



Tribological Evaluation of Candidate Gear Materials Operating Under Light Loads in Highly Humid Conditions

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Abstract

A series of pin-on-disk sliding wear tests were undertaken to identify candidate materials for a pair of lightly loaded timing gears operating under highly humid conditions. The target application involves water purification and thus precludes the use of oil, grease and potentially toxic solid lubricants. The baseline sliding pair is austenitic stainless steel operating against a carbon filled polyimide. The test load and sliding speed (4.9 N, 2.7 m/s) were chosen to represent average contact conditions of the meshing gear teeth. In addition to the baseline materials, the hard superelastic NiTiNOL 60 (60NiTi) was slid against itself, against the baseline polyimide, and against 60NiTi onto which a commercially deposited dry film lubricant (DFL) was applied. The alternate materials were evaluated as potential replacements to achieve a longer wear life and improved dimensional stability for the timing gear application. An attempt was also made to provide solid lubrication to self-mated 60NiTi by rubbing the polyimide against the disk wear track outside the primary 60NiTi-60NiTi contact, a method named stick or transfer-film lubrication.

The selected test conditions gave repeatable friction and wear data and smooth sliding surfaces for the baseline materials similar to those in the target application. Friction and wear for self-mated stainless steel were high and erratic. Self-mated 60NiTi gave acceptably low friction (~0.2) and modest wear but the sliding surfaces were rough and potentially unsuitable for the gear application. Tests in which 60NiTi pins were slid against DFL coated 60NiTi and DFL coated stainless steel gave low friction and long wear life. The use of stick lubrication via the secondary polyimide pin provided effective transfer film lubrication to self-mated 60NiTi tribological specimens. Using this approach, friction levels were equal or lower than the baseline polyimide-stainless combination and wear was higher but within data scatter observed in these preliminary tests. Based upon these results, self-mated 60NiTi gear teeth utilizing solid lubrication, is a reasonable approach for the target application.

Introduction

Polymer gear materials are often used for mechanisms that operate under light loads and low speeds because they are inexpensive to fabricate, are lightweight and do not rust. They are also self-lubricating and maintenance-free. Due to the intrinsically lower strength and wear resistance properties of polymers, compared to metals, they are rarely used for power transmission at high power levels. These attributes make them well suited to low cycle applications like office machines, automotive accessory applications (such as window lifts) and small appliances (Ref. 1).

One application well suited to the use of polymer gears is a vacuum pump on board the International Space Station (ISS) inside the wastewater processing system (Refs. 2 to 4). In this application, two mating spur gears drive separate lobes of a roots type blower that is used to reduce the ambient pressure inside a rotary distillation unit. By design, the gear set is exposed directly to the moist, warm process stream. To avoid contamination of the process fluid, no oils, greases or other toxic lubricants can be used to mitigate friction and wear of the meshing gear teeth. Figure 1 shows a cross section of the rotary distillation assembly and the location of the gears.

