 3. Eliminating the slope it can be observed that the actual depth of the damage is about 0.00006 inch. Consequently, any process that can remove this damaged area, while maintaining gear tooth geometry, could be used to salvage this gear. After evaluating a number of processes that are traditionally used for surface enhancement, the Isotropic Super Finishing (ISF) process(1, 2, 3, 4) developed by REM Chemical of Brenham, Texas was selected for this purpose.

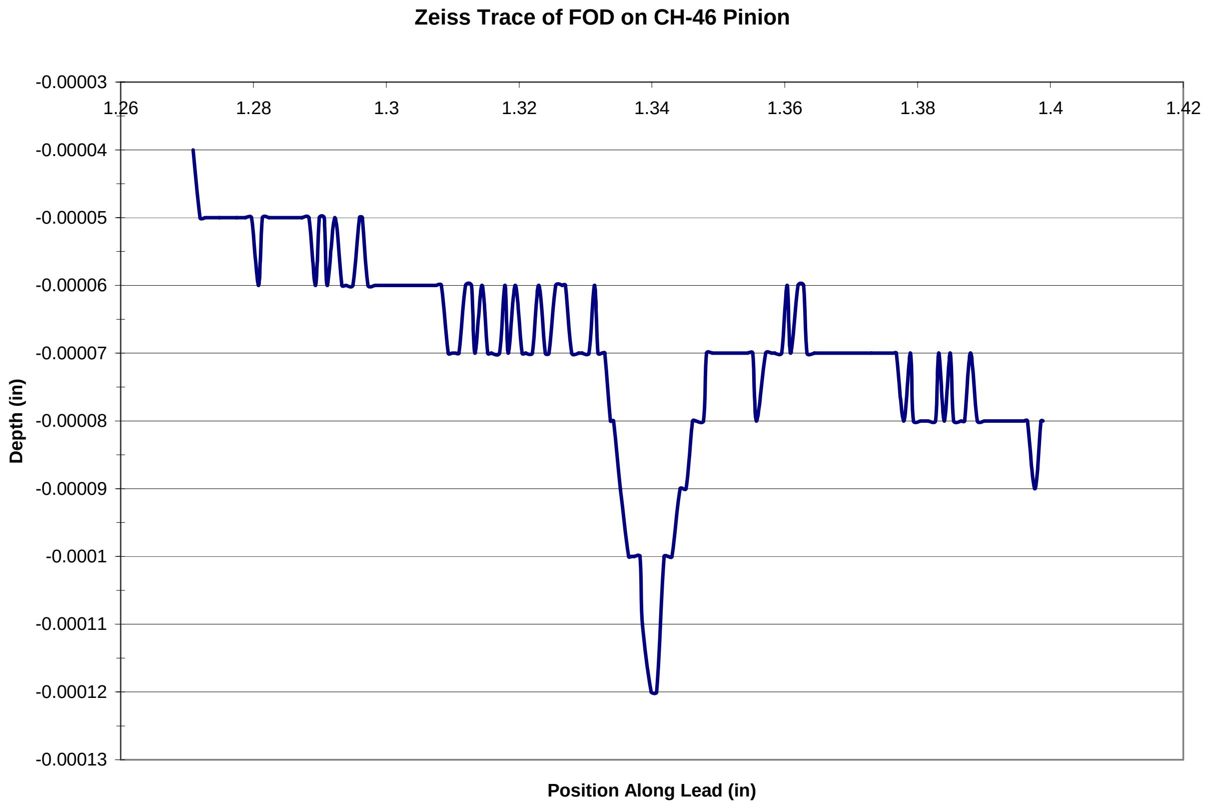


Figure 3: Typical Profile of Gear Tooth FOD

At the outset, scrapped gears from a CH-46, obtained from FRC CP were super finished to eliminate surface damage (FOD and gray staining) and analyzed for dimension, geometry and metallurgy(5). Efforts were focused on the input pinion, the spur pinion and collector gear of the Mix box and the sun gear in the main transmission of the aircraft. The results of the dimensional and metallurgical analysis demonstrated that scrapped gears can be super finished by the ISF process to remove surface damage, while maintaining all dimensional and geometrical tolerances within original equipment manufacturer (OEM) specifications. Typical dimensional and geometry changes on two gears are presented in Table 1 from Reference 5.

