Repair of High Value/High Demand Spiral Bevel Gears by Superfinishing

Eric C. Ames
Aerospace Engineer
US Army Research Development and Engineering Command
Aviation Applied Technology Directorate Ft. Eustis, Virginia
eric.ames@us.army.mil

This paper describes a research and development effort focused on the remediation of high value, high demand spiral bevel gears for the UH-60 helicopter tail rotor drive train. Spiral Bevel gears for the UH-60 helicopter are in generally high demand due to the needs of new aircraft production and the overhaul and repair of aircraft returning from service. This makes the acquisition of new spiral bevel gears to support R&D activities very challenging. These difficulties and the potential for significant cost savings, led to the assessment of an emerging superfinishing process, known as the Micromachining Process or MMP, as a repair technique for spiral bevel gears. The use of superfinishing also was believed to offer potential performance and durability improvements over the existing ground surface finish. Candidate gears were those previously rejected during overhaul for surface damage to the active tooth profile. Candidate rejected UH-60 Tail Take-off (TTO) spiral bevel gears were obtained from Corpus Christi Army Depot. A selection process involving inspection for cracks, and characterization of the surfaces was conducted. Two gears were selected for refurbishment using MMP. Surface replication and detailed coordinate measurements were conducted on the gears both pre and post MMP. One of these gears was then installed into a UH-60 main transmission and subjected to a 25 hr overload test. The results of the MMP process and the performance of the gear are described in this paper.

INTRODUCTION

Spiral bevel gears are high precision and high cost components that are used in the main powertrain of nearly all modern rotorcraft. Production of these gears is a complex process beginning with a forged shape of high quality aerospace steel, such as AMS 6265. The shape is rough machined into a precise 3-D geometry and heat-treated to achieve the desired strength characteristics that provide the desired combination of surface durability and bending fatigue resistance. The final geometry and surface finish are achieved by finish grinding and shot peening. The complete processing cycle can take from 6 to 9 months, creating a significant lead time for the acquisition of new production parts.

Production of new aircraft coupled with the overhaul of aircraft returning from service in both Iraq and Afghanistan has created a situation where the demand for new production spiral bevel gears is very high. Available gear assets are closely monitored by both the OEM and the government to ensure that an adequate supply is available for new production and overhaul purposes. This situation creates significant challenges in acquiring spiral bevel gear assets with which to conduct research and development programs.

This paper reports an investigation of an emerging surface finishing technology, known as the Micromachining Process (MMP), as a repair technique for aerospace spiral bevel gears. A prior study [1] has shown the potential of existing superfinishing methods (chemically assisted vibratory processes) to remediate the active tooth surfaces of spur and helical gears with light surface damage. Significant cost savings could be realized if more rejected gears could be reclaimed and put back into service.

The genesis of this investigation began with an evaluation of the overload capacity of the UH-60 helicopter tail rotor drive train. The UH-60 tail rotor drive train layout, which consists of six separate spiral bevel gears in three individual gearboxes, is illustrated in Figures 1 and 2. This evaluation was to consist of two separate 25 hr high load endurance tests at 150% of the rated continuous power, with an

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additional test at 170% power with transients up to 200%.

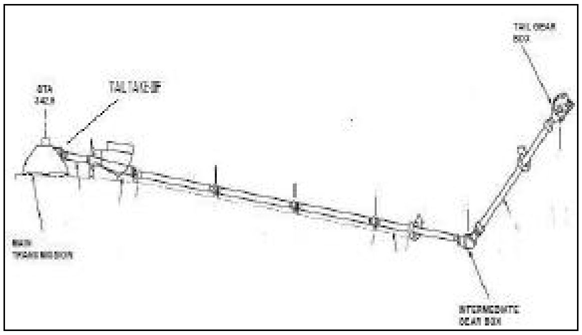

Figure 1. UH-60 Tail Drive Train Layout

Figure 2. UH-60 Tail Drive Train Spiral Bevel Gears

Block I Overload Test Results

The first block of testing was conducted in March of 2010 and utilized a mixture of new production gears and some with very low service usage. Testing revealed that the tail take-off bevel gear mesh has limited tolerance to sustained operation at these high overload conditions. Near the end of the test, a tooth fracture of the tail take-off (TTO) bevel gear was experienced. This fracture likely resulted from a line of micropits that formed on the root of the gear due to high contact pressures from the tip of the mating pinion. Figure 3 shows the posttest condition of both the TTO gear and its mating gear. Teeth of the TTO bevel gear are all heavily scuffed, and heavy wear, polishing, and scuffing are observed on the TTO pinion teeth.

Figure 3. TTO Bevel Gear and Pinion post Block I Overload Testing

Block II Overload Testing

Acquisition of new production gears to conduct the second block of testing proved to be very difficult. Several specific gears had delivery times of more than 12 months. Two specific gears, the TTO pinion, and the tail rotor gearbox output gear (TRGBX) proved to be in extremely high demand with all existing production parts assigned to either new production aircraft or those undergoing overhaul.

In order to conduct the Block II overload testing in a reasonable timeframe, an effort to remediate several TTO pinion spiral bevel gears previously rejected at overhaul was undertaken. Additionally, an effort to remediate several TRGBX output gears, previously run in a Naval Air Warfare Center - Aircraft Division (NAWC-AD) research effort was also undertaken. The candidate UH-60 TTO spiral bevel pinion gears were provided by the U.S. Army's Aviation & Missile Command (AMCOM), Storage, Analysis, Failure Evaluation and Reclamation (SAFR) program at Corpus Christi Army Depot (CCAD). Candidate TRGBX output spiral bevel gears were provided by NAWC-AD Propulsion and Power Division at Naval air Station, Patuxent River, MD. These gears were utilized to support previous UH-60 drive train seeded fault testing at NAWC-AD. Only the results of the remediation work on the TTO bevel pinions will be discussed in this paper, as the approach for the two different configurations was very similar.