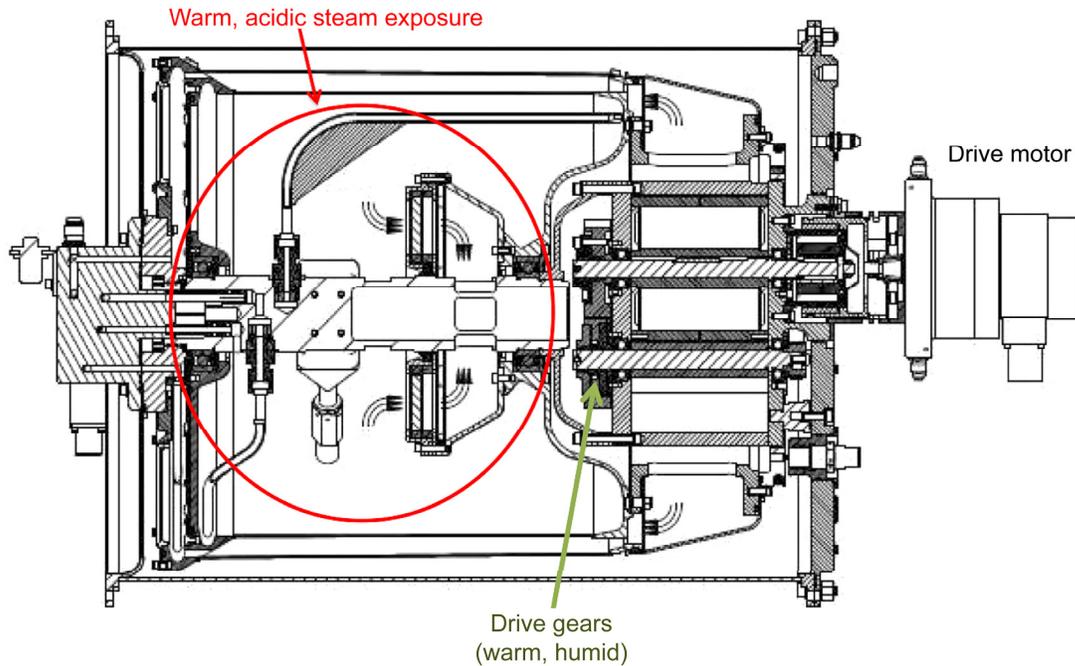


Figure 1.—Cross-section of distillation assembly showing location of drive gears. Sketch adapted from Reference 4.

In this application, the gears ensure accurate timing of the pump lobes to prevent lobe-to-lobe contact. As such, excessive wear of the gear mesh, as opposed to frictional power losses, is a primary consideration. Along with tooth wear, dimensional accuracy and precision is also a factor in maintaining proper timing of the pump lobes. Polymers tend to absorb moisture and have relatively high thermal expansion coefficients and these characteristics result in dimensional changes challenging timing accuracy. To minimize this effect while providing adequate self-lubrication, a mixed material, duplex gear approach that utilizes one stainless steel gear meshing with one polymer gear is employed. In this case, the stainless steel gear provides optimum dimensional stability while the mating polymer gear provides intrinsic self-lubrication to the meshing teeth.

The use of the duplex gear mesh approach has been successful overall but leaves opportunities for improvement on several fronts. Net-shape injection molding is often the preferred approach to achieving precision polymer gears. With this fabrication technique a precision steel mold is filled with uncured polymer resin that then hardens into the exact shape and size required. Unfortunately, such an approach is only practical for applications in which large numbers of gears are to be made. The ISS application is not high volume and this leads to the use of conventional machining of the polymer gear. On a per gear basis, such a labor-intensive manufacturing approach is costly. Further, the polymer gear must be initially undersized so that it can “swell” under normal operating temperature and humidity to the desired dimensions. Since installation and assembly is done at room temperature and low humidity conditions while the gear is undersized, achieving accurate gear timing in use is difficult. It would be desirable for this application if more dimensionally stable materials, like stainless steel, could be used for both gears while maintaining proper solid lubrication to achieve long life.

Aside from using the duplex gear approach, another means for solid lubrication is the use of thin solid lubricant coating on the surfaces of metal gear teeth to reduce friction and wear. For applications that have light loads, low sliding speeds and moderate wear life requirements, solid film lubricants are a reasonable approach (Ref. 5). Solid lubricant films for gear teeth applications can also be deposited and replenished by dynamically operating a metal gear against a sacrificial polymer gear through intentional transfer film (sometimes aptly named stick) lubrication (Ref. 6). Determining whether these approaches are valid normally requires a full-scale gear test. Such tests can be expensive and time consuming and are at times better preceded by a bench test experiment.

In this paper, the friction and wear behavior of candidate gear and solid lubricant materials for the ISS application are evaluated using a pin-on-disk friction and wear test rig (tribometer). Candidate test specimens and configurations include austenitic stainless steel, the baseline polyimide, the superelastic 60NiTi and a graphite filled PTFE solid lubricant coating. The tests are intended to identify new approaches to satisfy the application requirements and improve the overall cost and performance of the gear system.

Materials and Procedures

A pin-on-disk test is used to evaluate the candidate gear materials. Figure 2 shows the test rig. In this test, a hemispherical tipped pin is loaded in pure sliding against the face of a rotating disk. Friction is continuously monitored during the test and wear is measured by removing the specimens after testing is complete. The wear process leads to a flat, round wear scar on the pin and a shallow wear groove or track on the disk. Given the relatively modest loads and speeds for the current tests, disk wear is too small to accurately quantify so sliding friction and pin wear alone are used to gage material performance.