Table 1: 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.

Further, these “repaired” gears met OEM specifications on hardness, hardness profile, residual stresses and retained austenite. Examination of the microstructure indicated that the structure was consistent with properly heat treated SAE 9310, and showed no evidence of degradation (grain boundary etching, hydrogen embrittlement, etc**)** due to the super finishing process.

The key to establishing gear repair by the ISF process, as an acceptable practice, with significant cost savings, is to demonstrate the strength and durability of “repaired” gears versus new gears. This paper describes the gear testing which was conducted and the data obtained to establish this practice.

Description of Gear Test Procedures

Three major types of tests were conducted on the repaired and new spur pinion gears of the CH-46 Mix box. They are Single Tooth Bending Fatigue (STF) tests, power re-circulating Contact Fatigue (CF) tests and Scoring Resistance (SR) tests(6). Only a brief description of the tests follows, as details are available in the reference.

In order to establish a degree of credibility with the U.S. Navy, an endurance test plan, based on evaluating the above mentioned characteristics of the new and repaired gears, was defined and presented to NAVAIR (Naval Air Systems Command) for their concurrence and input. The only additional requirement requested by NAVAIR was data acquisition to demonstrate a lack of correlation of test induced failure to original damage on the repaired gears. Additional data, consisting of documentation of all damage on the scrap gears, before superfinishing, was accumulated to service this request.

Single Tooth Bending Fatigue Tests:

Figure 4 illustrates a cross section and a pictorial representation of the hardware to evaluate this gear related material characteristic. It consists of a means to hold the spur pinion, while

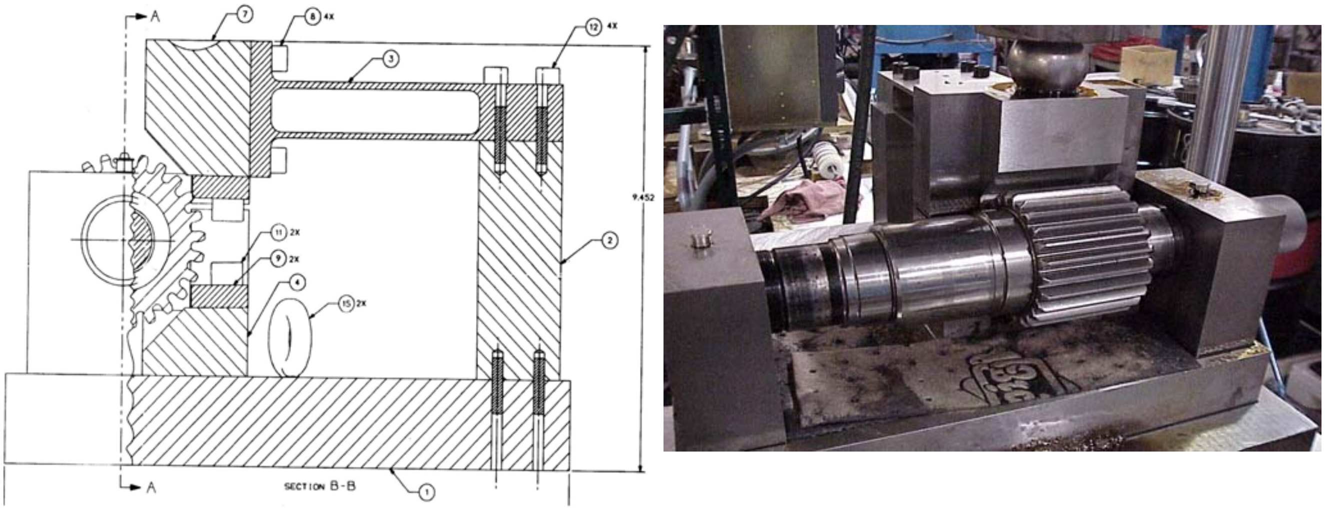


Figure 4. Single Tooth Fatigue Fixture

a cyclical load is applied between two teeth at a time, resulting in bending fatigue and ultimate failure of one of the gear teeth. These tests are carried out on an electro-hydraulic, Universal test frame. The load applied and the number of cycles to failure can be developed in a “Stress-Cycles” to failure (S-N) graph, which is representative of the bending strength characteristics of the gear material.