The Army's SAFR Program provides expert parts failure analysis, repair development and remediation solutions to military aviation maintainers in support of their critical supply needs. SAFR accomplishes this by collecting "select mission essential" candidate parts removed at CCAD or other depot maintenance facilities. These candidate parts no longer meet current technical repair criteria, or are "Beyond Economical Repair" (BER) due to funding, maintenance capability or obsolescence issues. SAFR does not collect crash damaged or mutilated parts. Candidate parts selection is based upon critical supply need, complexity to manufacture, raw materials availability and/or long procurement lead times. The high cost and demand for rotorcraft spiral bevel gears makes them a significant item for the SAFR program.

Costs of the six individual gears in the UH-60 tail drive train are shown in Table 1. These costs were obtained using the Defense Logistics Agencies Integrated Mobile Database Quick Search Application and were acquired in January 2010. While a detailed MMP treatment cost for each of these specific gear configurations has not been developed, based upon processing quantities of 20 or more parts in sequence, it is estimated that the processing cost should be less than $1,000 per part.

Table 1. Cost of UH-60 Tail Drivetrain Gears

Gear	Part Number	Cost
TTO Bevel Gear	70351-38167-101	$9,436
TTO Bevel Pinion	70351-48148-101	$7,291
IGB Bevel Pinion	70357-06314-101	$6,643
IGB Bevel Gear	70357-06315-101	$7,117
TRGB Bevel Pinion	70358-06619-101	$6,613
TRGB Bevel Gear	70358-06620-102	$18,521

Superfinishing Using the Micromachining Process

The MMP superfinishing method is a technique originally developed in Europe for creating appearance enhancing finishes for the luxury watch making, high end jewelry and premium eyewear markets (reference 2.). MMP is a physical-catalyst surface treatment applied to items placed inside a treatment tank. The process uses a unique formulation of media developed in-house by the company BESTinCLASS. The MMP process is available in the US through MicroTek, which formed a Joint Venture with BESTinCLASS in 2009. Potential advantages of the MMP are uniform material removal (heal to toe and root to tip) and a very smooth surface finish on the order or 0.5 micro inches .

Characterization of Candidate Gears

Four candidate TTO bevel pinions were provided by the SAFR program office for evaluation. Each of these four gears (Figure 4) had varying degrees of surface damage and wear. Photographs of the driving side of a select tooth from each gear are shown in Figure 5.

Figure 4. Candidate TTO Pinions as Received from SAFR

Figure 5. Driving Tooth Surfaces of Candidate Pinions

The candidate pinions were first sent to Overhaul Support Services (OSS), East Granby CT for nondestructive testing and ranking of the candidates in terms of suitability for repair and reassembly into the test gearbox. OSS is a FAA certified overhaul and repair facility specializing in dynamic components for Sikorsky Aircraft. Each of the pinions was subject to a magnetic particle inspection and found to be free of cracks. OSS ranked the damage of each of the pinions and recommended that two pinions (SN C518-00159 and SN A518-00011) were best suited for repair with SN C518-00159 being the least damaged.

These two pinions were then sent to Wedeven Associates (WA), Edgmont, PA for detailed characterization of the gear tooth surfaces. The techniques used by WA involved making silicone replicas of the gear teeth surfaces and subsequently using a Phase Shift Surface Interferometer to create 3-D representations of the tooth surfaces. These digital surface models were then analyzed to determine features such as overall roughness, wear and the maximum depth of specific defects or pits.

The replica material utilized, 101RF (general purpose/fast curing), was manufactured by Microset Product, Ltd. Warwickshire, UK. This product has been shown to have extreme sensitivity that can allow replication of the surface within 10 nanometers. Close-up photographs of the gear tooth surfaces and the associated silicone replicas are shown in Figures 6 and 7.