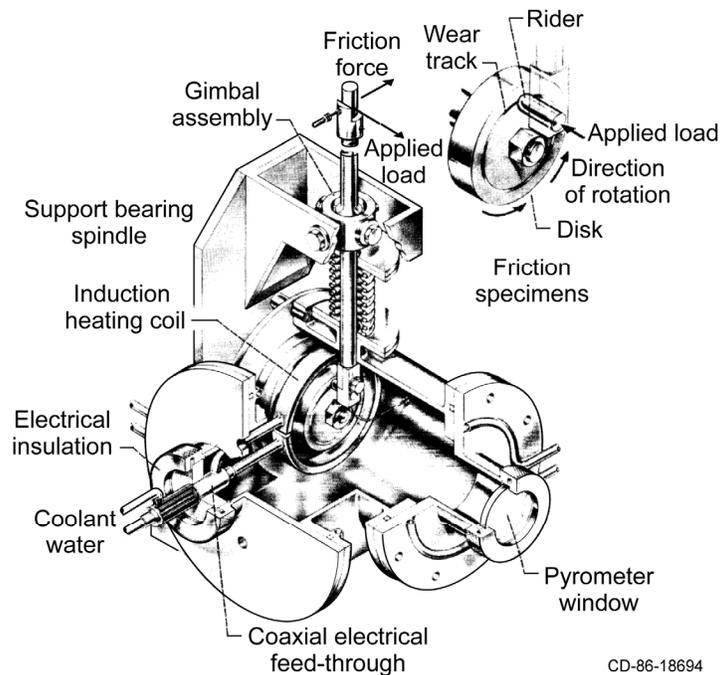


Figure 2.—Pin-on-disk tribometer used to evaluate friction and wear of candidate gear materials. Tests conducted in air at 25 °C, 50 to 60 percent relative humidity.

Hemispherical tipped pins are fabricated from the baseline polyimide, austenitic stainless steel and the superelastic 60NiTi. Disk specimens are made from austenitic stainless steel and 60NiTi. A graphite and PTFE filled solid lubricant coating is applied to selected disks or a sacrificial polymer pin is rubbed against the wear track 90° ahead of the pin-disk contact to achieve solid lubrication.

To maximize the relevance of this bench test to the full-scale gears, a series of calibration steps are taken to ensure that the bench test wear mechanism mimics the application. First an analysis of the gear contact is conducted to determine approximate load and sliding speeds. After these conditions are estimated, a series of calibration sliding tests are done to determine which test conditions result in wear surfaces and wear mechanisms that best resemble the gears taken from field service.

Since meshing gear teeth experience a varying degree of rolling-sliding contact at ever changing loads, the use of a pure sliding test like the pin-on-disk requires care. The contact to be simulated by the pin-on-disk test is the meshing teeth of two spur gears, approximately 150 mm in diameter, transmitting tens of watts of power at speed up to a few thousand revolutions per minute.

When the teeth first contact they experience the most sliding but the lightest contact load. When fully engaged, they experience near perfect rolling (no sliding) but the highest load. During disengagement, both teeth experience diminishing load and an increasing proportion of sliding contact. Thus a reasonable approach for experimental simulation to identify a range of loads and sliding speeds that encompass those experienced by the gear teeth. Two sliding speeds, one low (1.35 m/s) and one high (2.7 m/s) are chosen based upon an established gear geometrical model of spur gears (Refs. 7 and 8). To establish a load range, the power transmitted (~100 W) is combined with the typical running speed (~2000 rpm) yielding the torque and the resulting tooth-to-tooth loading. Three test loads, one low (4.9 N), one medium (9.8 N) and one high (14.7 N) span the region of interest for the application. For estimating the maximum stress the load resulting from power transmission is divided by an estimated contact area.

Using observations of the wear patterns of gears taken from service, the fully engaged tooth mesh area is approximately 32 mm². The product of these test conditions, also called the pressure-velocity (PV) value is a well-accepted parameter to judge the severity of operating conditions for polymer sliding. In our case, the P and V values yield a PV that ranges from ~3 to ~15 kg-m/cm²-s. The product literature PV limits for the graphite filled polyimide tested in this study is over 100, thus the test conditions are well within the manufacturer's load-speed design guidelines (Ref. 9).

Based upon the estimates introduced above, an initial pin-on-disk test condition matrix of three loads (4.9, 9.8, and 14.7 N) and two sliding speeds (1.35 and 2.7 m/s) were selected for experimental evaluation. Preliminary sliding tests in which polymer pins sliding against austenitic stainless steel were conducted under each of these test conditions. Four repetitions were done for each test to assess consistency. The wear surfaces were examined to identify one or more pairs of conditions that gave sliding surfaces that appeared similar to the gently worn gears taken from service. The data is shown in Table I.

