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Reducing wear of steel rolling on Ti6Al4V operating in vacuum

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ABSTRACT – This work was motivated by qualification test results of a mechanism for a space telescope. During the test undesired wear debris was formed. Alternative materials and coatings were tested with intent to reduce wear and debris when steel has a misaligned rolling contact on Ti6Al4V. Testing was done using a vacuum roller rig mimicking the mechanism's contact conditions. Ten configurations were tested, most of which resulted in significant wear debris. The best wear protection and least amount of visible debris was observed with the combination of hardened 440C, anodized Ti6Al4V smoothed by an ultrasonic process, and providing 1-micrometer thick nanocomposite coating to both rollers by sputtering.

1. INTRODUCTION

This work was motivated by results of a qualification test of a mechanism to be used for the James Webb Space Telescope [1]. The mechanism is part of the near infrared spectrograph (NIRSpec) instrument. The instrument features an array of micro shutters. All shutters are opened as a group by sweeping a magnet over the array, and then individual shutters can be closed as needed for observations. The sweeping motion of the magnet is guided by a set of preloaded steel rollers in contact with anodized Ti6Al4V flat surfaces. The qualification testing done in a cold vacuum chamber matched as closely as possible to the extreme deep space environment. Post-test inspections of the qualification test article revealed some wear of the steel rollers and mating Ti6Al4V surfaces, and some undesired loose debris was also found. This research describes results of roller rig tests of ten material configurations with the goal to minimize wear debris.

2. TEST APPROACH AND TEST RIG

Ten roller pair material combinations were selected based on review of literature and discussions with the subject matter experts. The ten roller-pair material configurations were evaluated using vacuum roller rig tests. Evaluations were based on qualitative assessment of roller surface conditions, mass lost or gained by each roller, wear phenomena as assessed by stylus profilometer, and SEM examinations. The ten selected materials combinations are shown in Table 1.

A vacuum roller rig (VRR) at NASA Glenn Research Center was used for this investigation. The VRR hardware includes drive motors, a vacuum system producing <$3x10^{-7}$ Torr, and a turntable that can provide roller misalignment angles up to +/- 1.4 degrees. The output shaft roller is driven through a torque-limiting permanent magnet clutch. The clutch torque and the output shaft motor speed settings resulted in a net torque of 1 Nm transferred through the rollers' contact and rolling slip of less than 2%. This closely approximated the roller contacts in the micro shutter mechanism that are essentially free rolling. A normal load sensor and a torque sensor were used to measure the force and torque between the rollers. A linear variable differential transformer measures shaft misalignment angle within 0.08 degrees accuracy. The drive shaft and the driven shaft were instrumented with encoders that provided 6,000 pulses/rev. A schematic of VRR is shown in Figure 1 and a schematic of the test rollers and measured forces is shown in Figure 2. The selected test conditions were normal load of 130 N, a shaft misalignment of 0.9 degrees, and test duration of 90,000 revolutions. This provided a suitable accelerated life test for evaluating materials and coatings.

Table 1 Ten roller material test combinations.

Roller Pair	Upper Roller	Lower Roller
1	440F, Annealed, Passivated	Ti6Al4V, Anodized
2	440C, Hardened, Passivated	Ti6Al4V, Anodized
3	Polyimide	Ti6Al4V, Anodized
4	440C, Hardened, Passivated, Bonded PTFE Solid Lube	Ti6Al4V, Anodized
5	440C, Hardened, Passivated	Ti6Al4V, PEO, Bonded Solid Lube
6	440C, Hardened, Passivated	Ti6Al4V, (WC)aC:H DLC
7	440C, Hardened, (TiC)aC:H DLC	Ti6Al4V (TiC)aC:H DLC
8	440C, Hardened, Passivated, Nanocomposite MoS_2	Ti6Al4V, Anodized
9	440C, Hardened, Passivated, Nanocomposite MoS_2	Ti6Al4V, Anodized, Nanocomposite MoS_2
10	440C, Hardened, Passivated, Nanocomposite MoS_2	Ti6Al4V, anodized, Ultrasonic Smoothing, Nanocomposite MoS_2