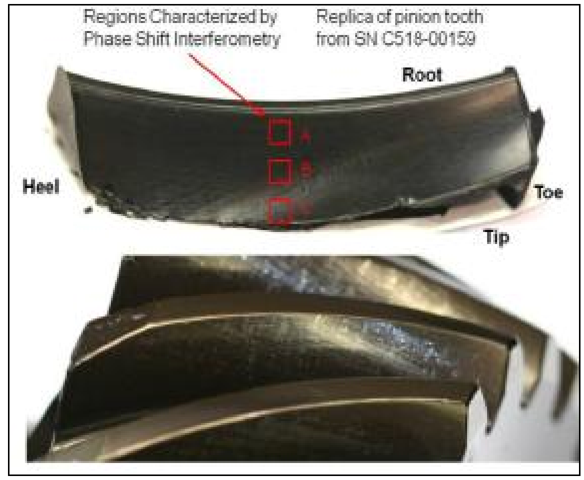

Figure 6. Silicone Replica of TTO Bevel Pinion SN C518-00159

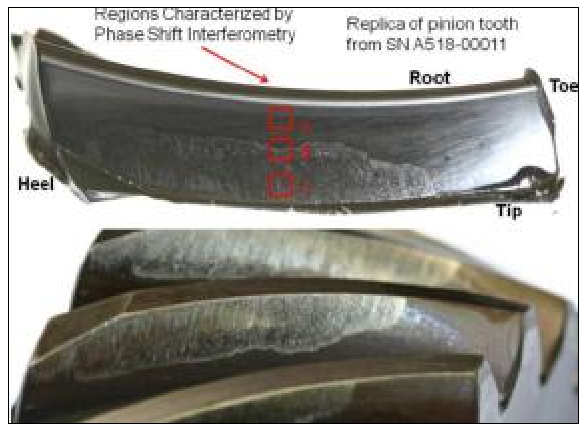

Figure 7. Silicone Replica of TTO Bevel Pinion SN A518-00011

The approximate tooth height from root to tip is 0.31 inches. Three-dimensional analysis of the replicated surfaces was conducted at mid-span of the tooth face width as shown in the figures. Specific regions near the root, center, and tip were analyzed for mean surface roughness (Sa) and maximum pit depth. Results of this analysis are shown in Figure 8. To enhance the visual appearance of the surface features, a 20X magnification in the Z direction (depth) was applied.

It should be noted that the surface roughness measurements acquired by various optical methods discussed in this paper (Phase Shift Surface Interferometry and Confocal Microscopy) are shown as 3-D parameters based upon an analysis of a defined local area of the gear tooth surface. The Sa parameter is the arithmetical mean height of the surface area and the Sq parameter is the root mean square height of the surface area. Other surface roughness measurements acquired by contacting methods are 2-D parameters and are relative to the direction which to probe is moved across the surface. Ra is a measurement of the average roughness or the height of the peaks from the mean surface. Rt is the total height of the profile from the lowest valley to the highest peak.

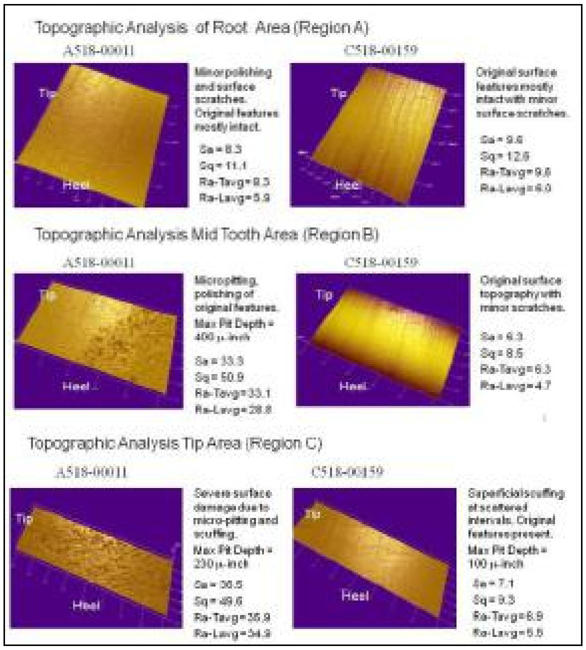

Figure 8. As Received Surface Finish and Topography of Candidate TTO Bevel Pinions

The surface of the TTO pinion SN C518-00159 was generally characterized as having minor damage consisting of surface scratches and some scattered superficial scuffing near the tooth tip. The surface of the TTO pinion SN A519-00011 shows severe micropitting and scuffing originating from the mid section of the tooth out to the tip. The depth of damage in this region is 100-200 micro-inches with a maximum pit depth of 400 micro-inches.

MMP Treatment Results

Upon completion of the surface characterization, both pinions were delivered to MicroTek's facility in Hamilton, Ohio to undergo of the MMP surface treatment. The MMP process produces a very highly polished surface with a high degree of reflectivity as can be seen in Figure 9. The effect appears to be uniform with the root and fillet areas having the same appearance as the tooth faces and top lands. To the casual observer, the part may appear to have been chrome plated post MMP.

Figure 9. TTO Bevel Pinion Post MMP Treatment

The pre and post MMP surface roughness of both candidate TTO bevel pinions was measured by MicroTek using a stylus based surface profilometer. Figure 10 shows the results for the TTO bevel pinion C518-00159. The values shown are an average of six individual measurements. It should also be noted that the drive and coast side measurements are in the transverse direction relative to any original finishing (grinding) features which tend to be longitudinally oriented (heal to toe) in nature. The longitudinal grinding features can be seen in the surface topography of the as-received C518-00159 in Figure 8. The root measurements were taken longitudinally or parallel to the lay of the grinding features.

Figure 10. Pre and Post MMP Surface Roughness of TTO Bevel Pinion C518-00159

The TTO bevel pinion A518-00011 proved to be more challenging for the MMP treatment as the surface damage was much more pronounced. Because this was the first time that MicroTek had attempted to reclaim a part of this particular material and geometry, the MMP method was conducted in two stages. The initial processing was deliberately light to assess the material removal rate versus time. Figure 11 shows the results obtained after the initial and final processing. The remnants of the original

Figure 11. Pre and Post MMP Surface Roughness of TTO Bevel Pinion A518-00011

pitting damage (shown in Figure 7) can clearly be seen on the tooth surface after the initial MMP treatment. The second (final) treatment essentially removed evidence of the damage, providing a very smooth surface finish.

Topographical Inspection

Both candidate gears were subject to a topological inspection to assess the total amount of material removed and assess the gears conformance to the drawing specifications. The TTO bevel pinion A518-00011 was sent to Gleason Works, Rochester New York for inspection at three different points in the process; prior to the initial MMP treatment, and after the initial and final MMP treatments. The TTO bevel pinion C518-00159 was inspected post MMP treatment by Sikorsky Aircraft against their digital master gear.