The lowest load (4.9 N), yielded smooth wear surfaces and low friction at both the low and high sliding speeds. Inconsistent wear surfaces were observed for the tests at the medium load (9.8 N) and high friction and uniformly rough wear surfaces resulted from the highest test load (14.7 N). Based upon this data, the low load (4.9 N) and high-speed (2.7 m/s) test conditions were chosen for the remainder of the tribology tests. This load-speed pair rapidly produces measurable pin wear data while yielding consistently smooth running surfaces that mimic properly operating gear teeth.

TABLE I.—TEST CONDITION EVALUATION-FRICTION AND WEAR SURFACE APPEARANCE
[Air at 25 °C, 50 to 60 percent relative humidity.]

Trial load, N	Trial speed, m/s	Friction range	Surface appearance
4.9	1.35	0.18 to 0.25	Smooth
4.9	2.70	0.25 to 0.36	Smooth
9.8	1.35	0.2 to 0.30	Rough to smooth
9.8	2.70	0.5 to 0.6	Rough
14.7	1.35	0.5 to 0.9	Rough
14.7	2.70	0.3 to 0.5	Rough

To conduct a materials evaluation, the selected pin and disk specimens are loaded into the tribometer; the motor is started and allowed to reach the test speed (1000 rpm, 2.7 m/s). The test load (0.50 kg, 4.9 N) is then applied. Four repeat tests of 1 hr each are run for each pin and disk specimen set. Pin wear after each one hour test is measured by removing the pin holder and measuring the flat, circular pin wear scar diameter that forms through the wear process on the pin tip using an optical microscope. The pin wear volume is calculated using simple geometrical relationships as described in the literature (Ref. 10). The surface appearance of the pin and the disk wear track are also noted after each test. The data is provided in the following results section.

Two dry film lubricants (DFL), one PTFE-based and one graphite-based, were evaluated using a modified test protocol. In these DFL evaluations, the disk specimen is coated with the DFL and slid against a 60 NiTi pin. The DFL coatings are much softer than the pin thus pin wear is not expected. The tests are ended when the coating wears through to the substrate. Prior to the test, a flat, circular wear scar approximately 3 mm in diameter is created onto the tip of the pin by sliding it against an uncoated 60NiTi disk. This reduces the contact stress in the DFL to about 0.6 MPa (100 psi) and more closely simulates the lightly loaded gear application. Testing then proceeds with the pre-worn pin riding against the DFL coated disk until the coating is worn through to the metal substrate. In these DFL tests, sliding distance to coating wear-out, rather than the pin wear factor, is the experimental result.

Results and Discussion

Table II gives the friction and wear summary for the selected tribomaterials candidates. An inspection of the data reveals some interesting observations.

The friction coefficient levels for the polymer pins sliding against stainless steel and 60NiTi disks were fairly consistent and relatively high (~0.3) considering that the pins are made from solid lubricant (graphite) containing self-lubricating plastic. Generally, one expects friction levels to be below 0.2 for tribomaterials marketed as solid lubricants (Ref. 9). However, the polyimides are well known to exhibit increased friction in the presence of atmospheric moisture. Both the application and these tests are under relatively humid conditions. In this context, the observed friction levels are not surprising. Further, because the loading between gear teeth is low, such friction coefficients are not a hindrance to good gear operation. The more important consideration is the running surface appearance after testing. For all of the polymer pin-metal disk tests, the wear surfaces are smooth. This behavior rightly indicates that the polymer gear-metal gear design approach is valid.

Another interesting and perhaps unexpected observation is the low friction coefficient observed for the case of self-mated 60NiTi. In this instance the friction was only 0.18. Literature friction values for dry sliding of 60NiTi disks against itself, alumina (sapphire) and 440C stainless give much higher friction coefficients ranging from 0.4 to over 1.0 (Refs. 11 to 13). Delving into this data more deeply, however, reveals that these high friction levels are normally associated with low sliding speeds, on the order of mm/s whereas our present tests are conducted at speeds greater by an order of magnitude or more.

