Sierra Nevada Corporation (SNC), along with NASA Goddard Space Flight Center (GSFC), tested several Harmonic Drive gears for their longevity and performance to determine the best material combinations for a mission, requiring an actuator life nearly ten times previously qualified. Accelerated life testing in both ambient and vacuum environments revealed two suitable candidates for the flight build. The combination of a Nitronic 60 circular spline and 15-5PH H1075 flexible spline was ultimately chosen. It was surprising though, that 15-5PH H1075 on both circular and flexible splines outperformed the heritage material combination (Melonited Flex Spline against a 15-5PH Circular Spline) and also could have been used in the flight build.

Introduction

The NASA Global Precipitation Measurement (GPM) mission required actuators for its High Gain Antenna System (HGAS) and Solar Array Drive Assembly (SADA) with a life significantly higher than the required life of heritage actuators previously qualified by SNC for the Lunar Reconnaissance Orbiter (LRO) mission and the Solar Dynamics Observatory (SDO) mission as shown in Table 1. One of the life-limiting components in the actuator design is the Harmonic Drive gear. Wear was observed in the circular spline teeth during the post-life test teardown inspection on the SDO and LRO actuators. This wear was determined to be acceptable for those missions, but when extrapolated out to the life requirements of the GPM mission, the effect of tooth wear on performance became uncertain. The heritage LRO and SDO actuators used T-Cup Harmonic Drive gears manufactured by Harmonic Drive LLC in Peabody, MA in order to provide a large through hole in the actuator. The drives had a 200:1 gear ratio and utilized a combination of a Melonite™ treated Flex Spline and 15-5PH Circular Spline. This particular material combination had not been life tested by either SNC or Harmonic Drive LLC for the number of cycles required for the GPM mission.

Table 1: Required Life Comparison

<table>
<thead>
<tr>
<th>Application</th>
<th>Cycle</th>
<th># of Cycles (for 1X Life)</th>
<th>Total Degrees</th>
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<tr>
<td>SDO</td>
<td>360° (continuous)</td>
<td>2,500</td>
<td>900,000°</td>
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<tr>
<td>LRO</td>
<td>180° CW, 180° CCW</td>
<td>5,700</td>
<td>2,052,000°</td>
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<tr>
<td>GPM SADA</td>
<td>250° CW, 250° CCW</td>
<td>17,500</td>
<td>8,750,000°</td>
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<tr>
<td>GPM HGAS</td>
<td>190° CW, 190° CCW</td>
<td>48,600</td>
<td>18,468,000°</td>
</tr>
</tbody>
</table>

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Hardware Configurations

Based on discussions between Harmonic Drive LLC and SNC, the following material combinations were selected for comparative life testing, with the goal of extending the life of the Harmonic Drive gear in order to meet the GPM HGAS requirement:

- 15-5PH H1075 Circular Spline against Melonited 15-5PH H1100 Flex Spline
  - Most similar to heritage
  - Removed weight reduction cuts for more repeatable performance
  - Reduced the size of the pre-melonite grit blast media for better surface finish
  - Increased the circular spline hardness from H1150 to H1075 for better wear resistance

- Nitronic 60 Circular Spline against Melonited Flex Spline
  - Same as above except for Circular Spline material
  - Nitronic 60 recommended by Harmonic Drive LLC based upon testing reported in Reference 1

- Nitronic 60 Circular Spline against 15-5PH H1075 Flex Spline
  - Same as above except for flex spline material
  - Melonite removed to result in less abrasive flex spline
  - Flex Spline hardness increased to H1075 for better wear resistance

- 15-5PH H1075 Circular Spline against 15-5PH H1075 Flex Spline
  - Chosen for test because the components were available from the other combinations
  - Low expectations due to potential for galling/cold welding from identical materials in contact

All Harmonic Drive gear configurations were customized HDT-25, 200:1, T-cup component sets manufactured in Peabody MA by Harmonic Drive LLC and all were of the same dimensional design. All combinations used the same wave-generator bearing material and design, and each was identically lubricated with Pennzane 2001-3PbNp oil and Rheolube 2004 grease per standard procedures. Table 2 summarizes the tested configurations with assigned part numbers.