Figure 12 shows the effect of the initial MMP treatment on the tooth topography of bevel pinion A518-00011. As expected, the changes were minimal with a maximum of 0.00009 inches being removed from the top land on the concave (driving) side of the tooth. It should

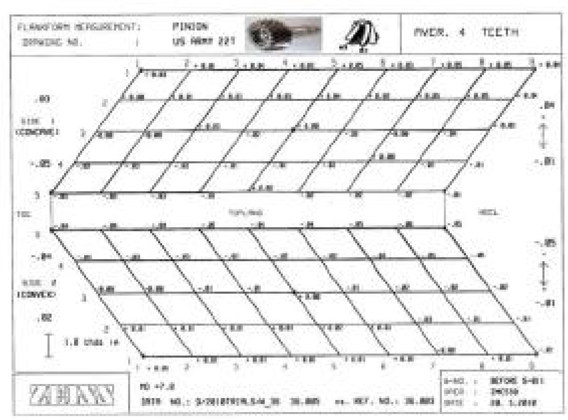

Figure 12. TTO Bevel Pinion A518-00011 Flank Form Analysis After Initial MMP Treatment

be noted that Gleason's analysis selects a center point on the tooth as a zero point. The positive values indicated in the root must be added to the negative values shown on the tip to arrive at the total amount of material removed. Figure 13 shows the results of the topographical inspection performed after the second MMP treatment of A518-00011. The material removal is significantly greater than that achieved in the initial processing. The distribution of material removal is generally uniform from the root

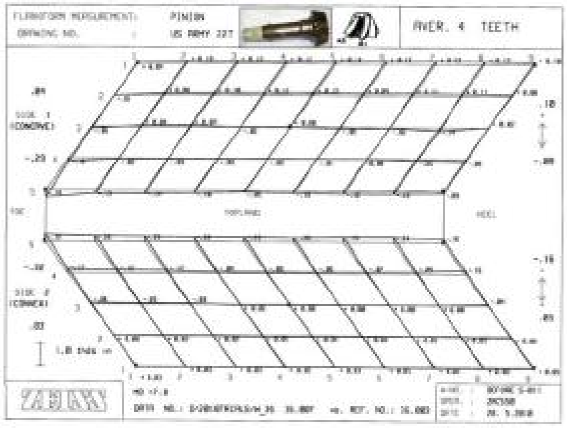

Figure 13. TTO Bevel Pinion A518-00011 Flank Form Analysis After Final MMP Treatment

up to approximately 75% of the tooth height and also from heel to toe. In the tip region of the tooth, more material was removed with a maximum reduction of 0.00039 inches on the toe end of the concave (driving) side and 0.00019 inches on the tip of the heel. Observation of the convex (coast) side of the tooth shows a very similar pattern with nearly equal material removal characteristics and the same toe bias. The amount of material removal is consistent with the depth of damage identified during the initial tooth replication and surface analysis as shown in Figure 6. Based upon the Gleason analysis, the change in tooth thickness was determined to be minimal and on the order of 0.0001 inches.

The results of the Sikorsky topological measurements of pinion C518-00159 are shown in Figure 14. The measurements shown are the total deviations from the digital master gear geometry. The maximum deviation on the concave (drive) side of the tooth is -0.00041 inches on the tip of the heel. This is within the 0.0005 inches tolerance allowed by Sikorsky for the drive side of primary power gears of this class and size. While the concave (coast) side of the tooth has significantly more deviation from the master gear, it too is well within tolerance as the requirements for the cost side are double (0.001 inches) that of the drive side. Measurement of the tooth thickness revealed that the change was very small and the pinion would provide a backlash of 0.055 inches when mated with its driving gear. The tolerance on backlash is 0.04 to 0.06 inches.

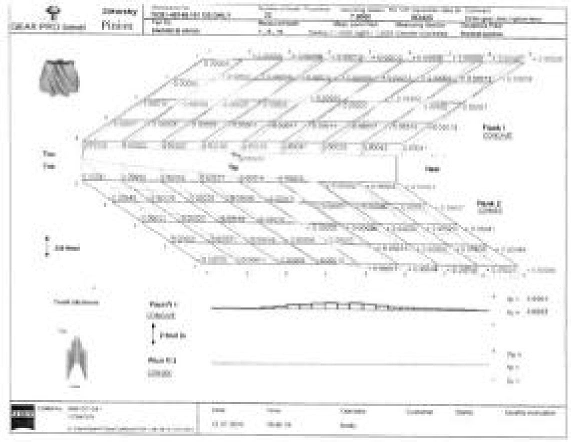

Figure 14. Flank Form Analysis of TTO Bevel Pinion C518-00159 After MMP Treatment

Post MMP Surface Analysis

Surface replicas were made of the same teeth on each pinion after the MMP treatment. The replicas were evaluated by Wedeven Associates and the results are shown in Figures 15 and 16.