TABLE II.—FRICTION AND PIN WEAR DATA SUMMARY
[Test conditions: 4.9 N load, 2.7 m/s sliding speed, air at 25 °C.]

Pin material	Disk material/surface coating	Friction coefficient	Pin wear factor, mm ³ /N-m	Surface appearance
SP21 Polyimide	316L SS	0.29±0.07	1.9±0.7×10 ⁻⁶	Smooth
SP21 Polyimide	304 SS	0.34±0.08	0.7±0.2×10 ⁻⁶	Smooth
SP21 Polyimide	60NiTi	0.28±0.04	2.1±1.5×10 ⁻⁶	Smooth
60NiTi	60NiTi	0.18±0.03	8.3±3.2×10 ⁻⁶	Rough
60NiTi + SP21	60NiTi	0.15±0.03	3.1±1.9×10 ⁻⁶	Smooth
^a 60NiTi	PTFE DFL	0.15±0.02	^b 184 to 348 km	Smooth
^a 60NiTi	Graphite DFL	0.17±0.02	^b 24 to 135 km	Smooth

^aTests initiated with pre-worn pin (~3 mm dia. Wear scar).

^bTests terminated when DFL wore through to substrate. No additional pin wear was observed.

To verify a speed effect, several short duration tests were run for self-mated 60NiTi from 0.27 m/s (100 rpm) to 5.4 m/s (2000 rpm). The friction coefficient dropped continuously from 0.45 to 0.20, respectively. At the highest test speeds vibration of the pin was observed. It is possible that simple rig dynamic loading-unloading effects caused by the rough surfaces resulted in lower average friction, in a skip-slip fashion. It is also possible, but not confirmed, that surface friction heating effects play a role. 60NiTi has a relatively low thermal conductivity, around 10 W/m-°K. It is only about half that of austenitic stainless steel and silicon nitride. For this reason, it is possible that during sliding the pin and disk wear surfaces are heating significantly resulting in the formation of lubricious surface oxides. Others have suggested that such oxides, especially of titanium, can have a beneficial friction reduction effect (Ref. 14). Notwithstanding the observed low friction, the self-mated and lubricated 60NiTi tests resulted in rough wear surfaces and relatively high pin wear. Based upon this alone, using a set of 60NiTi gears without adequate lubrication to mitigate wear is not a sound approach.

When solid lubrication of self-mated 60NiTi specimens is introduced via transfer film (stick) lubrication, the observed friction coefficient is reduced to 0.15 and wear is comparable to the baseline polymer-stainless tribopair. In this case, a second sliding contact consisting of a polymer pin pressed against the disk just ahead of the 60NiTi-60NiTi sliding contact effectively reduced pin wear, resulted in smooth surfaces and low friction. In effect, wear of the polymer pin provided a means to replenish solid lubricant to the 60NiTi disk surface. This approach has been demonstrated for metal gears destined for space use (Ref. 6).

In a research program from the middle of the last century, engineers were faced with providing a means to replenish solid lubrication to gears and bearings operating in a space vacuum environment where contamination by oils and greases were a key concern. In the test set-up described by Bowen, an idler gear made from polymer composite (PTFE and WSe₂) loaded against the metal gears in need of lubrication. The arrangement is shown in Figure 3.

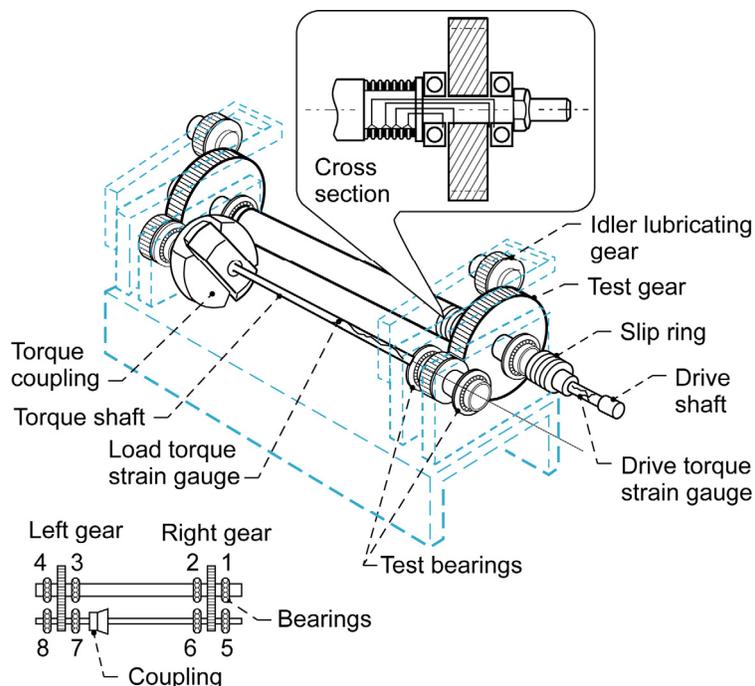


Figure 3.—Historical use of a solid lubricant idler gear to replenish solid lubricants to a metal gear mesh in a vacuum (Ref. 6).