<u>Power re-Circulating Contact Fatigue Tests:</u>

This test rig is based on the standard, power re-circulating, 4-square, kinematic configuration and consists of two gear boxes, a test gear box and a slave (reversing) gear box, as illustrated in Figure 5. These two gear boxes are coupled together in a manner that torque can be applied between the two gear pairs to load the gears. The adjustable speed drive motor supplies the power to operate the test and slave gear boxes, usually through a speed increasing gear box. The load on the gear teeth is a function of the torque applied within the 4-square loop and the motor only supplies the power to overcome the losses in the two gear meshes. The contact length of the gears in the reversing gear box is usually several times the contact length in the test gear box, causing higher contact pressures in the test gear box pair and failure due to one of the several modes of gear failure. The mesh conditions used in this test are to induce pitting failure, due to contact fatigue, on the driving flank of the test gear.

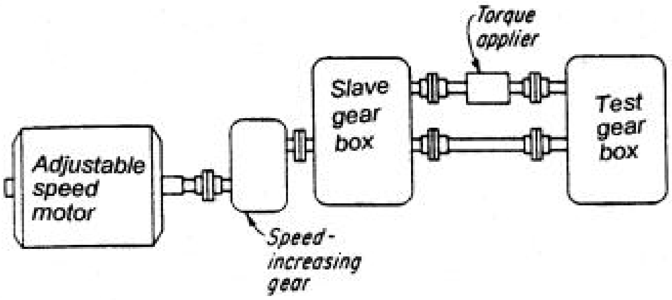


Figure 5: 4-Square Power Re-Circulating Gear Test Rig

The gear pair in the test gear box of the test rig designed and developed for this project is shown in Figure 6. For this project the spur pinion (gear on left) - collector gear (gear on right) pair was used. A similar pair is in the reversing gear box. The only difference between the two gear boxes is that the gears are offset and mesh only up to about 1/3 of their face widths in the test gear box. This offset was necessary in order to develop sufficient contact pressures on the gear teeth, and obtain gear failures in a reasonable amount of time. In addition to the increased face widths in contact in the reversing gear box, the gears in this box were both super finished in order to maximize their durability. In the test gear box new spur pinions were run against ground collector gears and repaired spur pinions were run against super finished collector gears.

A vibration sensor mounted on the test box is calibrated to the established failure criteria. Test conditions selected for this test were such that pitting failure would occur. A test torque that induced failure in new gears was identified by “searching tests”. All further tests on new and repaired gears were conducted at this torque. The number of cycles of operation before pitting failure occurred was used as a measure of the strength of the gear in contact fatigue.