3. RESULTS AND DISCUSSION

All ten different roller pairs after the test were photographed and are shown in Figure 3. *The 1st roller pair material combination* matched the qualification test materials. Significant adhesive wear and plastic flow of material occurred throughout the test. After 78,000 cycles high vibrations were occurring, and the test was stopped early of the targeted 90,000 cycles to avoid damage to the test apparatus. The upper steel roller lost 71 milligrams mass while the lower Ti6Al4V roller gained 59 milligrams mass. *The 2nd roller pair* showed significant adhesive wear after 25% of the test duration. Steel rollers lost mass and Ti6Al4V rollers gained mass, but the wear rate was greatly reduced as compared to the first roller pair. *The 3rd roller pair* showed a large amount of polyimide debris and the test was stopped after 38,000 cycles, much less that the intended 90,000 cycles test. The *4th roller pair* produced a great volume of powdery debris. The *5th roller pair* had the lower Ti6Al4V roller treated by plasma electrolytic oxidation (PEO) and a bonded solid lubricant. The wear of the solid lubricant film created a mixture of powder and large flakes of film, and eventually significant adhesive wear occurred. The final condition of the rollers for this configuration appeared visually similar to that of the 2nd roller pair. *The 6th roller pair* had the Ti6Al4V lower roller coated with a tungsten-containing diamond-like carbon (DLC). Wear and debris formation occurred throughout the test. During the first 25% of the test duration, the rollers surfaces showed abrasive wear, but towards the test end rollers surfaces appeared to be primarily adhesive wear. *The 7th roller pair* had titanium-containing DLC coatings that changed the wear behavior compared to uncoated or solid film lubricated rollers. Early in the test the wear may have been abrasive in nature, but as the test progressed the wear appeared to be adhesive wear. *The 8th roller pair* had only the upper roller coated with nanocomposite MoS_2. The results showed adhesive wear phenomenon was delayed and the overall wear rate was reduced as compared to tests without a solid lubricant film. *The 9th roller pair* used the same nanocomposite MoS_2 coating as was used in the 8th roller pair but in this configuration both rollers were coated. The test results demonstrated good wear protection. Both rollers lost some mass with no net mass gain by adhesive wear for Ti6Al4V as had occurred for uncoated roller pairs. From visual assessments wear protection was excellent, but a debris collection pan collected many bright particles reflecting light and easy to see without aid of magnification. *The 10th roller pair* was almost identical to 9th roller pair, except for an additional processing step of ultrasonically smoothening the rough Ti6AL4V rollers before sputtering the nanocomposite MoS2 coating. Results showed excellent wear protection. Six tests were conducted for this configuration to more than 87,800 cycles for each test. Four of the tests provided excellent wear protection. Two of the tests, while slightly lesser performing, still provided very good wear protection. For one of the two lesser performing tests, the coating thickness was about one-half of the intended thickness because of a temporary problem with the coating process. The thinner film was likely at least partially responsible for the less-effective wear protection. The undetectable wear on the lower roller was a great contrast to the behavior of the lower Ti6Al4V roller of the 9th roller pair in which a distinct wear valley of 1-micrometer depth was created. Many bright debris particles were seen without aid of magnification on the debris pan during testing of the 9th roller pair but were absent for the 10th roller pair. Average mass loss from the roller pairs for 10th roller pair configuration was 0.3 milligram. The ultrasonic smoothing process provided a more favorable surface for avoiding wear.

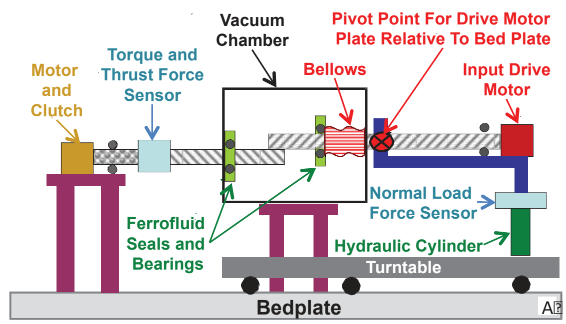

Figure 1 Schematic of the VRR, side view.

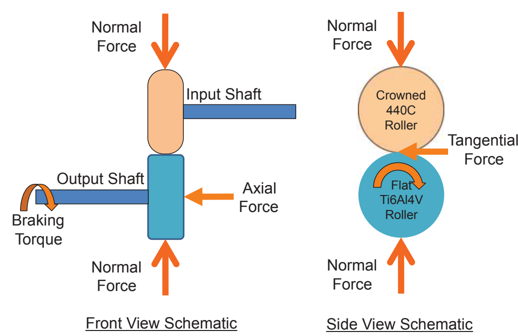

Figure 2 Schematic of the test rollers and forces.

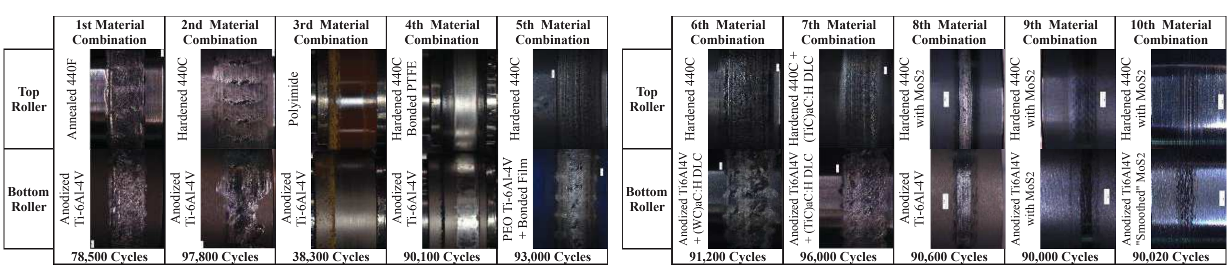

Figure 3 Photos of the 10 roller pairs after testing.

4. CONCLUSIONS

(a) Changing annealed 440F roller with 440C steel hardened to 60 HRC resulted in a reduction of overall wear by a factor of two to three.

(b) Use of a polyimide roller instead of a steel roller is not suited for this application.

(c) While diamond-like-carbon coatings altered the wear behavior, large amounts of debris were created.

(d) Application of a nanocomposite MoS_2 significantly reduced the wear and production of wear debris.

(e) Application of the nanocomposite MoS_2 film to both rollers provided better wear protection.

(f) The best wear protection and least amount of visible debris was observed with the combination of hardened 440C, anodized Ti6Al4V smoothed by an ultrasonic process, and providing 1 micrometer thick nanocomposite coating to both rollers by sputtering.

ACKNOWLEDGEMENT

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REFERENCE

[1] James Webb Space Telescope, https://www.jwst.nasa.gov/