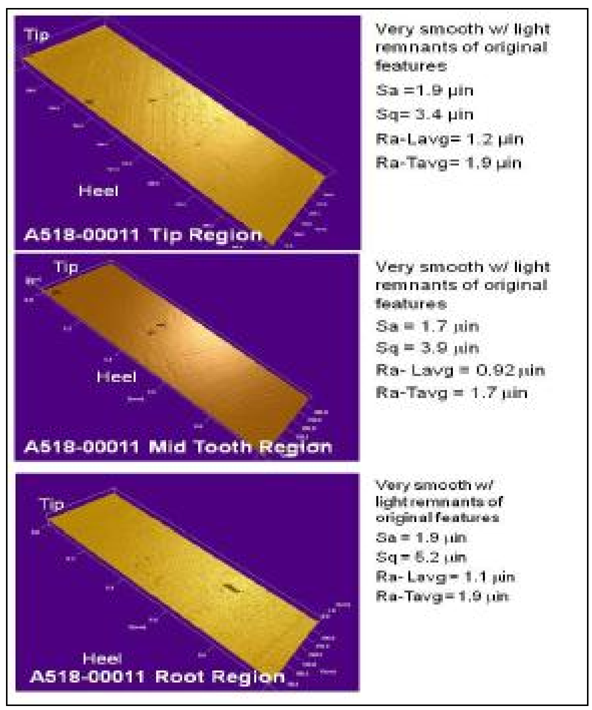

Figure 15. Pinion A518-00011 Post MMP Surface Finish and Topography Characteristics

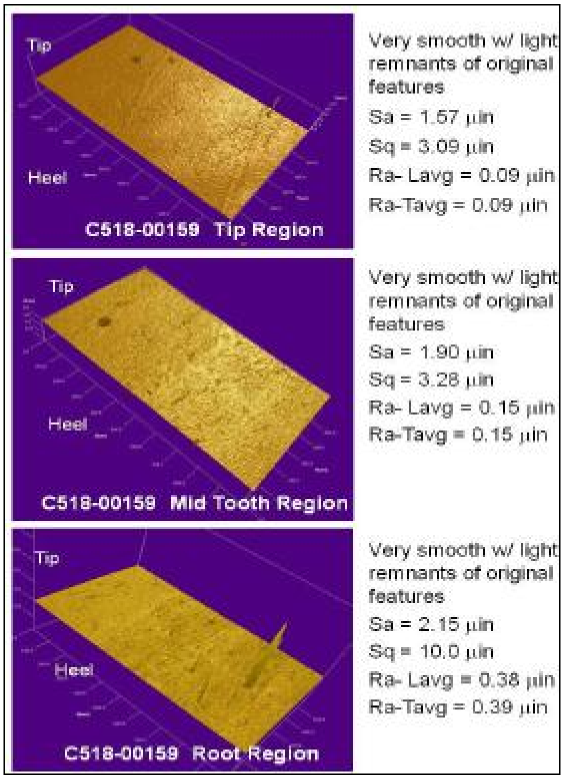

Figure 16. Pinion C518-00159 Post MMP Surface Finish and Topography Characteristics

The surfaces of the gear teeth have a significantly improved finish and exhibit a nearly isotropic texture with only faint remnants of the original wear and machining features. It should be noted that pinion A518-00011 has several randomly distributed pits in each of the three regions. The depth of these pits is approximately 10-20 micro inches (0.23- 0.45 microns) and is probably a remnant from the original surface damage as received (see Figures 7 and 8). Additional MMP treatment may have been able to reduce further the number of these pits. This type of investigation was not possible during this effort due to the small quantity of available assets and associated risk of removing too much material and driving the gear physical geometry past the allowable minimums for tooth thickness and deviation from the desired tooth topography.

Pinion Selection and Gearbox Assembly

While both pinions met the drawing specifications, pinion C518-00159 was the first to become available and was thus selected for assembly and test. In hindsight, this may have been fortuitous since it appeared to have less residual surface pits than A518-00011. Assembly of the test gearbox was performed by Overhaul Support Services (OSS), East Granby, Connecticut. OSS is an FAA certified repair facility for many models of Sikorsky helicopters including the H-60 line of aircraft. Assembly was completed without issue. An acceptable contact pattern was achieved and is shown in Figure 17. The full gear mesh can be seen in Figure 2.

Figure 17. Contact Pattern Achieve During Assembly with Pinion C518-00159

Gearbox Testing

The tests were performed at the Naval Aviation Warfare Center - Aircraft Division (NAWC-AD), Helicopter Drive System (HeDS) test facility located in Patuxent River, MD. The HeDS consists of a structural rig capable of physically supporting the MH-60K Main Gearbox MGB, the input modules, the IGB, and the TGB. Two T700-GE-701C (one engine operation was adequate for providing the necessary HP to the tail drive system) engines are used to drive the test gearboxes. The horsepower developed by the single engine was transmitted through the main input module and MGB. The IGB and TGB were driven as they are in the aircraft by the tail rotor take-off flange out of the MGB. The MGB was only lightly loaded for this test. The IGB and

TGB were loaded through a single-disk waterbrake dynamometer manufactured by The Kahn Company. The test gearboxes as installed in the HeDS facility are shown in figure 18. Testing was completed in September 2010. Approximately 32 hrs of total operation was accomplished with 16 hrs accumulated at 800 hp, 1 hr accumulated at powers exceeding 900 hp, and 47 minutes at powers slightly exceeding 1050 hp. It should be noted that the TTO gear mesh is currently qualified for maximum continuous operation at 524 hp. Figure 19 shows the posttest condition of the TTO pinion and mating bevel gear.