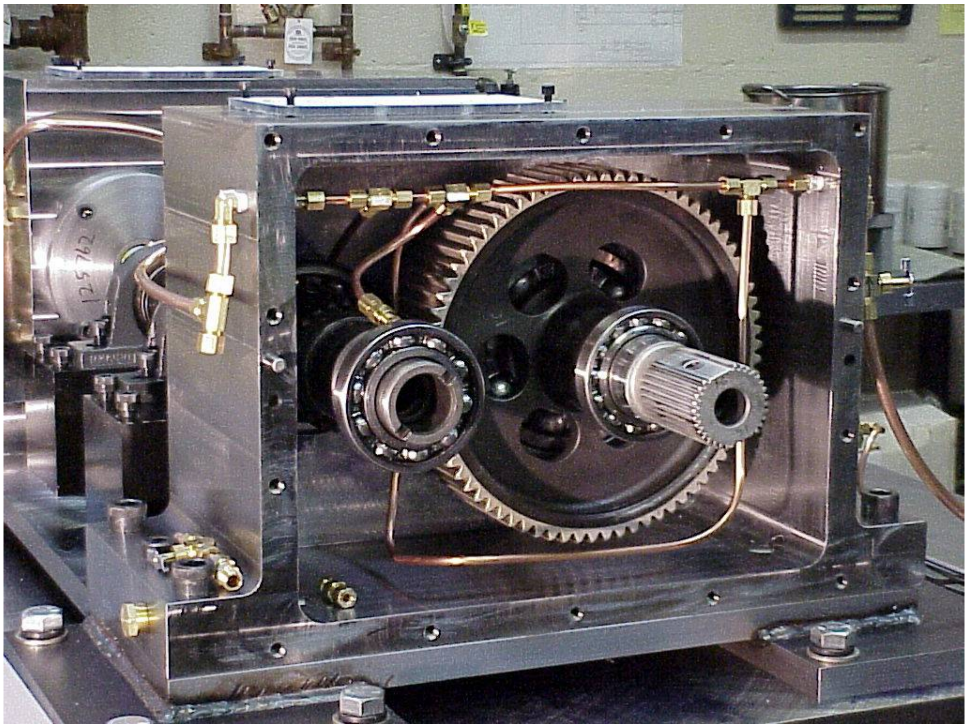


Figure 6: PC Test Rig for CH-46 Gears

Power re-Circulating Scoring Resistance Tests:

The same test rig used for contact fatigue is used for evaluating the scoring resistance of the gear pairs. However, in this test the temperature of the lubricant is increased, while the test torque is kept constant and until scoring failure occurs. The lubricant temperature at which scoring failure occurs is a measure of the surface's scoring resistance. As in the CF tests, new spur pinions were run against ground collector gears and repaired spur pinions were run against super finished collector gears, in the test box while a super finished gear pair was run in the reversing gear box.

Test Results and Discussions

The actual test procedures, test variables, and actual number of tests in each category were defined prior to initiating the program$^{(7)}$. Only the results of the tests are presented in this paper.

Single Tooth Bending Fatigue Tests: Eighteen STF tests on baseline gears, yielding 24 data points and twenty (20) STF tests, yielding 28 data points, were conducted in this project. These are plotted in Figure7. A test is considered a "run out" if no failure occurs after 7 million cycles. It is important to note that since two teeth are being tested at any given time, a run out yields 2 data points, while a failure yields only one data point..