Table 2: Material Combinations

<table>
<thead>
<tr>
<th>Part #</th>
<th>Circular Spline Material</th>
<th>Flexible Spline Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>36638-1</td>
<td>15-5PH H1075</td>
<td>15-5PH H1100 w/ Melonite</td>
</tr>
<tr>
<td>36638-2</td>
<td>15-5PH H1075</td>
<td>15-5PH H1075</td>
</tr>
<tr>
<td>36638-3</td>
<td>Nitronic 60 Annealed</td>
<td>15-5PH H1100 w/ Melonite</td>
</tr>
<tr>
<td>36638-4</td>
<td>Nitronic 60 Annealed</td>
<td>15-5PH H1075</td>
</tr>
</tbody>
</table>
Ambient Life Test Plan

The Life Test plan is shown in Figure 1. A standard run-in was performed by Harmonic Drive LLC on each Harmonic Drive component prior to the start of any testing. Following run-in, each Harmonic Drive gear was characterized by measuring starting torque and torsional stiffness. The starting torque of the Wave Generator input was measured in six equidistant positions with the Circular Spline fixed and no load applied to the Flex Spline output. Torsional stiffness was measured in six equidistant locations at the Flex Spline output with the Circular Spline and Wave Generator input held stationary. Once each Harmonic Drive gear was assembled into its life test fixture, the torsional stiffness test was repeated at 25 equidistant locations to characterize the baseline assembled condition. The ambient life test was conducted to simulate 2X the required mission life and was conducted in air at room temperature. The Harmonic Drive gear input was driven at a nominal input speed of 52.36 rad/s (500 rpm). The Harmonic Drive gear output was loaded to 2.93 N-m (26 in-lb) with a friction brake (see Figure 2) to simulate the application frictional load plus the load required to accelerate the specified inertia. The life test was run alternating between clockwise and counter-clockwise directions for approximately 24 hours at a time. At the conclusion of the life test, the Harmonic Drive gear had completed over 51,300 output revolutions in each direction (39,936,000° of total travel). Following the ambient life test, the units were again tested for torsional stiffness while assembled in the test fixture. The units were then disassembled, inspected, cleaned, and inspected further with findings documented below.

Figure 1: Test Flow

Figure 2: Ambient Life Test Setup
Ambient Life Test Results

Torsional Stiffness
As shown in Figure 3, the Harmonic Drive gears with a Melonite Flex Spline (36638-1 & 36638-3) showed a decrease in torsional stiffness (5 to 8%) compared to the 15-5PH Flex Splines which showed a slight increase (1% to 5%). As shown in Figure 4 and Figure 5, the shape of the post-life stiffness curves for the Harmonic Drive gears with the 15-5PH Flex Splines were very comparable to the pre-life stiffness curves. However, the shape of the post-life stiffness curves for the Harmonic Drive gears with the Melonite Flex Splines showed a significant reduction in low torque stiffness when compared to the pre-life stiffness curves. The reduction in stiffness on the Harmonic Drive gears with the Melonited Flex Splines was an early indication of increased wear in those drives.

Teardown Inspection
Each Harmonic Drive gear was disassembled to examine its components for wear and debris generation.

Circular Splines
Figure 6 illustrates the differences between the Circular Splines at the end of the life test. Configurations with the Melonite Flex Splines (36638-1 & 36638-3) contained metallic particles packed into the roots of the Circular Spline teeth. Numerous small fragments of metal were found in the roots of 36638-1 but were not as prevalent in 36638-3 even though the amount of wear was similar. The metal fragments were found to be fine metallic wear debris that had packed into the roots of the teeth and been formed into slivers as seen in the photo of the 36638-1 Circular Spline. Additionally there was a noticeable wear step on the 36638-1 & 36638-3 Circular Splines. The non-Melonite Harmonic Drive gears (36638-2 & 36638-4) showed only a slight wear step at the gear mesh and had no accumulation of metallic debris in the roots of the gear teeth. The lubricant color was darker than seen on the 36638-2 & 36638-4 flexible splines, further indicating an increased presence of wear debris.

Flex Splines
Figure 7 and Figure 8 illustrate the differences between the teeth and ID of the Flex Splines at the end of the life test. Configurations with the Melonite Flex Splines (36638-1 & 36638-3) showed very little difference between pre and post-life for both the teeth and the ID. The non-Melonite Flex Splines (36638-2 & 36638-4) teeth were visually worn in the area of highest contact, but the wear was comparable to that seen on their respective Circular Splines and not nearly as significant as seen on the 36638-1 & 36638-3 Circular Splines. The ID of the non-Melonite Flex Splines (36638-2 & 36638-4) were visually worn in the area of contact with the wave generator OD, but there were no signs of galling and the amount of wear was acceptable for a 2X life condition.

Wave Generator
Figure 9 and Figure 10 illustrate the differences between the OD and balls of the Wave Generators at the end of the life test. All Wave Generators showed some polishing on the OD from contact with the Flex Splines. The Melonited Flex Splines in 36638-1 and 36638-3 showed a higher level of polishing but not enough to cause any concern. The wave generator lubricant was lighter in the non-Melonite drives (36638-2 & 36638-4) indicating less wear particles present.