No other lubrication, such as the use of a solid lubricant coating, on the gear teeth was used. Their results showed adequate lubrication at light to moderate loads but gear seizure at the highest test loads. Since the intended gear application currently under consideration is lightly loaded it is reasonable to view the idler gear approach for lubrication in a favorable light. Another approach for lubrication is the use of a purposefully formulated and applied solid lubricant coating.

The use of dry film lubricants (DFL) for gears and space mechanisms is well established (Refs. 5 and 15). Soft metal films like lead and silver are often used for limited life applications and low loads. MoS₂ and graphite based coatings can be effective for highly stressed applications and are particularly well suited for vacuum and cryogenic operation because of their stability. For many dry running applications, DFL's are formulated from mixtures of solid lubricant pigments and tough, wear resistant binders. In a sense, many DFL's resemble thin layers of the graphite filled polymer currently used in the ISS application for one of the gear set. In this work, the DFLs tested were carefully formulated to avoid the use of toxic constituents and to be insensitive to the presence of moisture at temperatures between 25 and 100 °C. One DFL is a PFTE-based coating and the other is graphite-based. Both are intended to be air sprayed onto the gear teeth surfaces and heat cured in an oven prior to use. Based upon literature experimental results of similar DFL's under conforming contact sliding similar to the current pin-on-disk test, wear life was expected to be on the order of 10⁵ to 10⁶ cycles (Refs. 16 and 17).

Examination of the DFL test results shown in Table II confirms the effectiveness of solid film lubrication for 60NiTi. Friction coefficients between 0.13 and 0.19 were observed and wear lives ranged from 10⁵ to over 10⁶ sliding cycles. Furthermore, the use of DFLs resulted in smooth wear surfaces and steady friction coefficient levels with little scatter. Such characteristics are important to achieving quiet running gears.

Summary

The study described in this paper was undertaken to identify a solid lubrication method for a set of high-speed lightly loaded spur gears used to drive the compressor of the Urine Processor Distillation Assembly within the wastewater treatment system on the ISS. The solution currently employed utilizes one 316L stainless steel gear that meshes with a solid polymer gear. Dimensional stability and wear of the polymer gear are the impetus for seeking a more robust approach.

A series of pin-on-disk tribology tests were developed and run to provide a reasonable simulation of the gear tooth wear contact. Wear pins made from the gear polymer material were slid against disks made from the stainless steel gear material as a baseline. Polymer pins were slid against the 60NiTi candidate gear material. Self-mated 60NiTi tests were run with and without additional lubrication provided by rubbing a polymer pin against the disk just ahead of the primary wear contact. Lastly, dry film lubricant (DFL) coatings made from a polymer binder with graphite and PTFE (Teflon) solid lubricant additives were deposited on both stainless steel and 60NiTi test disks for evaluation.

The pin-on-disk test results illustrate that the baseline polymer-stainless steel wear couple exhibits generally low friction and modest wear. Tests of the polymer (pin) against 60NiTi (disk) give results comparable to the polymer-stainless steel baseline. Surprisingly low friction was observed for self-mated 60NiTi wear specimens but the wear was high.

The use of a polymer wear pin to deposit lubricant as a transfer film onto 60NiTi was effective at reducing friction and wear. By far, the best lubrication approach was the use of a DFL coating deposited onto the 60NiTi surface. Friction was smooth, steady and low and metal wear was too low to be measureable in these limited duration tests.

Though the quantitative predictability of the pin-on-disk test with regards to gear life is yet to be proven, the use of a DFL deposited onto 60NiTi gear teeth appears to be a reasonable approach. Should full-scale gear life tests show unacceptable wear, lubricant replenishment could be achieved through the use of a third idler gear made entirely out of polymer.

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