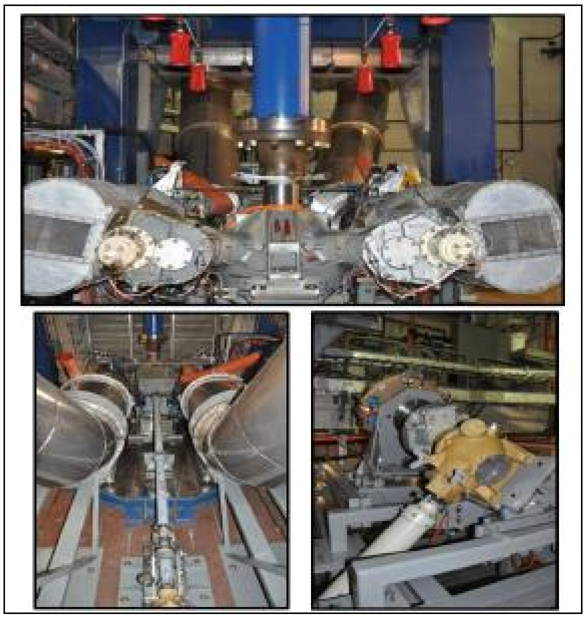

Figure18. HeDS Facility with Test Gearboxes Installed

Figure 19. Post Test TTO Pinion and Bevel Gear Gear Tooth Finish and Topography Changes During Testing

In order to observe the changes in surface finish and topography as the gear mesh accumulated cycles, silicone replicas were taken at several intervals during the test. This process included removal of the TTO pinion and thorough cleaning of both the pinion and the driving gear to get a quality replica. This proved to be a challenge for the TTO bevel gear as it was only accessible through the TTO pinion housing bore. After some trial and error, the HeDS technicians were able to develop a technique that produced high quality replicas. Replicas of the MMP treated pinion and the mating gear were taken after the 2 hour break-in run, after 12.5 hrs of running at 800 hp, and after 33.5 hrs of running which included the 900 hp operation and the transient runs to 1050 hp. Photographs of the replicas themselves are shown in Figure 20. The development of a line of micropits

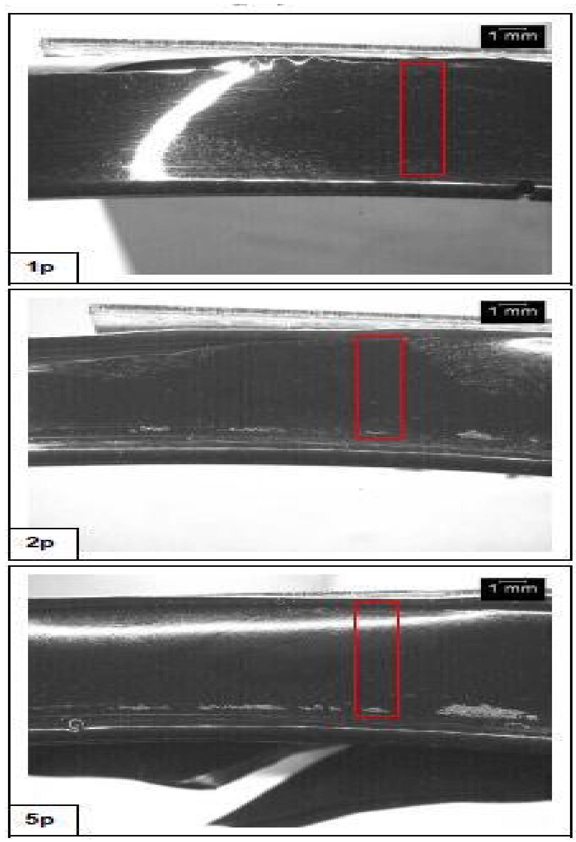

Figure 20. Replicas of TTO Pinion C518-00159 taken at 2 hrs (1p), 12.5 hrs (2p), and 33.5 hrs (5p) of test time

can clearly be seen in replica 2p which was taken at 12.5 hrs of running. This area corresponds to the root area of the actual pinion and is likely the result of an area of high contact stress due to the lack of adequate tip relief at the very high overload conditions applied during the testing. The growth of the line of these pits along the root of the pinion face can be clearly seen in replica 5p which was taken at the conclusion of the testing. A replica taken of the mating gear at the conclusion of the testing is shown in Figure 21. There are no indications of damage to the gear. The directionality of the surface topography of the gear, which was a new production part without the MMP treatment, can clearly be seen in the replica. The directionality of the surface is a direct result of the original grinding process.