Harmonic Drive LLC Inspection
The Harmonic Drive gears were thoroughly cleaned and sent back to the manufacturer to measure the tooth profiles. A total of four teeth were measured on each flexible and circular spline and compared to the theoretically perfect tooth. The Harmonic Drive gears using the Melonite Flex Spline (36638-1 & 36638-3) showed much more deviation from the theoretical tooth profile than the non-melonite flexible splines. The teeth on the non-Melonite drives (36638-2 & 36638-4) were still generally within the acceptable manufacturing standard tolerance range, with 36638-2 (15-5/15-5) showing the least amount of deviation.
Figure 3: Pre and Post Ambient Life Stiffness

Figure 4: Pre-Life Minimum Stiffness Curves (Radians vs. In-Lb)
Figure 5: Post-Life Minimum Stiffness Curves (Radians vs. In-Lb)

Figure 6: Circular Spline Teeth, Post Ambient Life
Figure 7: Flex Spline Teeth, Post Ambient Life

Figure 8: Flex Spline ID, Post Ambient Life
Figure 9: Wave Generator OD, Post Ambient Life

Figure 10: Wave Generator Balls, Post Ambient Life
Ambient Life Test Results Summary
The two Melonite Harmonic Drive gears (36638-1 and 36638-3) were eliminated from contention due to the reduction in torsional stiffness at the end of life and the presence of relatively large particles of metallic debris in the gear mesh. The two non-Melonite Harmonic Drive gears (36638-2 & 36638-4) were relatively comparable. 36638-2 visually looked slightly better, (primarily with regard to the circular spline teeth and gear lubricant) but the 36638-4 was nonetheless acceptable. The concern over how 15-5PH against 15-5PH would perform during vibration and in a vacuum environment, resulted in the 36638-4 configuration (15-5/Nitronic) being chosen as the least risky path forward for the flight build. A qualitative assessment of the key parameters of the post-life inspection is shown in Table 3. In parallel with building flight hardware with the chosen configuration, the program decided to further this study by performing a vacuum life test comparison between the non-Melonite drive configurations (36638-2 & 36638-4).

<table>
<thead>
<tr>
<th></th>
<th>36638-1</th>
<th>36638-2</th>
<th>36638-3</th>
<th>36638-4</th>
</tr>
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<tbody>
<tr>
<td><strong>Stiffness Change</strong></td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
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<tr>
<td><strong>Circular Spline Tooth Wear</strong></td>
<td>Poor</td>
<td>Average</td>
<td>Poor</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Flex Spline Tooth Wear</strong></td>
<td>Good</td>
<td>Average</td>
<td>Good</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Flex Spline Cup</strong></td>
<td>Good</td>
<td>Average</td>
<td>Good</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Wave Generator OD</strong></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Gear Teeth Lube</strong></td>
<td>Poor</td>
<td>Average</td>
<td>Poor</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Wave Generator Lube</strong></td>
<td>Good</td>
<td>Average</td>
<td>Good</td>
<td>Average</td>
</tr>
</tbody>
</table>

Vacuum Life Test Plan

Based on the ambient life test results and concerns regarding the validity of a life test in ambient air, a second round of testing was conducted in a vacuum. The testing was repeated on new Harmonic Drive gears with the best performing configurations from the ambient test, 36638-2 and 36638-4, in a vacuum environment combined with thermal cycling.

Testing was performed per the same flow shown in Figure 1 except as noted below. Baseline torsional stiffness testing was performed on the vacuum test Harmonic Drive gears prior to life testing as previously done with the ambient test to characterize the pre-life performance. The vacuum life test consisted of 100,000 cycles of reversing 180° output revolutions in a <5.0x10⁻⁵ Torr vacuum environment, cycling between 0 and 40°C. The input to the Harmonic Drive gear was set to 52.36 rad/s (500 rpm). A magnetic particle brake was used to apply a constant 2.93 N-m (26 in-lb) friction load to the output for the duration of the test. Following the ambient life test, the units were again tested for torsional stiffness while assembled in the test fixture. The units were then disassembled, inspected, cleaned, and inspected further with findings documented below.
Vacuum Life Test Results

Torsional Stiffness
As shown in Figure 11, there was very little difference between the post-life torsional stiffness of the two configurations. The 36638-4 saw a 5% reduction in torsional stiffness while the 36638-4 saw a 9% reduction in torsional stiffness, but based on the stiffness plots seen in Figure 12, neither drive saw a significant reduction in low torque torsional stiffness that was seen on the Melonited drives during the ambient life test.

Teardown Inspection
Each Harmonic Drive gear was disassembled to examine its components for wear and debris generation.