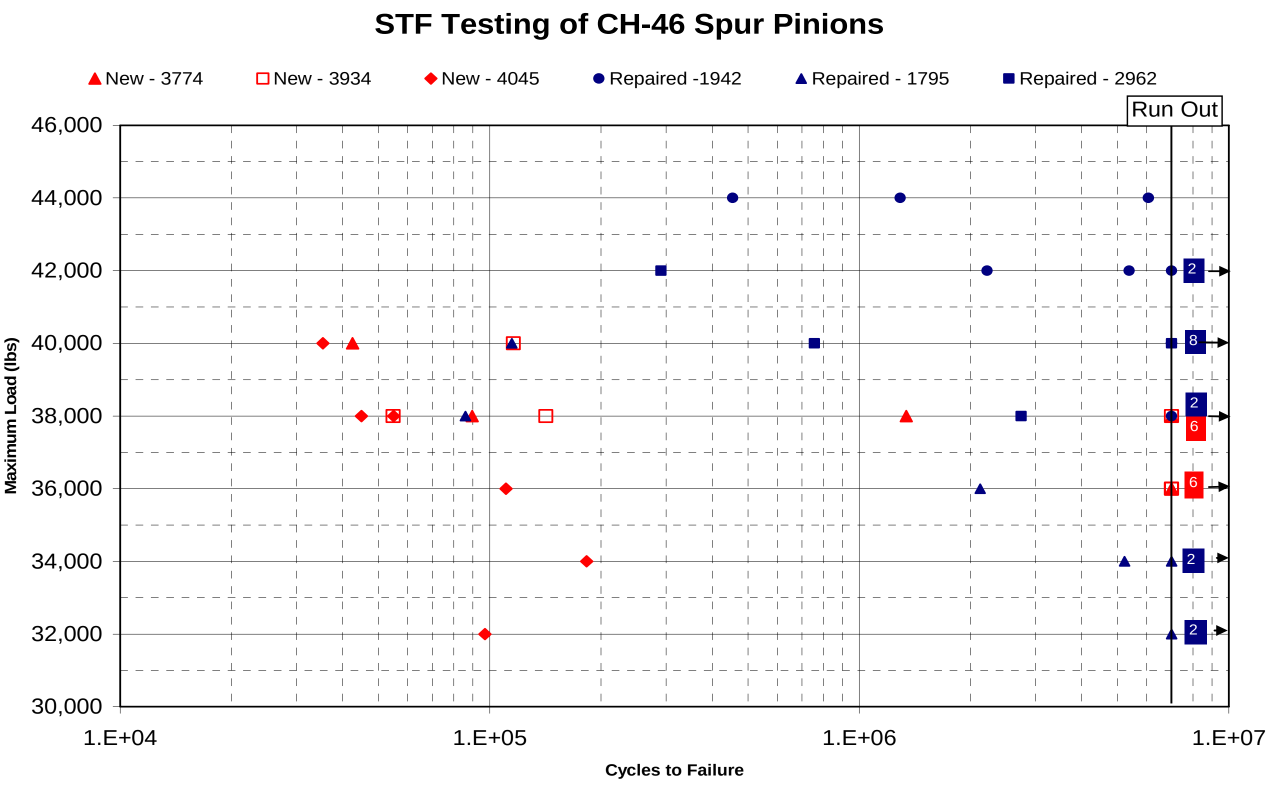


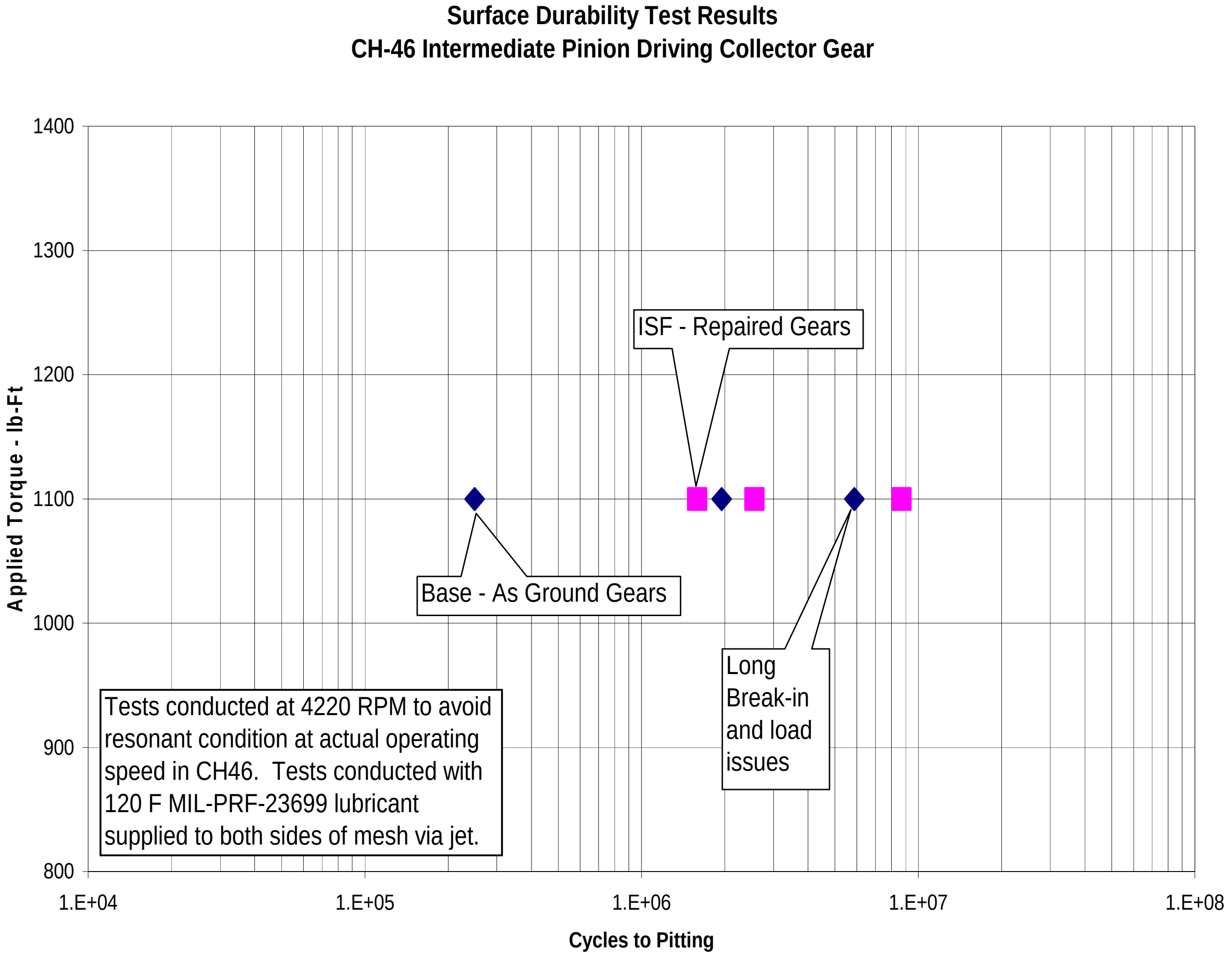
Figure 7. STF Data

From the data it can be concluded that the bending strength of the repaired gears meet or exceed the bending strength of new gears. A normal probability analysis of the data, which is summarized in Table 2, shows that the load required to obtain failure rates of 90%, 50% and 10% is greater for repaired gears than new gears.

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

Table 2. Load for Corresponding Failure Rates

Contact Fatigue Tests: The strategy pursued here was to identify the torque at which pitting failure occurs on the baseline spur pinions in a reasonable amount of cycles and establish the life of the repaired gears at the same load. The torque established on the new spur pinion was 1100 ft. lbs. to obtain pitting failure. After establishing that torque, two (2) further baseline tests and three (3) tests with repaired gears were conducted. The actual data points obtained in CF testing are plotted on Figure 8.



Surface Durability Test Results
CH-46 Intermediate Pinion Driving Collector Gear

Tests conducted at 4220 RPM to avoid resonant condition at actual operating speed in CH46. Tests conducted with 120 F MIL-PRF-23699 lubricant supplied to both sides of mesh via jet.

Figure 8. Contact Fatigue Test Data

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

Table 3: G50 Life for Different Levels of Confidence

Table 3, obtained from the Weibull analysis, tabulates the G50 life, in cycles, for various confidence levels. The life for repaired gears is consistently above the life for new gears, indicating that the contact fatigue characteristics of scrap gears, repaired by super finishing, are as good if not better than new gears.