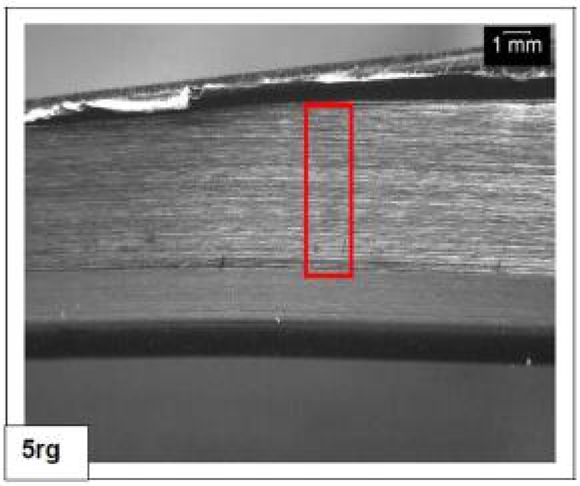

Figure 21. Replicas of TTO Gear Taken at 33.5 hrs (5p) of test time

A detailed 3-D analysis of these replicas was performed by Coubrough Consulting, LLC Independence, Ohio. The replica surfaces were measured using a NanoFocus µsurf topometer employing confocal technology. Localized regions of the tooth tip, mid, and root areas were evaluated similar to the pre-test evaluation. The pinion surfaces are shown in Figures 22 thru 24. The roughening of the tip region, slight polishing of the mid tooth region, and formation of a line of micropits in the root area can clearly be seen. The surfaces of the TTO gear that mates with the pinion are shown in Figures 25, 27 and 28. The TTO gear replica taken after 2 hrs of testing was of poor quality and prevented detailed analysis. Figure 25 shows the surface roughness and topography of the TTO bevel gear prior to testing. The surface finish was measured as 15 micro inches (Sa). It should be noted that the TTO gear is not shot peened. Measurements of a production intermediate gearbox spiral bevel pinion, which is ground and shotpeened (Figure 26) show a surface roughness of 12 micro inches (Sa). While the measured Sa values are similar, the texture of the two surfaces is clearly different with the shot peened surface having less directionality as the peaks of the grinding features are reduced. As the endurance testing progressed, a dark line developed on the root area of the TTO bevel gear (see Figure 19). The replica analysis failed to show indications of any change in topography associated with this feature which may be an oil stain. The effect of additional running at 800 hp and the higher transient loads appeared to have little further influence upon the TTO gear surface finish and topography with only a slight changes in surface finish as shown in Figures 27 and 28.

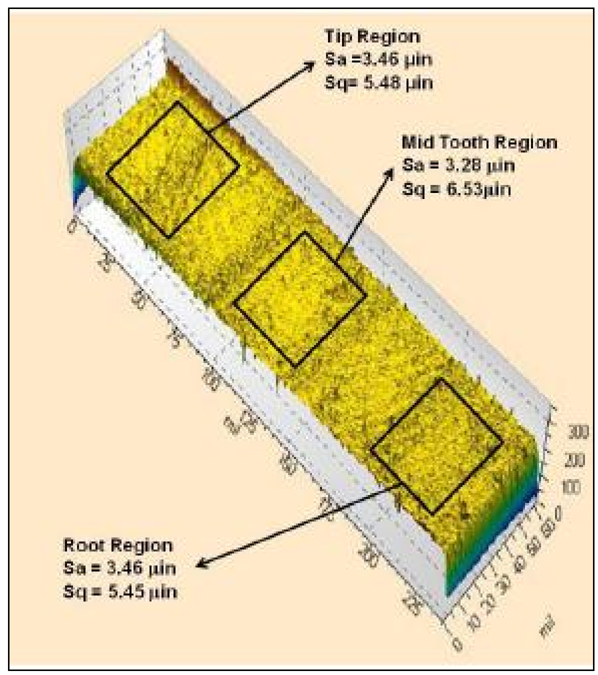

Figure 22. Surface Roughness and Topography of TTO Pinion After 2 hrs of Testing

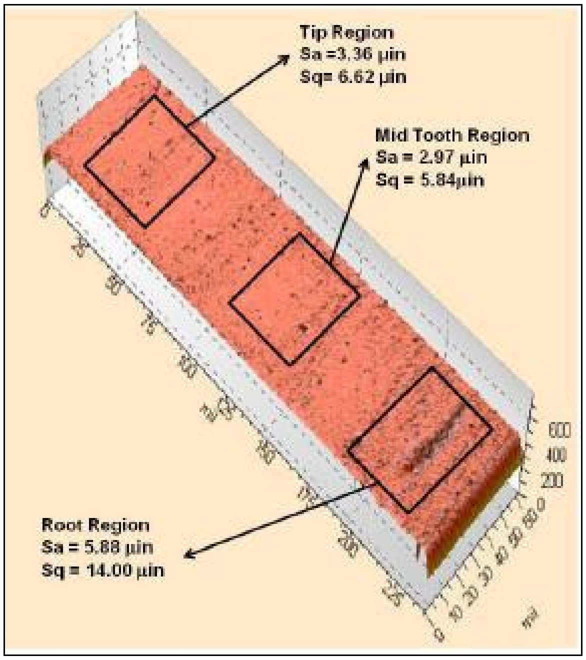

Figure 23. Surface Roughness and Topography of TTO pinion after 12.5 hrs of Testing

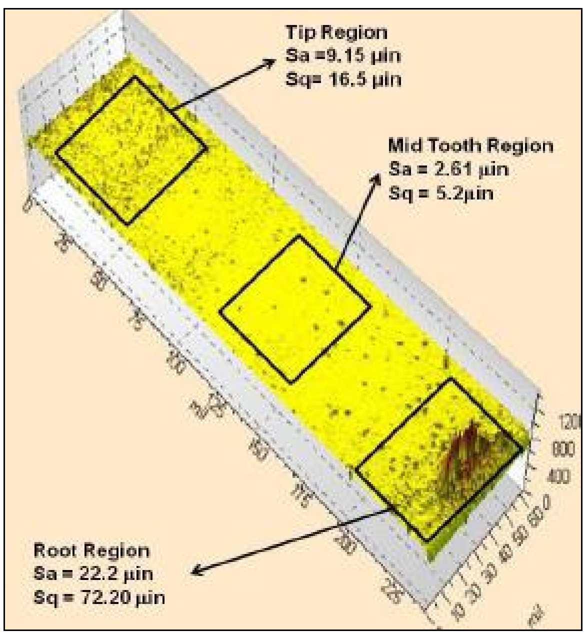

Figure 24. Surface Roughness and Topography of TTO Pinion After 33.5 hrs of Testing