Circular Splines
Figure 13 illustrates the differences between the Circular Splines at the end of the life test. The Nitronic 60 Circular Spline (36638-4) only showed a change in surface finish at the edge of flex spline contact, whereas the 15-5PH Circular Spline (36638-2) showed a slight wear step. Neither drive displayed significant generation of metallic debris or any buildup of debris in the roots. The gear mesh lubricant was lighter than seen after the ambient life test most likely due to reduced oxidation in vacuum.

Flex Splines
Figure 14 and Figure 15 show the teeth and ID of the Flex Splines at the end of the life test. The Flex Spline teeth of both drives were minimally worn in the area of highest tooth contact. There was no sign of galling or cold welding in the 36638-2 configuration (15-5PH against 15-5PH). The ID of the Flex Splines were visually worn in the area of contact with the wave generator OD, but there were no signs of galling and the amount of wear was acceptable for a 2X life condition and comparable to the ambient life test.

Wave Generator
Figure 16 and Figure 17 show the OD and balls of the Wave Generators at the end of the life test. Both Wave Generators showed some polishing on the OD from contact with the Flex Splines, but results were comparable to the ambient life test and to be expected for 2X life. Again, the wave generator lubricant was slightly lighter than seen in the ambient life test (less oxidation) and the 36638-4 configuration was slightly darker than the 36638-2 configuration.

GSFC Material Analysis
Very slight wear was observed on the flex spline teeth of both assemblies which appeared to be slight burnishing of the tooth surface. No pitting or scoring was visible. Grease from both assemblies exhibited evidence of metallic wear. Infrared spectroscopic analysis of the grease was inconclusive in determining a ‘winner’. In all the samples, a weak intensity carbonyl band was detected, indicating very little grease/oil degradation. The greater amount of metallic wear debris in the flex spline-circular spline contact of the 15-5PH & 15-5PH combination suggests the 15-5PH & Nitronic 60 is a slightly better configuration.
Figure 11: Pre and Post Vacuum Life Stiffness

Figure 12: Pre and Post Life Torsional Stiffness Plots
Figure 13 – Circular Spline Teeth, Post Vacuum Life

Figure 14 – Flex Spline Teeth, Post Vacuum Life
Figure 15: Flex Spline ID, Post Vacuum life

Figure 16: Wave Generator OD, Post Vacuum Life

Figure 17: Wave Generator Balls, Post Vacuum Life
Vacuum Life Test Results Summary
The vacuum environment had little to no effect on the wear rate of the two Harmonic Drive gears tested. The slight differences in wear between the two configurations are not significant, and changes in wear between vacuum and ambient tests can be attributed to normal variation from unit to unit. The results of the vacuum life test supported the decision by the program to use the 15-5PH against Nitronic 60 Harmonic Drive gear configuration (36638-4) for the GPM program. Surprisingly, the 15-5PH against 15-5PH configuration (36638-2) would have also been an acceptable choice. A qualitative assessment of the key parameters of the post life inspection is shown in Table 4.

Table 4: Qualitative Summary of Vacuum Life Test Results

<table>
<thead>
<tr>
<th></th>
<th>36638-2</th>
<th>36638-4</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>15-5PH / 15-5PH</td>
<td>Nitronic / 15-5PH</td>
</tr>
<tr>
<td>Stiffness Change</td>
<td>Good+</td>
<td>Good-</td>
</tr>
<tr>
<td>Circular Spline Tooth Wear</td>
<td>Good-</td>
<td>Good+</td>
</tr>
<tr>
<td>Flex Spline Tooth Wear</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Flex Spline Cup</td>
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<tr>
<td>Wave Generator OD</td>
<td>Average</td>
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<tr>
<td>Gear Teeth Lube</td>
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<td>Average</td>
</tr>
<tr>
<td>Wave Generator Lube</td>
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Conclusion
Accelerated Harmonic Drive gear life testing validated the concern that the heritage material combination of a Melonite Flex Spline running against a 15-5PH Circular Spline was not optimal for an extended life requirement of nearly ten times previously qualified. An alternate combination of a Melonite Flex Spline against a Nitronic 60 Circular Spline was also ruled out based upon test results. After completion of both Ambient and Vacuum accelerated life tests, two material combinations displayed test results indicating a high level of confidence in passing the increased life requirement. After joint deliberation between SNC and NASA GSFC, the combination of a 15-5PH H1075 Flex Spline and a Nitronic 60 Circular Spline was chosen for incorporation into the GPM HGAS and SADA actuators. Despite industry concerns over identical stainless steels operating in contact, the material combination of 15-5PH H1075 against 15-5PH 1075 performed nearly identically to the combination selected and would have been a high confidence selection as well.

References