While damage on the scrap gears were in several different locations on the gear teeth, the repaired gears all failed at one edge of the face width due to the offset loading strategy adopted in the contact fatigue tests. This implies that prior damage on the scrap gears does not appear to have any impact on the failure of the repaired gears. This lack of correlation between damage on the scrap gears prior to repair and on the gears, after repair, was considered significant from NAVAIR’s perspective.

The measured temperature of the oil coming out of the mesh shows a 20 degree F to 30 degree F reduction, when the repaired gears are run under load, in comparison to when new gears are run in the test rig. While quantification of the actual reduction in heat loss in the mesh could not be computed, because of chilled bearing lubricant mixing in the general area of the gear mesh, the fairly consistent drop in oil-out temperature indicates that repaired gears are running cooler due to their superior surface quality, in comparison to new gears that have been finished by grinding.

<u>Scoring Resistance Tests:</u> Since scoring resistance is a measure of the mating surface’s ability to operate in a condition where the lubricant film breaks down, the strategy in this test is to gradually increase the oil input temperature, with the gears operating at the torque used in the contact fatigue tests. The maximum oil input temperature at which scoring failure occurs is a direct measure of the tooth surface’s ability to resist scoring. The data obtained in this test is plotted in Figure 9.

The data in Figure 9 demonstrates that the repaired gears can be operated with a higher oil-in temperature than new gears, before scoring damage occurs. Consequently, it can be concluded that the repaired gears have a higher degree of scoring resistance. This can be directly attributed to the superior surface quality of the repaired gears over the new gears with a ground surface.