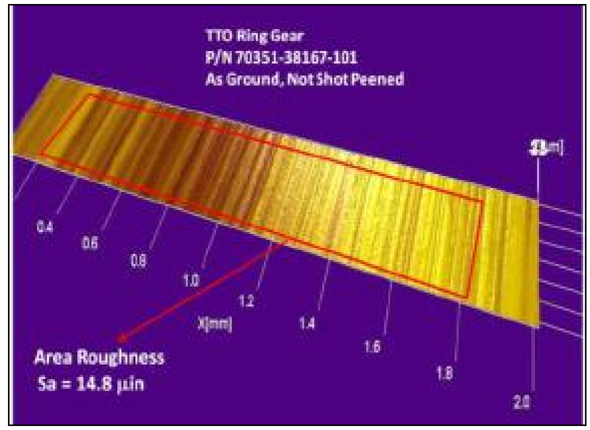

Figure 25. Surface Roughness and Topography of TTO Gear Prior to Testing

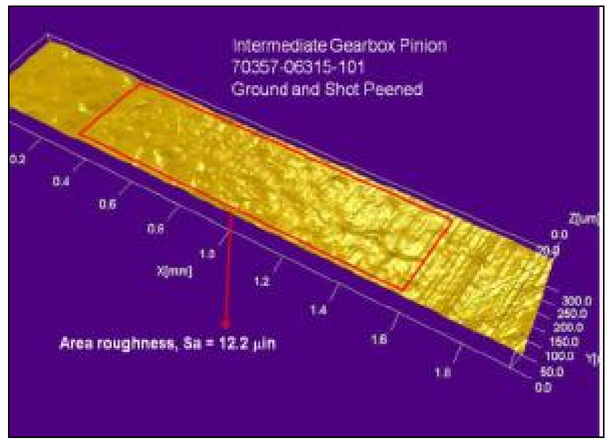

Figure 26. Surface Roughness and Topography of New Production IGB Pinion

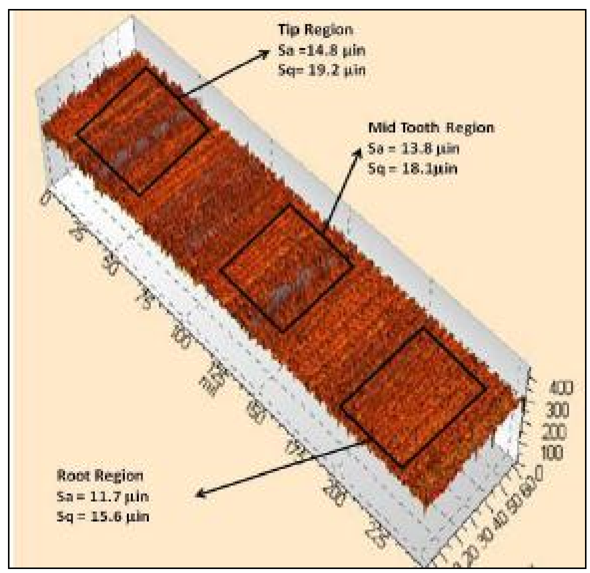

Figure 27. Surface Roughness and Topography of TTO Gear After 12.5 hrs of Testing

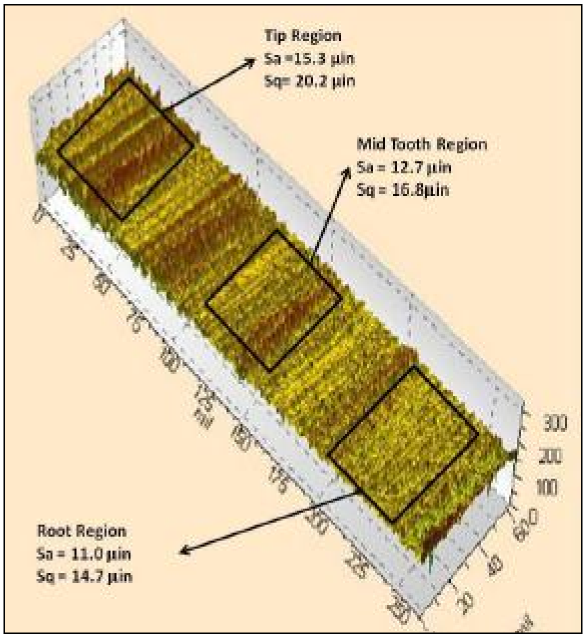

Figure 28. Surface Roughness and Topography of TTO Gear After 33.5 hrs of Testing

Conclusions

The use of the MMP superfinishing technique has strong potential as a cost saving refurbishment method for high value spiral bevel gears for rotorcraft.

The MMP technique provides a significant reduction in surface roughness that is well known to enhance the surface durability of high power aerospace gearing.

The superior performance of the MMP treated TTO pinion in the Block II testing versus the baseline gears in the Block I testing shows potential for the refurbished gears to have enhanced performance. It is likely that this same performance increase can be achieved in new production gears.

The amount of material removed by the MMP technique is controllable thus allowing gears with varying degrees of damage to be refurbished only to the degree necessary to remove the deepest damage.

The use of silicone replicas to record the condition of gear tooth surfaces combined with 3-D surface analysis by either phase shaft interferometer or confocal techniques can provide significant insight regarding the effects of surface finish and topography on spiral bevel gear performance.

Recommendations

Additional research into the surface durability of damaged tribological surfaces refurbished with the MMP treatment would increase confidence in the performance of repaired gears.

While the gear tooth surfaces repaired by the MMP process may conform to the desired finish and geometry characteristics, additional metallurgical tests such as Nital etching should be performed to evaluate the potential for more severe surface damage such as large areas of scuffing to have tempered or softened the surface.

Additional research to fully characterize the degree of gear tooth surface damage that can be economically repaired would enable a more accurate determination of potential cost savings.

References:

1. Repair of Aircraft Transmission Gears via Isotropic Superfinishing, Dr. Suren B. Rao, May 2009, Gear Technology

2. http://www.microtekfinishing.com

Acknowledgements:

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