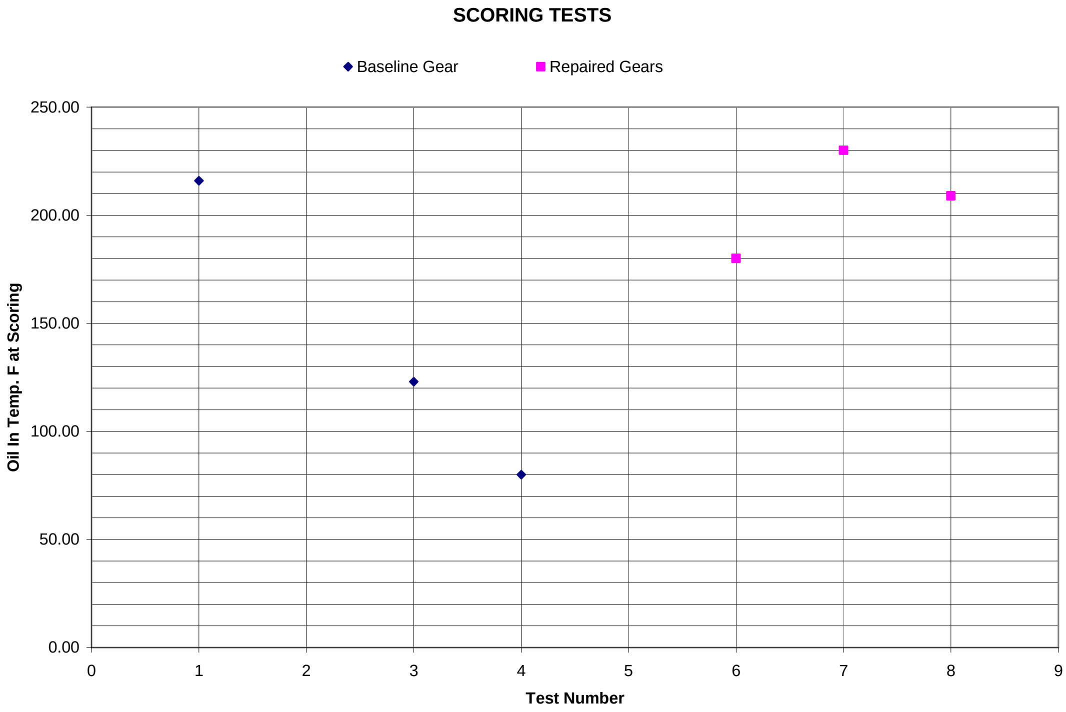


Figure 9. Oil Inlet Temperature for Scoring Tests

Conclusions

In order to save costs in the overhaul of helicopter transmissions, the concept of repairing and reusing gears appears very feasible. Using the ISF process, surface damage on gears can be removed, while maintaining original equipment manufacturer specifications and tolerances on gear geometry, dimension, and metallurgical characteristics. Strength and durability testing conducted on the repaired spur pinion gears of the CH-46 gear Mix box demonstrates that the bending fatigue, contact fatigue, and scoring resistance characteristics compares very favorably with new gears. In all instances these characteristics for repaired gears are as good, if not better than, as the characteristics of new gears. Further, the super finished gears appeared to run with less heat loss than new gears that had only a ground tooth surface.

While the data presented in this paper is very limited and preliminary in nature, it still illustrates a major opportunity for cost avoidance. The cost of helicopter gears is very high. If even a small percentage of such gears can be salvaged and reused without any loss of aircraft performance, significant cost savings will result. In spite of such favorable results, the prospect of implementing gear repair in the near future is unlikely as it faces daunting challenges. With flight safety and legal liability in mind, if a mishap occurs, very few in the DoD want to consider implementing this procedure without the strong endorsement and support of the aircraft's OEM. In addition to these issues, if this procedure is implemented, the OEM risks the potential reduction of a lucrative spare parts business. Consequently, OEM support is either unavailable or available at prohibitive costs. This procedure has the potential for reducing sustainment costs, but may not see the light of day due to lack of implementation. The fact that significant cost avoidance can be achieved gives reason for optimism.

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